Advances in the Environmental and Safety Considerations of a Four-Stroke Flex Fuel Snowmobile

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ABSTRACT

For 2012 the Clarkson University Clean Snowmobile Team's objective was again to improve upon the best available technology on today's market by reengineering several aspects of a newer snowmobile. The snowmobile of choice for the 2012 Clean Snowmobile Challenge is the same 2011 Ski-Doo MXZ Sport 600 ACE (Advanced Combustion Efficiency) used by Clarkson in 2011. The choice of the Ski-Doo MXZ Sport combines the ergonomics and performance of the Ski-Doo Rev XP platform with the efficiency and lightweight technology of the Rotax 600 ACE. The 600 ACE is a 600 cc 4 stroke motor produced by Rotax exclusively for Bombardier Recreational Products (BRP). The super-efficient combustion chamber design combined with the early engaging eDrive clutch, produces higher fuel mileage while producing excellent engine output. The handling characteristics are improved using new ski technologies. The exhaust system is again redesigned for improved flow over last year's design and lower emissions. An aftermarket fuel controller alters the fuel mapping using a GM/Delphi flex fuel sensor so the sled is able to run Ethanol concentrations from E10 to E39. The changes made to the snowmobile have not degraded the stock 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. 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 goal is to develop snowmobiles that would produce low enough emissions to be used in environmentally sensitive and protected areas like as national parks. Competing teams strive to reduce sound emissions, unburned hydrocarbons, carbon monoxide and oxides of nitrogen emissions, as well as utilizing ethanol gasoline blends from ranging from 10% to 39% ethanol. Maintaining or improving upon the stock performance and handling qualities that are valued by consumers are also expected. The competition emphasizes maintaining a reasonable MSRP to ensure that the solutions designed by competing teams have the potential to be marketed to consumers. The 2012 Clean Snowmobile Challenge will take place at Keweenaw Research Center, Michigan from March 5th through the 10th.

The following report describes how Clarkson University has further reduced the chemical and sound emissions of one of the market's newest environmentally conscious snowmobile, the 2011 Ski-Doo MXZ Sport 600 ACE. This past year, the 2011 Clarkson Winter Knights used the same 2011 MXZ 600 ACE and demonstrated a sled designed for the environmentally conscious rider. The design relied on a simple fuel system modification and dual catalytic converters integrated into the exhaust to reduce emissions. A few of the drawbacks of the design included a fuel interceptor unit with limited open-loop technology and an exhaust system with too much backpressure that was not properly tested. Staying with the 2011 MXZ Sport allowed for more time to properly redesign the exhaust and integrate a closed loop fuel system. The 600 ACE engine is easy to work with and the horsepower of the ACE will stay within the bounds of competition rules.

The MXZ Sport will benefit from a redesigned exhaust header system to improve flow and decrease backpressure into the muffler. The muffler can has also been altered to include a new higher flowing catalyst inside, reducing the emission of hydrocarbons, carbon monoxide and oxides of nitrogen. The fuel controller incorporated into the fuel system will allow for closed loop controlled lambda and fuel percentage altering based on the measured 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 MXZ Sport 600 ACE.

SNOWMOBILE SELECTION

The 2012 Clarkson Clean Snowmobile team chose to stay with last year's winning sled the Ski-doo MXZ Sport 600 ACE. Not only does the 600 ACE motor get the industry best fuel economy, but it tops the snowmobile Best Available Technology list presented by the National Parks Service producing 8 (g/kW-hr) of HC and 90 (g/kW-hr) of CO [3]. The MXZ 600 ACE also is near the top in the sound emissions list ranging from 71.3 to 75.1 dBA [3]. The MXZ Sport 600 ACE is still one of the lightest four stroke sleds on the market coming in at 454lbs and is extremely reliable[4]. The Ski-Doo was again the obvious choice for the team.

HANDLING & TRACTION

This year the team decided to take a chance on revolutionary technology again and implement another industry first to our machine. To improve on the snowmobile's handling characteristics, the team chose to install the new Split Rail Ski's featuring a unique design that sets them apart from any other ski seen on snowmobiles. Darting has virtually been eliminated versus the stock Pilot 5.7 skis that currently come on all Ski Doo models. Several experienced and non-experienced riders tested the machine under most trail conditions with the new skis. All riders confirmed that the skis are very predictable and provide more confidence when navigating through turns.

The turning radius of the snowmobile was compared side by side using both the stock skis first then the Split Rail skis. Figure 1 displays the results from the tests. The tests were completed in 6" of fresh powder using the same rider. The rider would enter the turn and attempt to turn as sharp as possible while maintaining the set speed without kicking the track out. Although it can't be seen clearly in the graph, the Split Rail did beat out the Pilot 5.7 ski at 5 MPH with a turning radius 5" smaller. At 10 and 15 MPH the Pilot 5.7 was able to turn a little bit quicker with some help from the track sliding. At 20 MPH the turning radius was much smaller for the Split Rail skis beating out the Pilot skis by over 14 ft. The rider also noted that the Split rail skis "bit in" harder when ridden more aggressively. This pattern suggests that if tests were continued the split rail would continue to perform better with higher speeds. These results however, do not apply on groomed trails, which would require more testing.

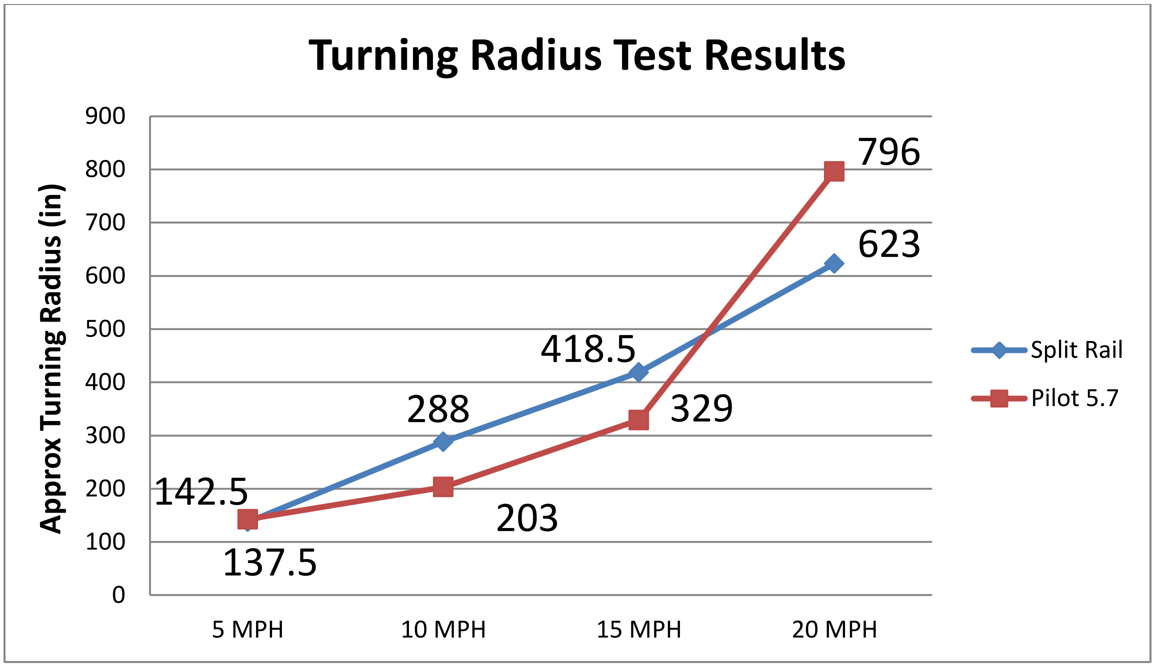


Figure 1 – Turning Radius in 6" Powder Stock vs. Split Rail

Both the Split Rail ski and the Pilot 5.7 skis were tested for resistance in the snow. The skis were pulled in the snow with a force gage to determine how much force it took to move them in the snow. Since the Split Rail skis had a mass just over 2 kg more, a 2.72 kg mass was strapped onto the pilot skis to even it out and help it stand up straight. After testing multiple times the force required was averaged and the unit force in N/kg required to slide the skis was calculated for comparison. The force required to move the whole front end is then calculated assuming that each side of the front end has a mass of 63.5 kg without skis. The total force required takes into account the mass difference between the two sets of skis. Table 1 below tabulates the results.

	Mass (kg)	Total Mass (kg)	Force Req (N)	Unit Force Req (N/kg)	Mass on Ski (kg)	Force Req	Force Req for whole Front end
Split Rail	6.03	6.03	15.25	2.53	65.59	165.94	331.87
Pilot 5.7	3.94	6.66	17.50	2.63	63.50	166.89	333.79

Table 1 – Ski Resistance Tests Results

The unit force required to use the Split Rail Skis versus the Pilot 5.7 stock skis turns out to be slightly less. However once the extra weight is added in and the whole front end is taken into account the resistance of the skis to slide in the snow turns out to be very close, giving no obvious advantage to either ski.

During testing it was noted that the Split Rail skis kick up much more snow than the pilot 5.7 skis under the same conditions. With the unique dual axis design snow is actually funneled through the center of the ski and directed to the track providing more lubrication and better cooling.

NOISE

Since the stock 600 ACE is already an extremely quiet machine, the focus was placed on other aspects of the snowmobile like under the hood and the exhaust system. To further reduce sound emissions from the exhaust, a catalytic converter was integrated into the existing muffler. The converter has a dual purpose in that it reduces harmful chemical emissions in the exhaust as well as decreasing the harshness of the noise emissions. The noise from the exhaust, created by the pulsating high temperature and pressure gases, travels down the pipes to the muffler where it enters the first chamber where the sound waves are reflected off the surfaces inside the converter and several become out of phase. The gasses then flow into the catalytic converter and onto the second chamber. The gases then flow into a third chamber through a perforated divider into exhaust packing. The exhaust then finds the exit of the muffler. As these out of phase waves reflect through the packing and back up the muffler and exhaust pipes, they cancel out incoming sound waves through destructive interference. The process of destructive interference aids in reducing sound emission from the snowmobile. The exhaust pipes were also constructed from slightly thinker material versus stock to reduce some of the" tinny" sound. Foam has been placed on most of the bare plastics under the hood to further reduce noises from exiting the engine compartment.

FUEL SYSTEM MODIFICATIONS

To make the OEM fuel system flex fuel compatible, an aftermarket electronic fuel injector (EFI) interceptor unit was installed. 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. Calculations were completed to determine the fuel changes required from E-10 to E-39. The EFI interceptor unit was then calibrated to run in parallel with the internal engine control unit (ECU). Since there are no available after market EFI controllers for the 600 ACE, the team worked with DynoJet Research to implement and test the first interceptor prototype for the 600 ACE engine based off of the Power Commander V.

Selecting the EFI Controller

The Power Commander V fuel and ignition module intercepts the injector signals and modifies them to add or subtract a precise percentage of fuel that is delivered to each cylinder. The Power Commander V allows for a -100% to +250% change in fuel based off the stock ECU as well as altering the spark timing by up to ±20 degrees. The controller allows the user to set up 2-D base fuel and spark maps in terms of percent fuel or degree changes over different rpms and throttle positions. The Power Commander V also has the ability to receive a 0-5V analog input signal and build a 2-D table based on the voltage. The table includes fuel percentage changes over the analog voltage and rpm. The intervals for rpms and throttle positions are set by the program but the analog voltage intervals are user set and offer great flexibility. Lastly the Power Commander V offers a closed loop lambda sensor operating mode called AutoTune in which the controller will trim the percentage change in fuel to target a specific lambda value. The target values are put into a 2-D table varying over rpm and throttle position. When auto tune runs it produces a trim table with small percentage changes for different rpms and throttle positions to target the chosen lambda values. The Power Commander V offers incredible flexibility and control while still leaving the complicated ECU system and algorithms intact. For these reasons the Power Commander V was the obvious path since it was simpler than a custom ECU but offered the flexibility and control of a closed loop system.

Calculations

The GM/Delphi flex fuel sensor is connected to a digital Zeitronix Ethanol content analyzer which has a 0-5V analog output wire. The analog output has a linear relationship with the percent ethanol in the fuel.

Therefore 0V equals E0 and 5V would equal E100, or 0% and 100% ethanol. All the rest of the voltage values are just linear interpolations between 0 and 100%.

The stoichiometric ratios for the range of fuels must be calculated in order to determine how much trim fuel is needed for each sensor voltage from E10 to E39. First E0 and E100 are considered with stoichiometric AFR ratios of 14.7 and 9.01 respectively. This means that for pure ethanol your only need 9.01 grams of air for 1 gram of fuel where for gasoline you need 14.7 grams of air for the same mass. Then, a weighted average of the two is taken based on the ethanol content. Equation 1 below shows the calculation for E30, or a 30% ethanol and 70% gasoline blend.

(1) $$\left[Ethanol_{percent} * Ethanol_{Stoich} + \left(1 - Ethanol_{percent}\right) * Gasoline_{Stoich}\ \right] = Exx_{Stoich}$$

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

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

The percentage fuel trim must be calculated now in order to build the base flex fuel trim map. Since the amount of air the 600 ACE engine is ingesting is not changing as the fuel is changing, then the trim table must be adding a certain percent of fuel. Let us assume the engine continues to take in 14.7 grams of air, but now the fuel is E30. This means that in order to stay at a lambda of one, the stoichiometric ratio of 12.993:1 must be met. Thus using equation 2 below we can calculate the grams of fuel required to meet a stoichiometric AFR of 12.993:1 when there is 14.7 grams of air available.

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

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

Then the trim value to put in the trim table for E30 would be the percent fuel change required to still have stoichiometric combustion with a constant 14.7 grams of air. Thus, through equation 3 below the percent of fuel addition required for E30 fuel is 13.138%.

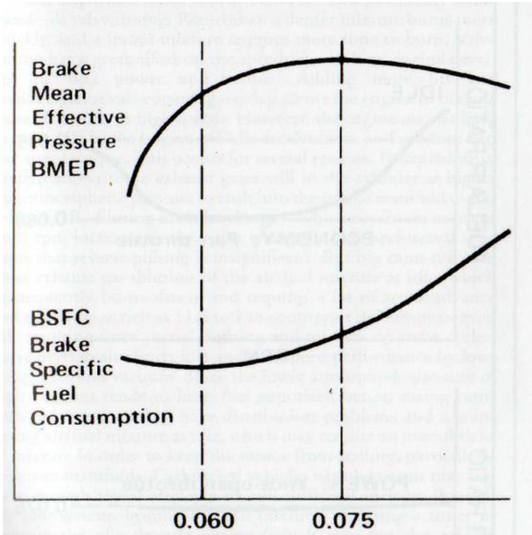
(3) $$\frac{|Grams\ of\ Gasoline\ Fuel\ Req - Grams\ of\ E30\ Fuel\ Req|}{Grams\ of\ Gasoline\ Fuel\ Req} * 100 = \%\ Change\ in\ Fuel\ Req$$

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

EFI Controller Implementation and Calibration

The Power Commander V was designed for easy access and works in conjunction with the DynoJet Wideband 2 O2 sensors that the team used previously. The Wideband O2 sensor is positioned after the two header pipes come together before entering the muffler and the catalyst. Once installed onto the chassis of the sled the target lambda map and the base fuel map must be created. Then calibrations can commence to fine tune for specific ethanol blends from E10 to E39.

First, the base target lambda table must be populated in the Power Commander V. This table is labeled as a target AFR table, thus the values entered into the table be target AFR values as if the fuel was E0. The signal coming from the O2 sensor is in terms of lambda, which is the ratio of the stoichiometric AFR to the actual AFR. Since the Power Commander V is hardcoded with a stoichiometric AFR of 14.7 for E0, when 13.0 is put into the target AFR table, it corresponds to a lambda value of 0.88. For this reason, even when the fuel is changed to E30, the Power Commander V still thinks it is running gasoline so it will target a lambda of 0.88. However, we know that the AFR for E30 at a lambda of 0.88 is 11.434:1. This means that since the O2 sensor measures lambda, AutoTune is tuning the trim table using lambda, not AFR, which is independent of the fuels stoichiometric ratio. In a way, the Power Commander AutoTune table is ignorant to the fuel changes and is just targeting the lambda values calculated from the target AFR table.



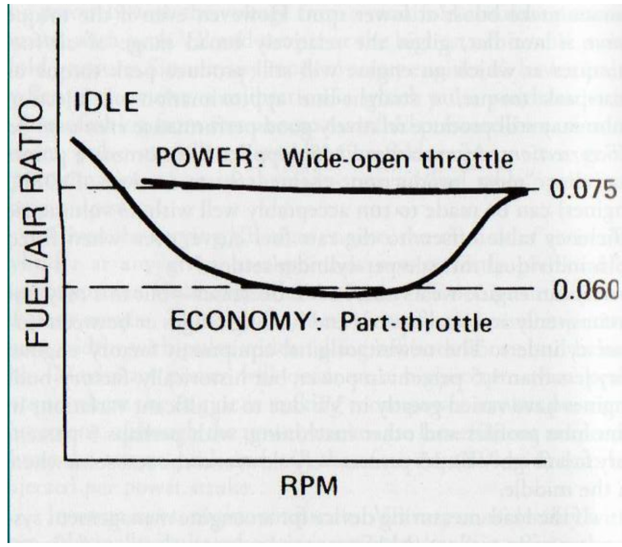


Figure 2 – $\frac{1}{AFR}$ vs. BMEP and BSFC **Figure 3 - $\frac{1}{AFR}$ vs. RPM's for Power and Economy**

Using figure 2 and figure 3 above as a guide, a lambda table was built for efficient operation. The table that is built runs a lambda value between 1.03 and 1.08 for good fuel economy and emissions while cruising between 35 and 55 mph. The lambdas at wide open throttle ranges from 0.94 at 2000 rpm down to 0.9 at redline for peak mean effective pressure. By maximizing the peak mean effective pressure the engine will produce its best power in these ranges. While at idle the snowmobile runs a lambda of about 0.98, just rich of the stoichiometric point for good idling performance.

Next the base fuel map is created by running the AutoTune feature to target the specific lambda values at specific rpms and throttle position. The engine is put onto a DYNOmite snowmobile engine dynamometer and held constant at specified rpm and throttle position points allowing the AutoTune to trim fuel to meet the target lambda values. Then the trims from the AutoTune session are accepted and transferred into the base fuel map using the Power Commander V interface Software. The trims are then cleared and the process is again repeated, however the AutoTune should not have to trim as much to meet the target lambda values since the previous trims were transferred into the base fuel map. This process was repeated until the team was satisfied with the map. This base fuel map now holds trims that the Power Commander V will put into effect at all times for all fuels to make the snowmobile run our specified lambda map.

Finally the analog input adjusting map can be fine-tuned. Initially, the 2-D map is filled with the calculated percent change in fuel for intervals of 2.5 as shown in table 2 below.

Sensor Volt	% Ethanol	% Fuel Change Req	Sensor Volt	% Ethanol	% Fuel Change Req
0	0	0.000	1.375	27.5	11.913
0.125	2.5	0.977	1.5	30	13.138
0.25	5	1.974	1.625	32.5	14.390
0.375	7.5	2.990	1.75	35	15.671
0.5	10	4.027	1.875	37.5	16.980

0.625	12.5	5.084	2	40	18.319
0.75	15	6.164	2.125	42.5	19.690
0.875	17.5	7.266	2.25	45	21.092
1	20	8.391	2.375	47.5	22.528
1.125	22.5	9.540	2.5	50	23.998
1.25	25	10.714			

Table 2 – Sensor Voltage and Percent of Fuel Trim Required for Specific Fuel Ethanol Contents

The table allows for different trim values over the rpm ranges, but not over different throttle positions. Thus, when the auto tune is run with E30, trims must now be put into the flex fuel map and have to be over all the throttle positions but can differ over the rpms.

Once satisfied with the flex fuel tables the Calibration process has been completed. Now the trim tables are reset and the AutoTune is left on only to make very small fine tuning adjustments in real time. By leaving AutoTune running, it allows for the snowmobile to make small adjustments due to air temperature and density changes. Auto tune is set up to start 3 minutes after the sled has been started up allowing the engine and O2 sensor to start warming up so fuel is not taken away from the stock ECU's enriching algorithm for cold-starting and the warm up period.

EXHAUST & EMISSIONS

In order to reduce the emissions levels on the stock 600 ACE engine, a new three-way catalytic converter was implemented. Three-way catalytic converters treat Carbon Monoxide (CO), unburned hydrocarbons (HC), and nitrous oxide (NO_X) pollutants. A three way catalyst works by reducing oxides of nitrogen into N2 and O2, then uses excess O2 in the air flow as well as O2 caught from the NOX to oxidize carbon monoxide as well as un-burnt hydrocarbons. The chemical reduction and oxidation equations are shown below.

$$2NO_x \rightarrow xO_2 + N_2 \qquad\qquad 2CO + O_2 \rightarrow 2CO_2$$

$$C_xH_{2x+2} + \left(\frac{3x+1}{2}\right)0_2 \rightarrow xCO_2 + (x+1)H_2O$$

Since the CSC 2012 emissions event is again based on these three major emissions levels the three-way converter will provide the best results. A single wideband 2 O2 sensor will be in service to determine the lambda of the exhaust gases before entering the muffler. The Power Commander V runs in closed loop mode to keep targeting the lambda for the specific scenarios described in the EFI controller section. When the lambda value is fluctuating around 1.0 then the distribution of the pollutants and available oxygen are at an optimum level with each other for the catalytic converter. The best results for minimizing the pollutants will be found under these conditions.

The three-way catalytic converter was supplied by EMITEC and coated by Aristo. In order to design the converters for the specific use on the 600 ACE, the mass flow rate of the exhaust was calculated and reported. The team also supplied EMITEC with the target AFR ratios and the torque and power curve of the engine. The converter that EMITEC fitted to our application measures 88.9 mm in diameter and114.3mm in length. The converter is substantially larger in diameter than the ones used last year and the substrate density measures 400 cells per square inch which should allow for less backpressure than last year.

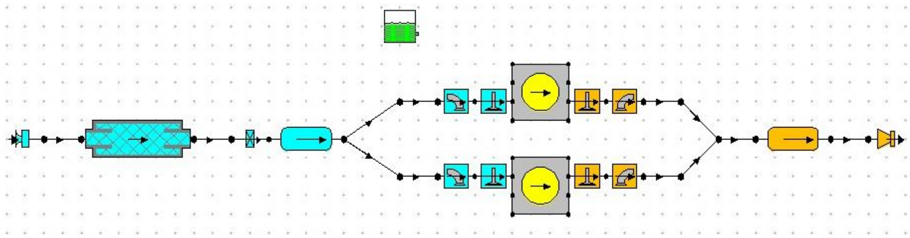


Figure 4 – Lotus Engine Simulator 600 ACE model

Since the team decided to go with one wideband O2 sensor the header pipes needed to be re-designed so that the exhaust flow from each cylinder would collect into one flow before the muffler and catalytic converter. In designing the new exhaust headers there were a few considerations to take into account. First the team decided to build a simple model of the 600 ACE with Lotus Engine Simulation software, as shown above in figure 4. Then using the parametric optimizer the team varied the exhaust header lengths from 100 to 600 mm and then varied the collector pipe length from 50 to 250 mm. The optimizer ran 7 rpms from 1000 to 7000 and then the results for brake specific fuel consumption and volumetric efficiency were graphed over the range (Figures 5 & 6).

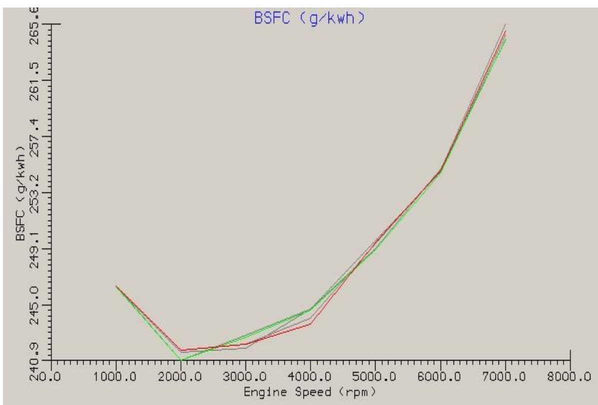


Figure 5 – BSFC vs. RPM

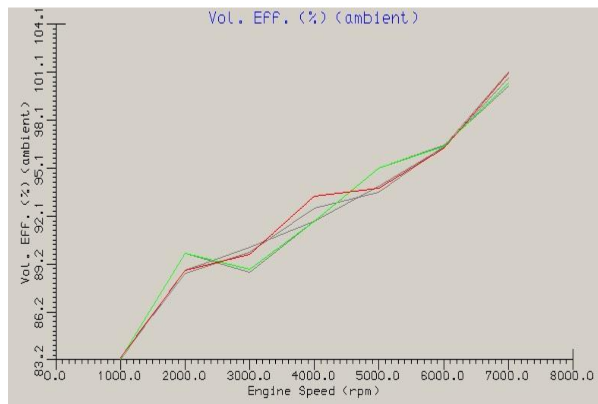


Figure 6 – Volumetric Efficiency vs. RPM

Based on a weighting table set by the user, the program then highlights the best choice. Since the team was designing of overall optimal efficiency at all rpms the weight table was not altered and considered all rpm gate values evenly. The best setup to minimize BSFC and maximize Volumetric Efficiency uses header lengths of 300 mm and a 200 mm collector pipe before the muffler, as notated by the red line in each graph.

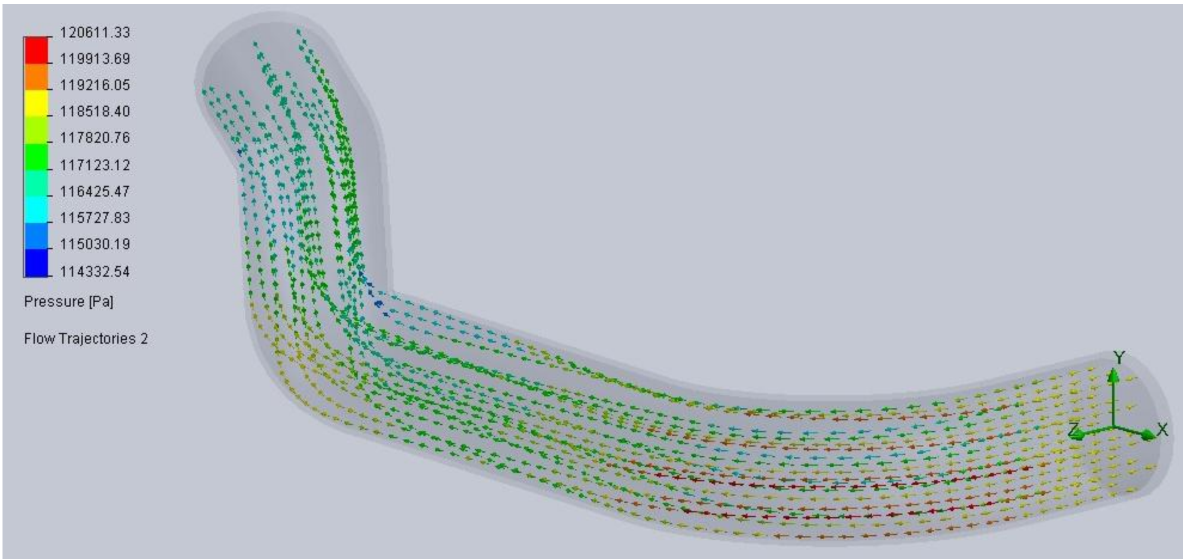


Figure 7 – Stock MAG Header Pressure Profile

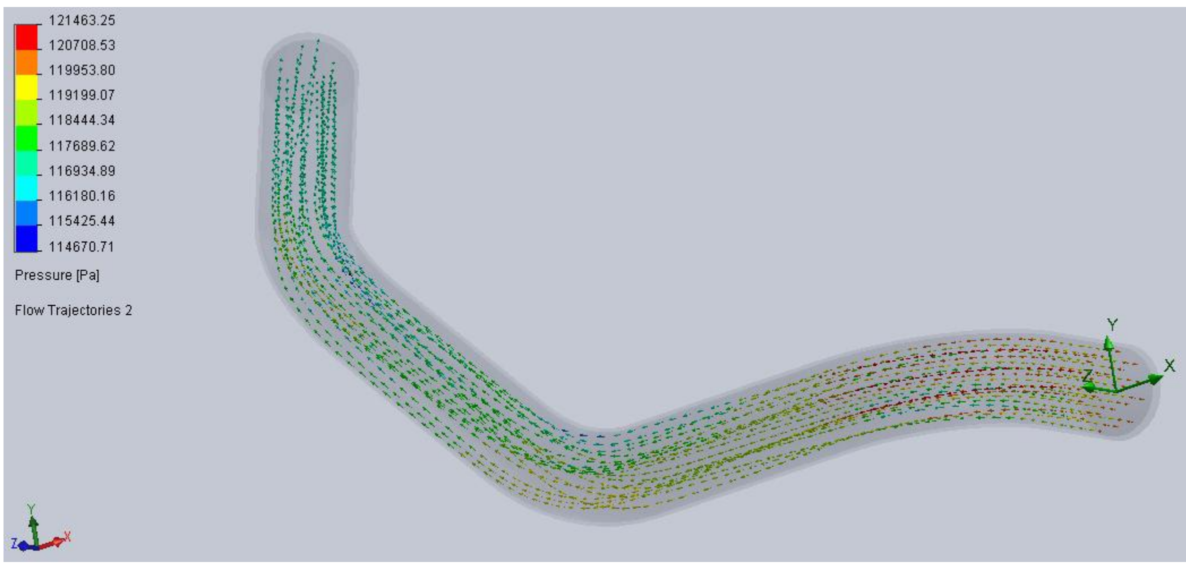


Figure 8 – Stock PTO Header Pressure Profile

The stock header pipes for the 600 ACE were drawn up in Solid Works along with the new headers and collector to analyze the flow and pressure drop across the pipes for comparison. For equal comparison, the pressure at the beginning of all the flow simulations was 125 kPa and the conditions at the end of the pipes were set to 117 kPa. The stock headers are pictured above in figure 7 and 8 shows the high back pressure at the beginning of the header by the 90 degree bend there. When compared to the pressure profiles of each cylinder exhausting as show in figures 9 and 10, the new headers reduced the pressure resistance at the exit of the cylinder ports. By reducing the resistance for the exhaust gases to flow, better scavenging of the cylinders should occur and offset the increased backpressure caused by the added catalyst in the exhaust. On average the back pressure has been reduced by almost 2 kPa (20 mbar) on the on the PTO header and about 1 kPa (10 mbar) MAG side. Ideally the team would have liked to drop the resistance to flow even further but this was not possible due to size and engine compartment constraints.

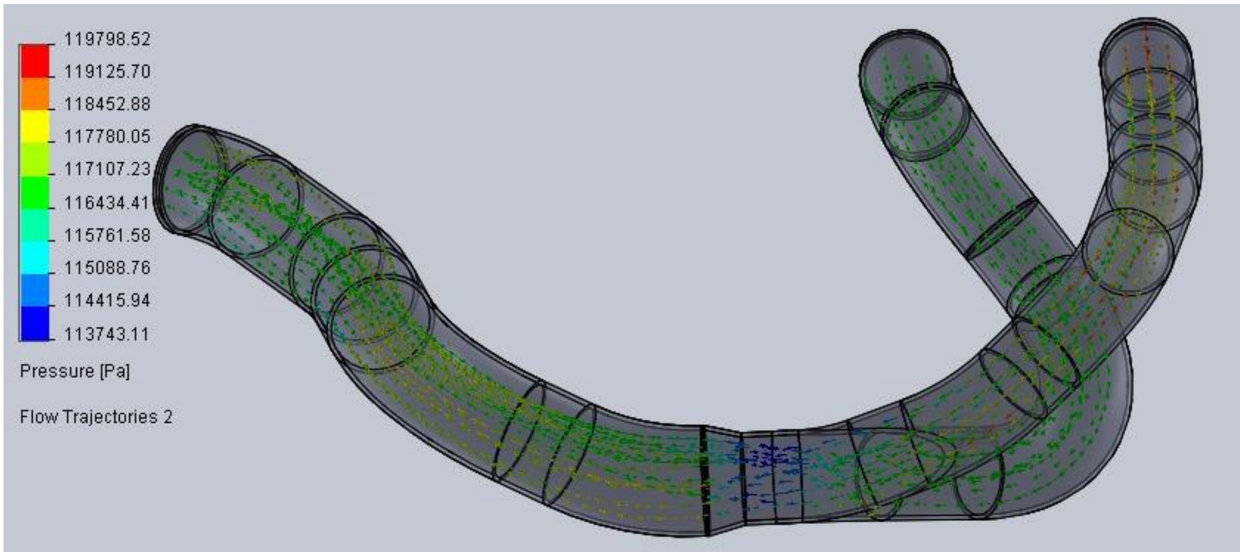


Figure 9 - Header Pressure Profile when PTO Cylinder is on Exhaust Stroke

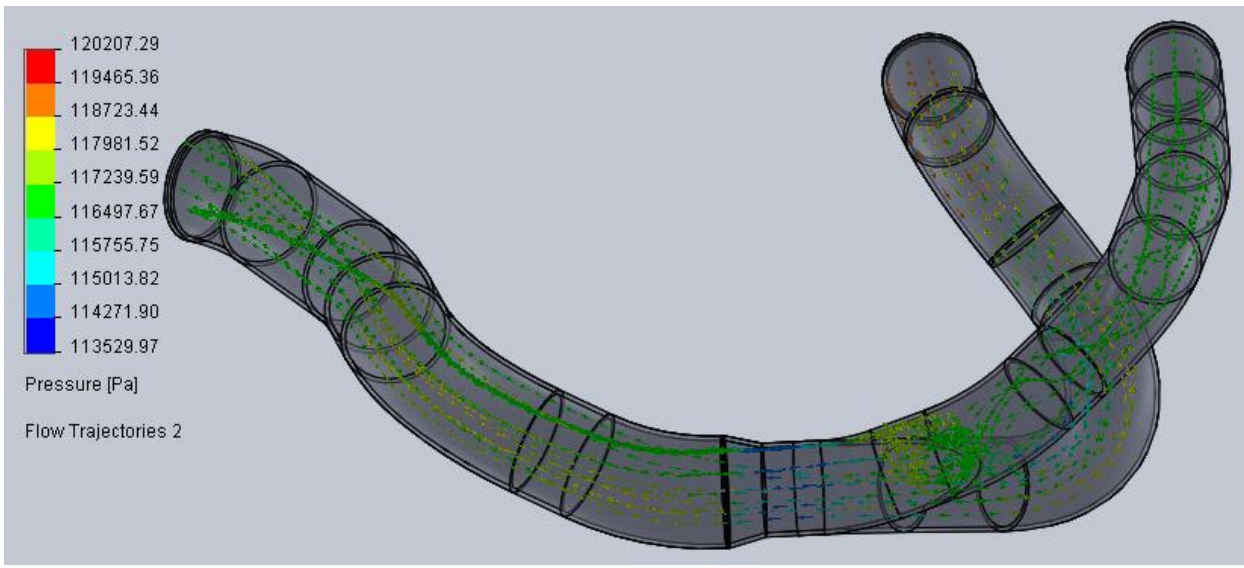


Figure 10 - Header Pressure Profile when MAG Cylinder is on Exhaust Stroke

After flowing through the new exhaust headers and collector pipe the gases travel into the muffler which houses different chambers and the catalytic converter for emissions reduction as described before. The exit of the muffler is fitted with a Marman clamp end to attach the exhaust pipe extension for emission sampling.

CONCLUSION

The 2011 Clarkson University Clean Snowmobile Team started by selecting a snowmobile that sets a higher benchmark to start from. The handling and user confidence is greatly improved with the dual carbide split rail skis. In order to meet the large range of ethanol content the fuel system was modified to detect the fuel composition and adjust the amount of fuel injected into the engine. By doing so, the fuel system is compatible with any ethanol/gasoline mixture from E0 to E39. The exhaust system was redesigned to incorporate a single closed loop O2 sensor with closed loop control to target emissions reduction through a single catalytic positioned in the muffler. The header and collector design was conducted using engineering tools to optimize overall performance and flow of the pipes. The stock snowmobile already exceeds EPA requirements and improving upon those standards will set the bar higher and higher for future competitions. The improved snowmobile will prove to be cleaner and quieter while still providing recreational fun for all ages.

BIBLIOGRAPHY

1. Society of Automotive Engineers, Inc., 2012 SAE Clean Snowmobile Challenge Rules, 2011.
2. Hartman, Jeff. *How to Tune & Modify Engine Management Systems*. St. Paul, MN: Motor International, 2003. Print. Motorbooks Workshop.
3. United States. National Parks Service. Snowmobile Best Available Technology (BAT) List. , 2011. Web. 20 Feb 2012.
4. "MX Z X-Rs." Ski-Doo n. page. Web. 22 Feb 2011.
5. Basset, Jerry. "2011 Ski-Doo Expedition Sport 600 ACE Review." snowmobile.com 22 Nov 2010: n. page. Web. 23 Feb 2011.
6. *Lotus Engine Simulation*. Computer software. *Http://www.lesoft.co.uk*. Vers. 5.07. Lotus Engineering. Web. 5 Jan. 2012.
7. *Solidworks Student Edition*. Computer software. *Http://www.solidworks.com*. Vers. 2011. Dassault Systems. Web. 20 Feb. 2012.

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