2017-20-February

Exhaust Gas Recirculation and Sound Improvements on Rotax 600 ACE

Austin Donhauser, Joshua Wyant, Keenan Lynch, Shawn Schneider, Andrew Spaulding
Clarkson University Winter Knights

Abstract

The Clarkson University Clean Snowmobile SAE team set a goal to reduce exhaust NOx levels and noise at idle. The Ski-Doo Rev XS platform teamed with the 600 ACE (Advanced Combustion Efficiency) engine has proven successful for Clarkson in past years. A 2017 Ski-Doo Renegade Sport was chosen for this year's challenge. A custom built EGR (Exhaust Gas Recirculation) system greatly reduces emissions at the exhaust while under load, and maintaining sufficient power. A new MoTeC M130 ECU (Engine Control Unit) allows for added control of aftermarket components as well as extensive tuning. The M130 paired with a GM Continental flex fuel sensor gives the 600 ACE the ability to run on ethanol levels up to 85% while maintaining great fuel economy, power and emissions. Significant sound reductions are accredited to a passive exhaust valve, taking much of the noise at idle to a minimum. The stock skid and drivers are replaced by an R-Motion rear suspension and Silent Drive Technology, thus further increasing the snowmobile's efficiency and reducing sound levels. These modifications encourage Ski-Doo's already BAT (Best Available Technology) snowmobile to be a more environmentally friendly option in the industry.

Introduction

Created in 2000 by the Society of Automotive Engineers (SAE), the Clean Snowmobile Challenge (CSC) is committed to developing cleaner, quieter and more efficient snowmobiles. On March 6, 2017, universities will bring a custom snowmobile to Houghton, MI that has been engineered to reduce emissions such as noise, carbon monoxide (CO), oxides of nitrogen (NOx) and unburned hydrocarbons (HC). Exceptional fuel economy and reliability are expected to be achieved, while still maintaining sufficient power characteristics and customer appeal. An added requirement for these snowmobiles is to have the capability to efficiently run on blends of ethanol up to 85%.

Designed for the 2017 CSC, the Clarkson Winter Knights have utilized Ski-Doo's Renegade Sport 600 ACE model. This document will cover:

- Base Snowmobile/Engine Selection
- Engine Management
- Fuel System
- Exhaust System
- Driveline Modifications
- Ride Quality

Base Snowmobile Selection

As previously mentioned, the Winter Knights have decided to further the design on the 2017 Ski-Doo Renegade Sport 600 ACE chassis. This model was selected after much deliberation and analysis through the development of a design matrix. This was considered to be the best starting platform based on the specifications of the competition. Our design matrix was developed in order to compare snowmobiles from each major snowmobile manufacturer, assigning each of them a weighted numerical value. This value was based on the point breakdown of the CSC events, which resulted in a clear winner - the 2017 Ski-Doo Renegade 600 ACE.

Engine Selection

Being one of three BAT certified models for 2017, as well as a familiar engine for Clarkson, the 600 ACE is a great choice. Clarkson compared many engines early in the year when selecting a new platform. The previously utilized 600 ACE was a strong contender in the analysis, as it has won the challenge in some form for the past five years. Its sister model, the 900 ACE, was also investigated for use in this year’s challenge. Specifications comparing the two engines are shown in **Figure 1**.

Engine	600 ACE	900 ACE
Stroke	4-Stroke	4-Stroke
Cylinders	2 - horizontal in-line	3 - horizontal in-line
Displacement	600 cc	900cc
Dry weight	41.1 kg	51.8 kg
Performance	42 kW/ 57 HP	64.5 kW/ 88 HP
Torque	55 Nm @ 6000 rpm	83 Nm @ 6500 rpm
Fuel Economy	29 mpg or 8 L/100km *	21.8 mpg or 10.8 L/100 km *

* Based on data in ECO mode
Referenced from [2] and [3]

Figure 1

Based on the data that was gathered, the 600 ACE was determined to be the best option. With numerous spare parts for the 600 ACE and previous success, it was hard to change to an altogether new platform. The 600 ACE is also a leader in fuel economy while still maintaining respectable power, which are main constraints of the competition.

Engine Modifications

Engine Management

The Winter Knights took on an extensive task this year by using a standalone engine control unit (ECU). With plans of incorporating many new additional systems, it was easy to see that the stock ECU could not meet our needs. Many considerations went into the selection of the new ECU, with customer support being highest priority. Additional factors in ECU choice included cost, software platform, and control capabilities.

It was soon determined that the MoTeC M130 would fit the needs of the team. MoTeC has been known for exceptional customer support, which was an important element for Clarkson. MoTeC has created their own Windows based program that is user friendly for both creating custom software as well as extensive tuning. The M130 is capable of handling 24 outputs, 7 digital inputs and 12 analog inputs which is adequate for controlling current design items, as well as room for future modifications.

Closed Loop Fuel System

A MoTeC LTCD Lambda Controller was selected to control two Bosch 4.9 LSU oxygen sensors, one for each cylinder. The choice to run dual oxygen sensors was based on the examination of spark plugs, before any modification to the stock engine. The examination showed that the 600 ACE runs lean in cylinder 2, or the magneto side. With different combustion from each cylinder, this causes uneven cylinder pressures and power distribution.

Using the dual lambda control, it is possible to trim each cylinder individually. Thus, the M130 can use the oxygen sensor readings to run a closed loop system and achieve a target AFR value at all times. To do so, the M130 runs open loop until sensor heating is completed, at which time it begins to trim fuel and ignition maps in closed loop mode.

Fuel System

Ethanol Content Compensation

The 2017 Clean Snowmobile Challenge requires that snowmobiles are able to run on 0-85% ethanol content. To adapt to the changing ethanol content, we have fitted a flow through GM Flex Fuel sensor made by Continental. This sensor was chosen not only for its compact size, but also for its low cost. Under normal conditions, this sensor sends out a 50-150Hz signal which is read by a Zeitronix Ethanol Content Analyzer (ECA). The ECA then creates a 0 to 100% linear scale based on the 0-5V signal. This percentage is then received by the M130 via an analog voltage input. The M130 then has the capability of using a pure gasoline and a pure ethanol fuel table in conjunction with a scaling table to create the map for the signaled ethanol content.

The stock 600 ACE injectors are rated at 211 cc/min and as tested in previous years by Clarkson, use an 86% duty cycle for E40 fuel. For this year's competition, with fuel levels up to 85% ethanol, we must use larger injectors which allow for a higher flow rate. Clarkson teamed with Injector Dynamics to obtain a set of ID1000 fuel injectors. The ID1000 injectors have a nominal flow rate of 1015 cc/min at 43.5 psi, which is sufficient for our application.

As calculated in previous competition years, stoichiometric ratios were used to create the trim levels in which to use the ID1000 injectors. **Equation 1** uses 30% ethanol gasoline in relation to pure gasoline to find a stoichiometric AFR.

$$[Eth_{\%} * Eth_{Stoich} + (1 - Eth_{\%}) * Gasoline_{Stoich}\ ] = Exx_{Stoich}$$

$$[0.30 * 9.01 + (1 - 0.30) * 14.7\ ] = E30_{Stoich}$$

$$Stoichiometric\ AFR\ for\ E30 = 12.993:1\ (By\ Mass)$$

Equation 1

Equation 2 shows how the mass of ethanol in E30 fuel is calculated. Using these results, **Equation 3** calculates the percent change in fuel which is required for the 30% ethanol content.

$$\frac{AIR_{grams}}{Fuel_{grams}} = E30_{Stoich} \quad \rightarrow \quad Fuel_{grams} = \frac{AIR_{grams}}{E30_{Stoich}}$$

$$Fuel_{grams} = \frac{14.7}{12.993} = 1.13138\ grams\ of\ E30$$

Equation 2

$$\frac{|Grams\ of\ Gasoline\ Fuel\ Req - Grams\ of\ E30\ Fuel\ Req|}{Grams\ of\ Gasoline\ Fuel\ Req} * 100 = \%\ Change\ in\ Fuel\ Req$$

$$\frac{|1.00 - 1.13138|}{1.00} * 100 = +13.138\ \%$$

Equation 3

Exhaust

The exhaust system contains three main custom built components; a muffler, catalyst, and an electric passive exhaust valve.

Key Components:

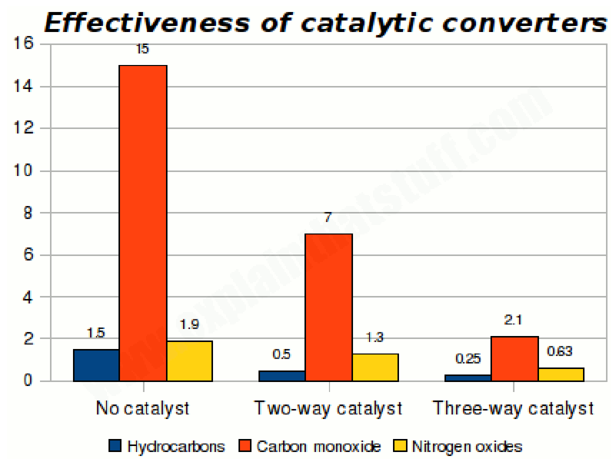
- Headers
- Catalyst
- Muffler
- Passive exhaust valve
- Heat shield

Headers

The Rotax 600 ACE contains a custom set of 30mm headers that combine into one 44.5 mm pipe, which is 228 mm off the front of the exhaust ports. The y-pipes were made the same length to ensure even exhaust gas distribution. In every exhaust stroke there is a positive pressure wave that propagates and travels down the exhaust pipe. The effect of this is the creation of a negative pressure wave behind the leading edge of the positive region. With equal length headers, this wave's negative pressure zone is entering the y-pipe just before the other cylinder's positive wave reaches the y-pipe, effectively pulling the other cylinder's exhaust, increasing efficiency.

Catalyst

In order to reduce hydrocarbon emissions, the exhaust system utilizes a Continental Emetic catalyst. The catalyst substrate is specifically engineered to be more effective in a combustion engine that is fueled with ethanol content gasoline. Knowing the engine out mass flow and estimated power output, the specific density was chosen to allow for maximum mass transfer to the substrate with minimal increase in backpressure. Incorporating the catalyst into the exhaust system introduced a diverging, converging setup, which is dual purpose. In one aspect the divergence slows the fluid flow over the substrates in the catalyst which increases mass transfer to effectively lower emissions. The other factor is that it acts as a resonator in the converging portion of the nozzle by reflecting sound frequencies back towards the exhaust ports and canceling with oncoming sound waves. The catalyst reduces the emissions of the engine by using a chemical reaction to break apart pollutant gases and converting them into gases that are not as dangerous as ordinary engine pollutants.



From "Catalytic Converters" by Chris Woodford [4]
Figure 2

Muffler

The muffler used in this sled uses a combination of refraction and absorption to enhance sound reduction. The use of absorption to reduce sound is accomplished by using low density materials such as fiberglass packing for the exhaust gasses to flow through, during which, energy is drawn out of the flow. Refraction is achieved when the exhaust gases going thru the chamber undergo a series of refractions, changing the frequency and speed of the exhaust gas wave. Our teams exhaust system also encompasses an attachment at the bottom of the muffler which aims the escaping exhaust noise at the track. This attachment allows the track to absorb a lot of the noise the engine creates.

Passive Exhaust Valve

A special incorporation to this exhaust system was a 2" electric exhaust cutout valve.

Evil energy 2" electric exhaust cutout valve

The team elected to use this valve because it is easily controlled by the M130. The movement of the exhaust valve is based on throttle position. At idle, the valve remains nearly closed to reduce engine noise. As the throttle is applied, the exhaust valve opens so that flow is not restricted, therefore preventing the restriction of power. Since the sled is not accelerating while at idle, the cut back on power due to restricted airflow will not hinder overall sled performance. Sound testing conducted using with a Larson Davis LXT sound meter shows that exhaust noise is 4 decibels quieter when the exhaust valve was closed at idle vs. open.

Heat Control

In order to account for the amount of heat our exhaust system emits around sensitive equipment, our team elected to wrap the exhaust with titanium header wrap. The exhaust wrap can withstand direct heat of 1800 degrees Fahrenheit, and intermittent heat of 2500 degrees Fahrenheit. The improvement in thermal protection caused by the exhaust wrap increases the performance of the 600 ACE engine. It accomplishes this by reducing engine bay temperatures, which results in cooler air intake for the engine.

EGR

Key Components:

- Custom Piping
- EGR Valve
- Custom Intake

Reasoning

In order to reduce the emissions of the snowmobile, the team decided to implement an EGR system. EGR systems reduce emissions by reducing NO_x levels. This is accomplished by recirculating a controllable portion of the engine's exhaust back into the intake. The recirculating exhaust gases displace fresh air that is entering the intake to lower the amount of oxygen that is available for combustion. The reduced oxygen levels in the intake effectively lower the air to fuel ratio, reducing emissions. In order to control the amount of recirculating exhaust gases entering the intake, a valve is used to control the flow of gas. The valve may be closed completely to keep lower intake temperatures, such as at idle. By burning excess fuel from exhaust gases, there is a reduction in the proportion of cylinder contents available for combustion. This leads to peak cylinder pressure and lower heat release, thus reducing the formation of NO_x.

EGR Valve

For the EGR system, our team elected to use a Wells EGR4355.

Wells EGR 4355

Our team chose this valve because it is compact and electronically controlled by the M130. This EGR valve is programmed based on engine load. Load is determined by calculating the inlet manifold pressure divided by standard atmospheric pressure. After researching the substantial increase in MSRP due to an EGR cooler, observation and testing showed that an EGR cooler was not necessary for our application. Due to the fact that we are not utilizing an EGR cooler, the valve is only able to be opened when the snowmobile is at cruising speed. This is partly due to the fact that we are trying to limit the temperature of the intake manifold. The benefit of this EGR system is that the fuel and timing tables are actively trimmed when the valve is open, reducing fuel consumption.

Intake

Due to high temperature gas recirculating through the intake, we were required to replace the stock plastic intake. Our team elected to go with a custom made aluminum intake to be sure that it would withstand the flowing exhaust heat within the system.

Ride Quality

To improve the rolling resistance and sound produced by the snowmobile, we fitted Ski-Doo SilentDrive drivers to our machine. These drivers differ from the stock drivers in a few ways. The stock drivers include teeth that hit the inner windows of the track which creates added friction. As a result of this, more track noise is produced. The SilentDrive system does not hit the inner windows of the track and rotates the track by hitting the rubber cogs instead. The stock drivers have a 2.52" pitch, whereas the SilentDrive drivers have a 2.86" pitch. The longer pitch between the drive cogs allows for less contact time with the inner cogs, reducing rolling resistance of the track on the drivers. The SilentDrive system not only reduces noise, it also reduces vibration. This allows for a more comfortable and quiet ride.

Since our snowmobile modifications focused on creating a more economic snowmobile package, we designed the handling and ride quality of the snowmobile around this concept. In order to accomplish this goal, we fitted a 137" R-motion skid to the chassis. This suspension design has a surfeit amount of benefits over the stock SC-5 skid. First, the R-motion skid is a progressive rate travel system. This allows for better absorption of smaller bumps and large mogul sized bumps. The longer style skid allows for a smoother transition between bumps as it allows the snowmobile to bridge across them. Furthermore, by skimming across the bumps there is less impact and rolling resistance acting to impede the motion of the snowmobile, which will further increase engine efficiency. This smooth transition between smaller and taller bumps can also be accredited to the rising rate motion ratio of the shocks and springs. Second, the R-motion is equipped with a longer front arm. This is beneficial over the shorter arm that comes on an SC-5 skid because it allows for more ski pressure which is beneficial in the overall balance of the snowmobile while handling corners. Third, this skid comes stock with interchangeable spring compression, which offers an increased range of adjustability in terms of spring dampening.

Furthermore, aftermarket slides were used to replace the slides that come stock on the R-motion in order to decrease rolling resistance and increase longevity. Many consumers will use the same slides for years without realizing how worn and inefficient they have become. For this, two choices were available to possibly replace the stock slides. The first was a graphite blend slide that would likely reduce rolling resistance, but do little towards increasing slide longevity. Therefore, to tackle both resistance and longevity issues from the stock slides, our team decided to implement Hiperfax slides, which utilize teflon inserts. These slides are notable for reduced rolling resistance and a higher melting temperature. This higher melting temperature reveals the strength of the Hiperfax slides and the toughness of the material that will lead to increased longevity [6].

To improve the traction of the snowmobile, our team decided to utilize Woody's 6" trailblazer IV carbide runners in the central slot and Woody's 4''Extender-Trail III carbides in the outer slot, and pilot ski navigators. This product helps reduce the darting of the snowmobile while performing on trail. This product also improves traction due to the increased carbide length from the stock 4" carbide, as well as the additional 4'' carbide in the outside slot, compared to no carbide. In addition, the navigator is designed to improve the circulation of snow through the ski, which also helps minimize darting. Traction was also addressed in the rear of the snowmobile with the addition of the 137.28”x15”x1.22” Camso Ice Attak XT. This track differs significantly from the stock Cobra 137”x15”x1.25” in the aspect of material, lug height, and inner lug pitch. The Ice Attak XT is designed for trail riding and is fitted with shorter lugs and a different style rubber compound for better traction on trails. The modifications that help increase the traction of the snowmobile in the situation of acceleration, also better the performance in the aspect of deceleration of the snowmobile.

Cost

With careful consideration for the added value of our modifications, the MSRP that we would suggest for our prototype snowmobile is $12,639. This excludes the cost of several items which were included solely for research purposes. Based on the research and data displayed in this document, the Clarkson University CSC team feels that the return on investment for each modification is fully justified.

Conclusion

The 2017 Clarkson University competition entry features a modified Ski-Doo Renegade with the ROTAX 600 ACE engine. To achieve our goals of sound dampening, we utilized the Ski-Doo SilentDrive axle assembly and Camso Ice Attak Track. The integration of a passive exhaust valve and extra fiberglass packing in the muffler provides a much quieter exhaust. Most importantly, to suit the main goal of the competition and improve environmental friendliness, we introduced a custom built exhaust with a catalytic converter and an EGR system. The ability to run on ethanol fuel blends up to 85% is achieved using a GM flex fuel sensor. Lastly, to control all added components of our complex design, we were able to team with MoTeC to utilize the M130.

Acknowledgements

Ski Doo, Ingles Performance, 139 Designs, Solidworks, Aristo Catalyst Technology, Bite Harder, BTD Manufacturing, Camso, Cintas, Continental Emitec, DynoJet, Klim, Molex, MoTeC, NYS Snowmobile Association, PCB Piezotronics, Pink Ribbon Riders, REM Surfacing, Ricardo, Rox Speed FX, SAE International, Snap-On, Windsor Landscaping

Abbreviations

CSC-Clean Snowmobile Competition
ACE- Advanced Combustion Efficiency
BAT- Best Available Technology
ECU-Engine Control Unit
HPG-High Pressure Gas
AFR - Air Fuel Ratio
CO - Carbon Monoxide
ECA - Ethanol Content Analyzer
EGR - Exhaust Gas Recirculation
GM - General Motors
HC - Hydrocarbons
LTCD - Lambda to CAN Dual
NOx - Nitrous Oxides
NYS - New York State
SAE - Society of Automotive Engineers

References

1. Hussain, Jaffar. “Effect of Exhaust Gas Recirculation (EGR) on Performance and Emission characteristics of a Three Cylinder Direct Injection Compression Ignition Engine.” Pondicherry Engineering College. Accessed 20 February 2017: http://www.sciencedirect.com/science/article/pii/S1110016812000907.
2. “Rotax 600 ACE.” BRP. Accessed 20 February 2017: https://www.rotax.com/en/products/rotax-powertrains/details/rotax-600-ace.html
3. “Rotax 900 ACE.” BRP. Accessed 20 February 2017: https://www.rotax.com/en/products/rotax-powertrains/details/rotax-900-ace-snow.html

4. Woodford, Chris. “Catalytic Converters.” Last updated: 29 July 2016. Accessed 20 February 2017: http://www.explainthatstuff.com/catalyticconverters.html
5. “2016 Ski-Doo Expedition® Sport Rotax® 600 ACE™.” Fort Kent Powersports. Accessed 20 February 2017: http://www.fortkentpowersports.com/inventory/v1/2016/Ski-Doo/By-Model/Expedition/Expedition-Sport/Rotax-600-ACE--Fort-Kent-Maine---2698341
6. “Which Hyfax.” Snow Tech Magazine. Accessed 20 February 2017: https://www.snowtechmagazine.com/which-hyfax/