Emissions Optimization of a Four-Stroke Flex Fuel Snowmobile

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ABSTRACT

The Clarkson University Clean Snowmobile Team's objective was to improve upon the best available technology on today's market by reengineering several aspects of a 2011 snowmobile. Based on the criteria put forth by the team, the snowmobile of choice for the 2011 Clean Snowmobile Challenge was a 2011 Ski-Doo MX Z Sport 600 ACE (Advanced Combustion Efficiency). The choice of the Ski-Doo MX Z Sport combines the ergonomics and performance of the Ski-Doo Rev XP platform with the green technology of the 600 ACE. The 600 ACE is a 600 cc 4 stroke motor produced by Rotax exclusively for Bombardier Recreational Products (BRP). The fuel injection technology in the 600 ACE combined with the new eDrive clutch system offered by Ski-Doo, produces higher fuel mileage while maintaining performance. Selecting a snowmobile that sets a new standard in the industry poses a challenge but gave the Clarkson Snowmobile Team a goal to not only improve upon the best, but set new standards in CSC. Using catalytic converters and a redesigned exhaust system improved both noise and chemical emissions. Aftermarket fuel controls modified the fuel mapping so the sled was able to handle the higher concentration of ethanol in the fuel. The changes made to the snowmobile did not affect its current performance standards so that it continues enticing riders.

INTRODUCTION

The intent of the Society of Automotive Engineers (SAE) Clean Snowmobile Challenge (CSC) is to encourage undergraduate research and design of methods to reduce emissions of original equipment manufacturer (OEM) snowmobiles. The goal is to develop snowmobiles that would produce low enough emissions to be used in environmentally sensitive and protected areas, such as national parks. Competing teams strive to reduce sound emissions, unburned hydrocarbons, carbon monoxide and nitrogen oxide emissions as well as utilize E-20 to E-29 fuel, all while maintaining the stock performance and handling qualities that are valued by consumers. The competition also emphasizes maintaining a reasonable MSRP to ensure that the solutions designed by competing teams have the potential to be marketed to consumers. The 2011 CSC will take place at Keweenaw Research Center, Michigan from March 7th through the 12th.

The following report describes how Clarkson University has further reduced chemical and sound emissions of the market's newest environmentally conscious snowmobile, the 2011 Ski-Doo MX Z Sport 600 ACE. In the past, the Clarkson University team has used a 2006 Polaris FST Classic with the Weber 750 turbocharged engine. The design relied on fuel system modification as well as high exhaust temperatures coming out of the turbocharger to improve emissions. The greatest drawbacks of this snowmobile, however, were the weight of the snowmobile, the lack of space in the engine compartment and the newly instituted horsepower restriction. The selection of the MX Z Sport puts this year's weight lower compared to the FST Classic, the engine compartment is spacious due to the small size of the 600 ACE, and the horsepower of the ACE is within the bounds of competition rules.

The MX Z Sport will have dual catalytic converters incorporated into a redesigned exhaust system reducing the emission of hydrocarbons, carbon monoxide and nitrogen oxides. The fuel controller incorporated into the fuel system will allow for fine control of how the engine adjusts for the ethanol fuel mixture being used for the Clean Snowmobile Competition. This report will discuss in detail the process of re-engineering a stock 2011 Ski-Doo MX Z Sport 600 ACE.

SNOWMOBILE SELECTION

The selection of the team snowmobile was a carefully thought through decision that included lengthy research and debate amongst the team. The selection criteria were first decided on based upon the competition format. The competition focuses on fuel economy, noise, emissions, weight, reliability in cold weather, and handling/acceleration. These criteria are prioritized differently for the purpose of the competition than the typical snowmobiler. Weight, however, is a common issue among both engineers and riders[1].

As a team it was decided to find the best snowmobile on the market that satisfied the given criteria and improve the best technology further. In the past, Clarkson has used an engine that was considered to be the best on the market at the time. The Polaris FST Classic engine, the Weber 750, is an efficient engine but placed into a heavy chassis. Using one of the newest snowmobiles on the market will help the team take a high benchmark for the industry and improve upon the technology. As a student run team the criteria is slightly different then most because of certain restrictions such as budget, time, and skills/capabilities of team members. The team's criteria in choosing a snowmobile were as follows: (1) cost, (2) fuel economy, (3) emissions, (4) noise, (5) capability for modification, (6) weight, (7) handling/ acceleration, and (8) cold start/reliability. Once the criteria were ranked in order of importance it was easy to determine the best snowmobile for the 2011 Clean Snowmobile Challenge.

As an engineering team with a fixed budget, cost is the first priority. Snowmobile prices vary across different styles of snowmobiles such as entry level, power cruiser, luxury, crossover, mountain and utility. A typical entry level snowmobile costs roughly around $8500[2] compared to a luxury snowmobile which costs around $10,600[3]. The difference in price is accounted for in added features such as plug-ins for heated shields and better suspension[3]. These features do not have a significant value to the team. Many of the other snowmobiles also have engines with much higher horsepower which excludes them from the search based on the competition limit of 130 horsepower snowmobiles. A difference of $2000 is a large portion of the budget and based on the teams needs, the decision was made to focus the search on entry level machines.

Focusing on entry-level snowmobiles only limits the search slightly. There are four large snowmobile manufacturers including Ski-doo, Polaris, Arctic Cat, and Yamaha. The next limiting factor was machines with impressive fuel economy. In the snowmobile market there are also a difference in engines from two-stroke to four-stroke, and carbureted or fuel injected motors. Four-stroke engines typically are more fuel efficient so the team's efforts went into comparing four-stroke snowmobiles. Out of the four snowmobile competitors Ski-doo and Yamaha have four-stroke machines with the best fuel economy. Ski-doo's 600ACE in the MX Z Sport provides a user with a fuel economy of estimated 29 mpg[4], which creates the new standard in the market. The next best snowmobile for fuel economy is the Yamaha Phazer which uses a GENESIS 80FI getting an estimated 20 mpg[5]. These two machines were the top two snowmobile choices that were explored by the team.

The emissions produced by a snowmobile are just as important as its fuel economy. Therefore, evaluating and comparing stock emissions of snowmobiles was the team's next concern. The main purpose of the competition is to use a snowmobile in areas such as the National Parks and the big factor in this is emissions. Snowmobile exhaust emits Nitrogen Oxides (NO_X), 200,000 tons of hydrocarbons (HC) and 531,000 tons of carbon monoxide (CO) into the atmosphere each year[6]. The National Park Service (NPS) and the EPA have been creating lower and lower emission standards for snowmobiles. The NPS has created a list of snowmobiles which pass its tight emission requirements. The Snowmobile Best Available Technology (BAT) List includes machines from all four manufactures. Comparing Ski-doo MX Z ACE and the Yamaha Phazer, the Ski-doo MX Z ACE satisfies the BAT requirements and the Yamaha Phazer does not. The ACE in fact appears to set the standard for emissions producing 8 (g/kW-hr) of HC and 90 (g/kW-hr) of CO, the least of any machine on the list[7].

According to the NPS the two factors that are dangerous to the environment are the emissions and the noise. Snowmobiles with low emissions were previously evaluated on the BAT list. This list was also referred to for the noise requirement. The stock snowmobiles with the best sound emissions on the BAT list are all Ski-doo machines. The Ski-doo MX Z ACE in particular having one of the lowest ratings of 71.3 - 75.1 dBA.

Starting with advanced technologies was an important criterion to the team. There also has to be the capability to make modifications and the room to further add features that will make the snowmobile cleaner and quieter. When comparing the two main choices, the Yamaha Phazer and the Ski-doo MX Z ACE, this was a significant factor. The Yamaha Phazer had little room when considering any design changes or engineering modifications. In comparison the Ski-doo MX Z ACE had a large amount of space under the front cowl. For the team, more space meant more possibilities, which made the decision easier.

The weight of the snowmobile chosen was a consideration but was not a deciding factor. The two seriously considered snowmobiles, the Yamaha Phazer and the Ski-doo MX Z ACE, are two of the lightest on the market. The 2009 Yamaha Phazer weighed 515lbs[8]. Comparing that to the Ski-doo MX Z ACE coming in at 454lbs[9]. For a good power to weight ratio the 50lbs can make a difference. For most snowmobilers the power to weight ratio is the most important feature when shopping for a snowmobile[1]. A lighter snowmobile can also contribute to better fuel economy, better acceleration and handling.

As the last two criteria in choosing a snowmobile handling/acceleration and cold start/reliability are expected from most brand new snowmobiles. In researching the new 2011 snowmobile line, there was an abundance of positive feedback about all Ski-doo machines. In particular there was also excellent feedback about the ACE engine. One article noted "It has also been developed to be one of the most trouble-free and maintenance-free engines in the Ski-Doo line."[10] Another enjoyable feature of the Ski-doo MX Z ACE is its new eDrive clutch that engages smoothly at 2800 RPM[11]. This new set up is also lighter and operates at a cooler temperature than previous designs.

Based on the criteria set forth, the team decided to choose a 2011 Ski-doo MX Z Sport 600 ACE to re-engineer for the Clean Snowmobile Challenge.

TRACTION

To improve upon the handling and performance of the snowmobile, studs may be added to the track. Adding the studs to the track can improve many aspects, such as acceleration, handling, and stopping distance. Studs reduce the chances of the track fishtailing around corners by producing additional grip that would overcome icy and hard packed trail conditions. They can also be an important safety improvement because they will decrease the stopping distance of the snowmobile by creating extra surface area to come into contact with the snow[12]. The addition of studs allows for better control of the snowmobile even though it creates additional noise while in use. The snowmobile had holes pre-drilled for 48 studs to be added in the event of icy conditions being present at the competition.

NOISE

Since the 600 ACE is already a quiet operating engine, the focus was placed on other aspects of the snowmobile such as the exhaust system. To reduce sound emissions from the exhaust, catalytic converters were added to both primary exhaust pipes. The converters are dual purpose in that they reduce harmful chemical emissions in the exhaust as well as noise emissions. The noise from the exhaust, created by the engine compression, travels down each primary exhaust pipe to the catalytic converters. As these sound waves arrive at the converter, they are reflected off of the surfaces inside the converter and several become out of phase. As these out of phase waves reflect back up the exhaust pipe, they cancel out incoming sound waves through destructive interference. The process of destructive interference aids in reducing sound emission from the snowmobile.

FUEL SYSTEM MODIFICATIONS

To make the OEM fuel system flex fuel compatible an aftermarket electronic fuel injector (EFI) controller was utilized in an open loop manner. Fuel lines and connectors did not need to be replaced as Ski-Doo OEM currently uses flex fuel certified hardware to comply with recent regulations. An open loop system was chosen because it is cost effective, compatible with a range of fuels, and simple. Calculations were done to determine the desired air to fuel ratio (AFR) for E-20 to E-29. The EFI controller was then programmed to run in parallel with the internal engine control unit (ECU). Currently there are no available after market EFI controllers for the 600 ACE. The team worked with BoonDocker Performance by providing measurements and data to determine which existing EFI control box would be compatible. The collected data and measurements are discussed later in this section.

Preliminary Measurements –Selecting the EFI Controller

A BoonDocker Performance fuel controller intercepts the injector signals and modifies them to add a precise percentage of fuel to each RPM range. Since BoonDocker Performance does not manufacture a controller specifically for the Ski Doo MX Z Sport 600 ACE, important injector and mapping information needed to be determined. The data revealed that the injectors were high impedance with a resistance of 12.3 ohms, which works well with their 4B (internal designation) control box. Information on the injector signals was also needed, such as duty cycles and pulse widths for various RPM ranges. This allowed the team to discover whether or not there were multiple pulses per intake stroke, or if the signal wire pulled to ground when the injector is on. Determining this would show if the BoonDocker Performance control box is usable. The collected data is shown in the figures and table below which were measured using an oscilloscope by connecting to the signal side of the injectors.

Table 1 - RPM vs. Pulse Data

RPM Range	Pulse Width	Pulse Delay
[rpm]	*[ms]*	*[ms]*
IDLE	1.20	38.00
3500	1.20	15.00
5000	1.2 - 1.4	10.00
6000	2.00	6.00
WOT 7780	4.00	2.00

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Figure 1 – Signal for 3500 RPM

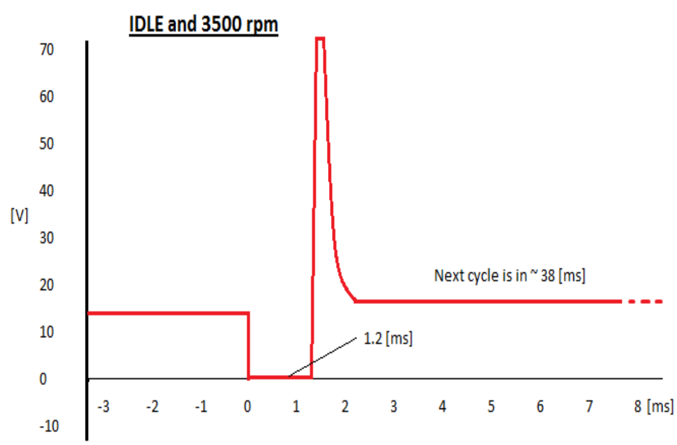


Figure 2 – Signal for 5000 RPM

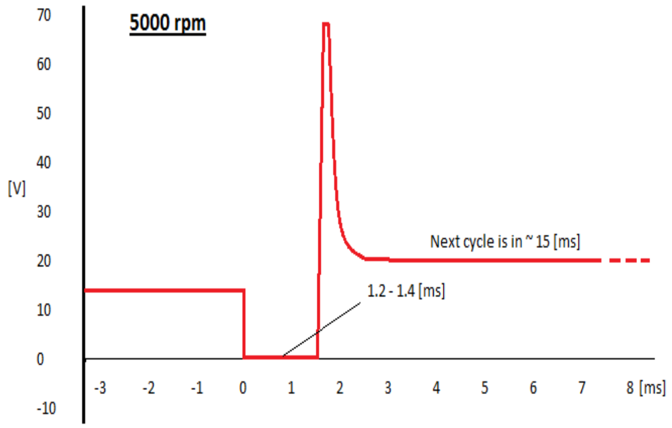


Figure 3 - Signal for 6000 RPM

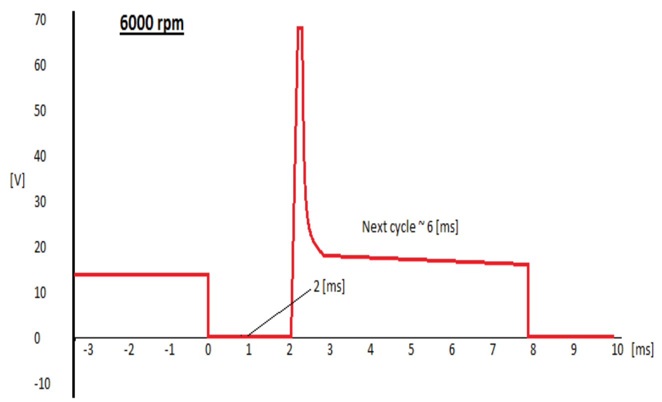
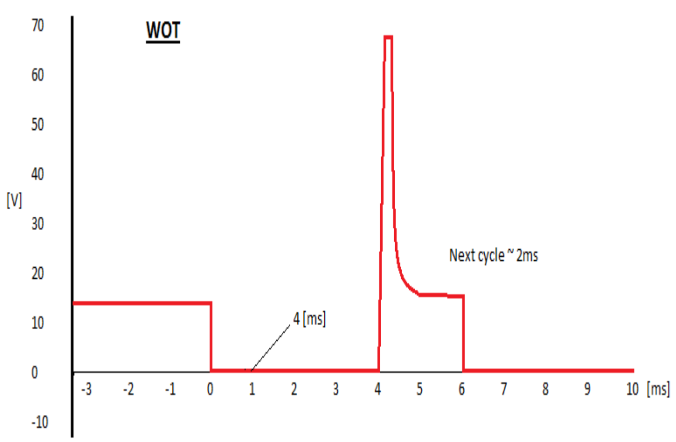


Figure 4 - Signal for WOT at 7780 RPM



The plots illustrate the injector signals of the motor's engine control unit (ECU). Fuel injection systems monitor fuel based on two parameters. These two parameters are pulse width and pulse delay. Each pulse operates the piezoelectric solenoid in the injector, opening the passages in the injector to allow fuel flow. Engine speed is accounted for by varying the delay in pulses. Shorter delays result in an increase in the rate of fuel injection. This allows the injector to stay in time with higher engine speeds. Pulse width variance is a method of fine tuning the air to fuel ratio for the engine. As the engine speed increases, the pulse width increases, adding a richer fuel mixture to the engine. A rich air to fuel mixture allows for a cooler combustion, which will not overheat critical engine components. According to the plots, nothing abnormal was occurring with the injector signals thus showing the Boondocker control box would be a proper solution to modify the existing fuel mapping.

Once the data was known, an electronic fuel controller designed for the Polaris Dragon was selected. This decision was made based on the similarities of the pulse signals between the two snowmobiles.

Calculations:

To determine the percent of fuel that needs to be added to each RPM range, the team chose to calibrate the fuel system to E25; +/- 10% ethanol only changes the fuel properties approximately 3–5%. Therefore, the air fuel ratio for E25 needed to be calculated to program the control box to account for more fuel. It was determined that running E25 versus E0 the team would need around 10.6% more fuel. Using that, the team was able to figure out the quantity to add to each fuel selection for each RPM range.

Table 2 - Molecular Mass Table

Chemical	Molecular Mass
Ethanol: C_2H_6O	46.068 grams/ mol
Oxygen: O_2	32.00 grams/ mol

The ethanol combustion equation, as shown below, was used to calculate the desired AFR. Note that the equations immediately below show the fuel to oxygen ratio, not fuel to air. Air is accounted for later on.

$$C_2H_6O + 3O_2 \rightarrow 2O_2 + 3H_20 \quad (1)$$

$$2(3\text{mol})\ O_2 \ :\ 1\ \text{mol ethanol}$$

$$96.00\ \frac{\text{g}}{\text{mol}}\ O_2 \ :\ 46.068\ \frac{\text{g}}{\text{mol}}\ \text{ethanol} \quad \text{or}\ 2.0838 : 1$$

The above ratio is for ideal combustion. With air assumed to be 23.133% oxygen the theoretical AFR for Gasoline 14.64:1 and for pure ethanol (E100) 9.0078:1. Therefore, the AFR of a fuel mixture of E25, as calculated in equation (2), equals 13.23195: 1 is a reasonable AFR.

$$\{Percent\ AFR\ Ethonol + Percent\ AFR\ Gasoline = AFR\ E25\}: 1 \quad (2)$$

$$[25\%(9.0078) + 75\%(14.64)]: 1$$

$$AFR\ E25 == 13.232: 1 \text{ (By mass)}$$

Implementation:

The correctly programmed EFI control box will adjust the AFR so that the lambda value is equal or close to 1.0. Lambda is simply AFR divided by stoichiometric AFR. Values less than 1.0 are fuel rich mixtures, and lean mixtures have lambda values greater than 1.0. To achieve optimal fuel efficiency and catalytic reaction, lambda values close to 1.0 are desired. Calibrations must be done to achieve this value at all RPM ranges.

To measure AFR while the engine is running, oxygen sensors were added to each of the exhaust pipes before the catalytic converters. Various data measurement tools were considered for use such as, the NGK AFR systems, ETAS LA4 Lambda Module, and the DynoJet Wideband 2 in combination with the LCD-200 screen. The selected device was the DynoJet Wideband2 because of its desirable features and data logging capabilities. The LA4 was expensive and did not have dual sensor capabilities without making further investments. The NGK model did not fit the needs of the team because it did not have PC connection capabilities or data logging.

With the DynoJet Wideband 2 the LCD-200 screen, the team was able to record the outputs of AFR, calculated lambda values, throttle position, percent oxygen in the exhaust and RPM. With that data, the team was able to calibrate the fuel system and adjust the AFR to get lambda as close to 1.0 as possible.

EMISSIONS

In order to reduce the emissions levels on the stock 600 ACE engine, catalytic converters were implemented. Three-way catalytic converters treat Carbon Monoxide (CO), unburned hydrocarbons (HC), and nitrous oxide (NO_X) pollutants. Since the CSC 2011 emissions event will be based on these three major emissions levels the three-way converter will provide the best results. Two oxygen sensors are used to measure the air fuel ratio and lambda values just before the converters. Using the data retrieved from the Dynojet Wideband 2 system, the Boondocker EFI controller was calibrated to obtain the best stoichiometric ratio providing a lambda value closest to 1.0 at specific RPM ranges. When the lambda value is reading near or at 1.0 then the balance of the pollutants and available oxygen are at an optimum balanced level with each other for the catalytic converter. This leads to the optimal efficiency in the catalytic converters when reducing emissions.

The dual three-way catalytic converters were supplied by EMITEC and Aristo were incorporated into the custom exhaust. In order to design the converters for the specific use on the 600 ACE, testing was done to find the dynamic pressure out of the exhaust. This then lead to the mass flow rate of each exhaust pipe being calculated. Knowing the mass flow rate, the exhaust gas temperature, or EGT, at open throttle, and the maximum back pressure, a custom substrate set up was built by EMITEC.

The converters each measure 80 mm in diameter and 160 mm in length. The converters are substantially larger in diameter than the exhaust pipes for improved flow characteristics and minimal back pressure.

The decision to implementing catalytic converters into the 600 ACE exhaust system required a substantial redesign of the exhaust header layout. First, it was decided that the new headers would be encased in a fiberglass wrap to keep the temperature of the exhaust gas hot for the catalytic converters. The exhaust headers stay separate before and after the catalytic converter section since the stock muffler was designed for two inlet pipes. Not only did the redesign of the headers allow for catalytic converters to be introduced into the system, but also to take the opportunity to design tuned header pipes.

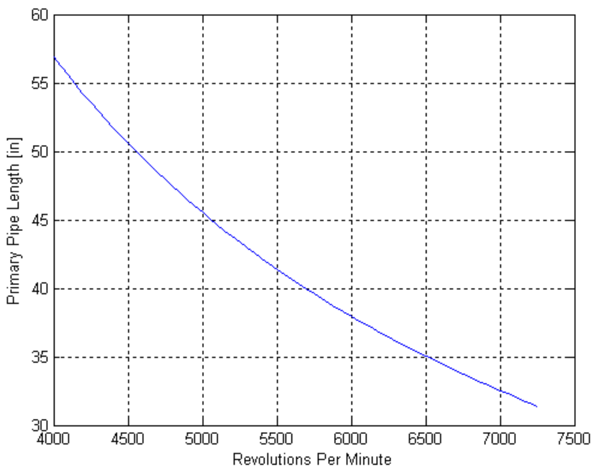
Tuned header pipes use the exhaust pressure pulses to increase the scavenging effect of the engine. Exhaust scavenging occurs when the kinetic energy from the exhaust pulse leaving the cylinder causes the cylinder pressure to drop below atmospheric at top dead center, or TDC, thus drawing in a new charge. In a tuned header pipe, the length of the pipe is designed to reflect back the pressure pulse caused by sound so that it returns to the valve at a set crank angle. Then it is reflected back away from the cylinder causing a second low pressure wave which forces the remaining charge in the cylinder to evacuate the chamber quicker and more efficiently. The gains from this effect are twofold. First, since the volume of exhaust gas remaining in the cylinder when the exhaust valve closes is lower, the new air being drawn is not subject to as much pre-heating due to leftover hot exhaust gas. Cooler air temperature leads to a cooler combustion, which reduces NO_X emissions and lowers the back pressure. Secondly, the volumetric efficiency of the engine is increased because there is a higher concentration of fresh air in the cylinder instead of left over combustion materials from the last ignition. This in turn leads to more torque for the same amount of fuel since there is more oxygen for the fuel to burn with.

Although the tuned header is an experimental science, a general initial estimate for the pipe length can be calculated using equation 3, where a represents the speed of sound and T is the desired time for the wave to return to the valve in crankshaft degrees.

$$L = \frac{a * T}{RPM} \quad (3)$$

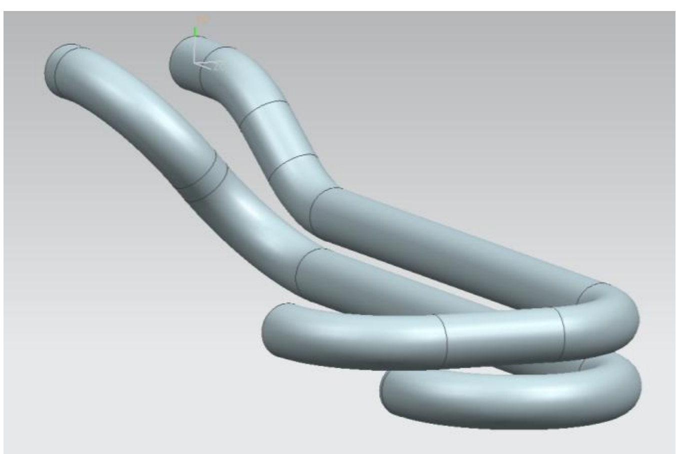
The speed of sound of the gas was calculated to be 1897 ft/s by finding the EGT just after the exhaust port. The desired return time in crankshaft degrees was chosen to be 120 degrees. Then, the pulse is returned and reflected about 60 degrees before TDC. Figure 6 relates the RPM to the optimal pipe length.

Figure 5 - RPM vs. Pipe Length



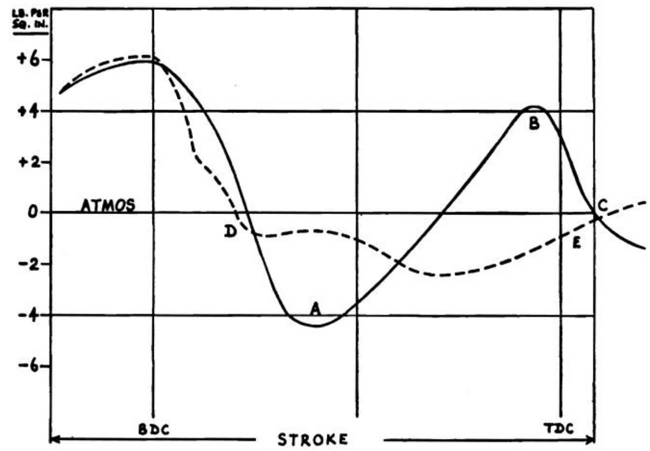
The target RPM range was chosen to be 6500 rpm because of space constraints and the torque curve of the 600 ACE which drops off significantly when accelerating up to the redline. It would have been difficult to fit a pipe any longer than 35 inches in the engine compartment, while still including catalytic converters. Figure 7 is the 3-D primary pipe design that was drafted up in CAD software to ensure equal length, while still fitting in the engine compartment.

Figure 6 - Exhaust Header Configuration



For simplicity, the pipes used to fabricate the new headers measured the same diameter as the stock OEM headers. The scavenging effect at 5500 RPM is increased, but is not as significant as at 6500 rpm. Figure 8 shows the time it takes for the pressure wave to return to the cylinder in crankshaft degrees[13].

Figure 7 - Theoretical Pressure Curves of Poor (full line) and Good (dotted line) Scavenging



CONCLUSION

The 2011 Clarkson University Clean Snowmobile Team improved on previous entries by selecting a snowmobile that sets a higher benchmark to start from than in previous years. The lighter Ski-Doo Rev XP chassis reduced the weight of the sled by about 130 pounds (dry weight) compared to the larger Polaris FST Classic model used in previous years. The exhaust system was redesigned so that it incorporated two catalytic converters to maintain a dual pipe interface with the headers coming from the engine. These converters contained a three-way catalyst to eliminate harmful emissions. The fuel system was modified so that the fuel would be delivered to the engine more efficiently. By doing so, the fuel system would be compatible with the new ethanol/gasoline mixture. The stock snowmobile already meets or exceeds EPA requirements and being able to improve upon those standards will set the bar higher for future competitions. The improved snowmobile will effectively be better for the environment and provide an excellent base for future competition improvements.

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