Emission and Performance Optimization of a Flex-Fuel Snowmobile

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ABSTRACT

The Clarkson University SAE Clean Snowmobile Team's objective for the 2013 Challenge was to further improve upon our 2011 Ski-Doo MXZ Sport which is certified as best available technology (BAT), powered by the Rotax 600ACE (Advanced Combustion Efficiency) twin cylinder four stroke engine.

Due to proven success with a GM/Delphi oxygenate sensor paired with a Power Commander V with AutoTune capabilities for accommodating various blends of ethanol, this system was further modified and retained for 2013. With this years Challenge using E40 to E85 fuels, additional fuel system changes were needed. Higher flow fuel injectors had to be fitted as the stock injectors were not capable of delivering sufficient fuel at full throttle with blends exceeding E40.

To further improve emissions and performance, a Garret GT12 turbocharger has been fitted to the engine, along with custom low compression pistons. This serves to lower tailpipe emissions while also boosting performance, and enhancing the appeal of the snowmobile to the consumer. Integrating a 3-way catalyst into the OEM muffler allows for packaging ease while further reducing emissions.

These modifications serve to improve both the performance and environmental responsibility of an already popular and appealing snowmobile.

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 oxides of nitrogen emissions, as well as utilizing ethanol gasoline blends from ranging from E40 - E85. 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 2013 Clean Snowmobile Challenge will take place at Keweenaw Research Center, Michigan from March 4th through the 9th.

The following report describes how Clarkson University has further reduced the chemical and sound emissions while improving the overall performance of one of the cleanest and most efficient snowmobiles offered by manufactures. This past year the 2012 Clarkson Winter Knights used the same 2011 MXZ 600 ACE and demonstrated a sled designed for the environmentally conscious rider. The design utilized a closed loop fuel system using one wideband lambda sensor with a custom 2-1 exhaust. A drawback to this design was that essentially lambda was being averaged between the cylinders, therefore not taking the fuel offsets between the two cylinders into affect. Continuing to use the 2011 MXZ Sport allowed for more design and testing time to continue improving our closed loop fuel system while also developing a custom turbo kit to enhance performance and reduce emissions.

The MXZ Sport will benefit from modifications to the Power Commander V and custom turbo integration. The fuel controller incorporated into the fuel system allows for closed loop controlled lambda for each cylinder accounting for any fuel offsets as well as fuel percentage adjustments based on the measured ethanol fuel mixture being used at the Clean Snowmobile Competition. 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. This report will discuss in detail the process of re-engineering a stock 2011 Ski-Doo MXZ Sport 600 ACE to the ultimate Clean Snowmobile.

FUEL SYSTEM

Our theory on solving the problem of compensating for ethanol in the fuel is unchanged from previous years, due to it being highly successful in simplicity, effectiveness, and reliability. Pressurized fuel passes through a GM/Delphi oxygenate sensor, identical to that which is found in GM built flex-fuel capable automobiles. This sensor outputs a square wave signal to an Ethanol Content Analyzer built by Zeitronix. This Analyzer displays to the rider the current ethanol percentage (i.e. E40), as well as outputs that percentage as a linear 0-5 volt analog output, with E0 being 0 volts and E100 being 5 volts. This signal is transmitted to a custom hand built Dynojet Power Commander V (PCV) “piggyback” style ECU. Our team worked closely with Dynojet to modify and develop a PCV for the Rotax 600ACE to suit our needs of incorporating both an ethanol content input, as well as input from a Pressure/Temperature sensor to control fueling and ignition with turbocharger boost. Typical off-the-shelf PCV’s, which are now available to the public because of the Clarkson Winter Knights, only adjust fuel, they do not have the ability to adjust ignition timing, or have a Pressure Temperature input.

With the system in place, values were calculated for “target” lambda rations across four dimensions: RPM, throttle position, ethanol percentage, and manifold absolute pressure (boost). This is done with Dynojet’s Power Commander software linked to the actual controller box via USB cable. This also allows us to view all the inputs and automatic tuning “trims” in real time via laptop while testing is in progress and make instant changes. In addition to our established method for tuning against ethanol content, this year’s specially modified PCV can also accept input from a Bosch MAP sensor with an operating range of 20kPa to 250kPa gauge pressure, or up to 30psi of boost.

In addition, the PCV system allows the engine to be tuned for different target lambda values for efficiency. For example, in the mid-range of the RPM scale under steady, moderate throttle position, the engine can be tuned to a slightly lean (lambda >1.0) condition to maximize economy for a typical trail speed cruise (30-45mph). It can also run slightly rich at full throttle and peak boost to provide supplemental cooling to the pistons when engine load is at its maximum. This kind of versatility gives nearly all the controls of a standalone aftermarket ECU, while preserving the features of the snowmobile the stock ECU controls, such as the D.E.S.S security system, multi-function gauge cluster, and OEM fail safe modes without the need for complicated and costly external controls and drivers.

The stock Bosch Motronic ECU utilizes a single pressure-temperature sensor, located in the intake plenum downstream of the throttle body. This sensor reads up to 115kPa, or just slightly above atmospheric pressure. The ECU uses this to richen the mixture for cold starting, as well as controlling idle speed via the vacuum reading. This presented a challenge, since when the engine is operating under greater than atmospheric pressure (boost), the sensor maxes out and the ECU’s fail-safe disables the engine. The sensor cannot be removed otherwise the check engine indicator is turned on and the ECU locks into “limp home” mode limiting performance. It also cannot be re-located outside the plenum box, since this would compromise idle function. To solve this problem, a device called a Voltage Clamp was implemented. This signal conditioner intercepts the stock sensor’s 0-5V output signal before it reaches the ECU. It allows the output to function normally below a set voltage, and once a limit is reached it conditions or “clamps” the voltage steady. This prevents the sensor from maxing out under boost and tripping the ECU failsafe while preserving cold start and idle functions. The stock sensor’s output voltage follows a linear relationship with pressure, with 0 volts corresponding to the minimum reading of 10 kPa and 5 volts corresponding to the maximum of 115kPa. Under stock operating conditions, the measured pressure in the intake plenum would peak at slightly below atmospheric pressure at full throttle, approximately 98 kPa. Using interpolation, this corresponds to a sensor output voltage of 4.2 volts.

The stock 600 ACE injectors are rated at 211cc/min, which from last year's testing data at the maximum E40 fuel, the duty cycle approached 86% at full throttle. Larger injectors were needed to accommodate fuel blends up to E85. We determined the most economical and affordable solution was to use the stock fuel injectors for this engine's "big brother", the Rotax 1200. Since the fuel rails on the 600ACE and 12004-tec are identical, and the injectors are also identical in physical size and electrical response, the only difference is the fuel rate and spray patter. The new flow rate was increased to 333 cc/min. This allowed us to compensate for any additional fuel demands due to the high ethanol content and turbo system. At low RPM's and low ethanol content, the injector pulse widths needed to be decreased by about 35%. These changes can be seen in Table 1 for stock engine configuration as follows:

Table 1- *Fuel Trim Requirements for Specific Ethanol Contents – Naturally Aspirated, Stock Compression Ratio*

Fuel E%	Stock Injectors Duty Cycle Change	1200 Injectors Duty Cycle Change
0%	0.0%	-36.4%
10%	4.0%	-34.1%
20%	8.4%	-31.5%
30%	13.1%	-28.8%
40%	18.3%	-25.7%
50%	24.0%	-22.4%
60%	30.2%	-18.8%
70%	37.2%	-14.7%
80%	44.9%	-10.2%
85%	49.0%	-7.8%
90%	53.5%	-5.2%
100%	63.2%	0.5%

Stoichiometric ratios for this range of fuels were calculated and were used to create the table above expressing the required change in duty cycle for the new 12004-tec injectors. The stoichiometric ratios were calculated using Equation 1, below. In these examples, a sample fuel of E30 was used.

Equation 1

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

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

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

Now to calculate the percentage change in fuel needed to meet the previously calculated stoichiometric ratio, Equations 2 and 3 were used, illustrated below.

Equation 2

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

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

Equation 3

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

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

ENGINE AND PERFROMANCE

To maximize performance, increase mile/gallon fuel efficiency and reduce overall emissions, this year the team decided to turbocharge the Rotax 600ACE. The new forced induction system utilizes a Garrett GT1241 fixed vane turbocharger with oil journal bearings and liquid cooling. This unit was initially selected using Garrett's "Boost Advisor", which uses inputs such as engine size, peak RPM, and other factors to determine the most suitable compressor. Calculations were done to assess critical factors related to tuning the turbo application, summarized in Table 2 below.

Table 2- *Turbocharging Calculations*
**table 2 in appendix*

Due to the 600 ACE's already high stock compression ratio of 12:1, adding a suitable amount of boost for noticeable performance and efficiency gains would place undue stress on stock engine components, and increase the chance of fuel pre-ignition (detonation). To combat this, we worked with Wiseco Performance to develop custom low compression pistons. These pistons were designed to fit in the stock bore size allowing for minimal, if any engine modifications. This allowed us to utilize the stock valve train, connecting rods, and crankshaft could be retained. These pistons lower the compression ratio to approximately 10:1, using Equation 4. Supporting specifications and calculations were provided to Wiseco during the development phase. The Clarkson Winter Knights provided all parts needed to develop and build castings. In return Clarkson is the first consumer in the world to use these low compression pistons.

Equation 4

$$\mathrm{CR} = \frac{\frac{\pi}{4}b^2 s + V_c}{V_c}$$

Where *b* indicates cylinder bore, *s* indicates stroke length, and Vc indicates clearance volume or "squish zone", the volume remaining in the cylinder with the piston at top dead center. Since bore and stroke were to remain the same and the clearance volume was reduced by "dishing" the pistons. Based on calculations illustrated above in Table 2. The difference between the stock (left) and low compression (right) pistons is depicted in Figure 1 below.

Figure 1- *Comparison of Stock and Low Compression Pistons*

We chose to not go lower than this since significantly lowering the compression ratio can compromise low speed power and "drivability", undesirable factors to the final consumer.

To improve the thermal efficiency of the turbocharger system, a custom air to air intercooler was designed and manufactured to our given dimensions and specifications by Bell Intercoolers. An air/air style Intercooler was chosen for snowmobile application since they are typically operated in sub-freezing weather, greatly improving their effectiveness in reducing the temperature of the intake charge. A 12 volt electric fan was fitted to keep air flowing through the intercooler at low operation speeds and prevent clogging of the intercooler substrate when riding in deep or powdery snow.

EXHAUST AND EMISSIONS

With the goal to further reducing emission levels on the 600ACE a three-way catalytic converter was implemented into the OEM muffler to eliminate packaging issues and keep the stock look. In cooperation with Emitec and substrate coating by Aristo, this catalyst is designed to reduce unburned hydrocarbons (HC), Nitrous Oxides (NOx), and Carbon Monoxide (CO) in the tailpipe exhaust. As the exhaust flows the catalyst initiates a reaction that reduces nitrous oxides into N2 and O2, and uses free oxygen in the exhaust flow to oxidize carbon monoxide into carbon dioxide. The following chemical balances model this reaction:

$$2NOx \rightarrow xO_2 + N_2$$

$$2CO + O_2 \rightarrow 2CO_2$$

$$C_xH_{2x+2} + (3x+1/2)O_2 \rightarrow xCO_2 + (x+1)H_2O$$

The substrate was chosen with the assistance of Emitec, based on calculated mass flow rates of the exhaust, as well as the measured power and torque curves of the engine. Emitec recommended a catalyst 89mm in diameter and 114mm in length, with a substrate density of 400 cells per inch to minimize added backpressure to the exhaust system.

In addition to a conventional “hot” catalytic converter, we have integrated a cold catalyst into the crankcase vent line, which recirculates blow-by gases back into the intake. The SMART MR-100 device, developed by Extreme Energy Solutions, is a proprietary catalyst substrate of precious metals that installs in the crankcase vent line to convert blow-by gases into flammable gases that can be burned by the engine, rather than simply recirculated. Using a Snap On HH5GA Five Gas Analyzer, we ran tests at both idle and partial throttle with a simulated load from a DYNOmite dynamometer with and without the SMART device to quantify and emissions reduction. Based on obtained numbers from the analyzer, we found the unburned hydrocarbon levels averaging around 180ppm (parts per million). With the SMART device installed and the same test run again, we found HC levels had increased to an average of 360ppm. Readings on other measured gases (free O_2, CO, CO_2, and NOx) were similar or slightly improved. The company states that initially the device slightly raises emissions, as seen by our average measurements. As the catalyst begins to age emissions levels will begin to decrease. Extreme Energy Solutions completed an independent study with a fleet of Yellow Cabs. Seen in Table 3 below are emission measurements for one of the vehicles, which show an overall reduction in emissions and slight improvements fuel economy. With the addition of the SMART Device, we hope to further improve or emissions and fuel economy.

Table 3*- SMART Device Data*

1. **California Yellow Cab Service Vehicle #787: 2007 Ford Crown Victoria**
VIN: 2FAHP71W27X150221
Fuel: Gasoline
Retrofitted with the SMART Emissions Reducer Model: R200

Mileage (Baseline - Pre SER)	Mileage (Emissions Test with SER)	Total Mileage
101344	120237	18,893

Emissions	Emissions Baseline Test (Before SER Installed) 8.10.12	Emissions Test (120 days with SER) 12.12.12	Emissions Results (difference)	Percentage Change
NOx	0	0	0	0%
CO	1.00	0.04	-0.96	-96%
HC	47	10	37	-78.72%
CO2	14.7	14.7	0	0%
O2	0.95	0.96	+.01	+1.05%

MPG Average (w/o SER)	MPG Average (w/ SER)
16	17.8

+1.8 miles per gallon
+11.25% increase in fuel efficiency

The stock 600ACE engine uses two single pipes, each feeding its own inlet to a common silencer. These pipes were modeled in Solid Works to analyze flow and pressure characteristics as illustrated in the following Figures 2 and 3 below.

Figure 2 *- Magneto (MAG) side head-pipe pressure profile*

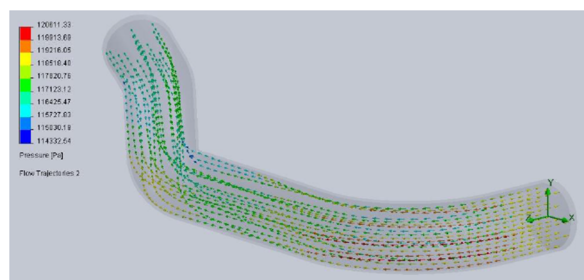
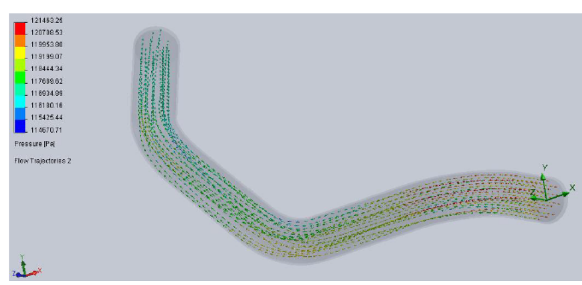


Figure 3*- Power Take Off (PTO) side head-pipe pressure profile*



In the simulations, the inlet pressure was set at 125kPa, and the outlet at 117kPa. The areas of red near the engine side illustrate the high backpressure caused by the sharp 90 degree bends the stock exhaust uses to conserve space and materials.

The exhaust integrates a 2-into-1 design to the turbocharger, and a single 1-1 pipe from the turbine to the silencer pack. The design considered the physical space limitations of the snowmobile as well as minimizing backpressure to improve the scavenging effect and reduce turbo lag. Before the collector at the turbine inlet, each header features a bung for an exhaust gas temperature probe as well as a bung for a standard wideband lambda sensor. This enables both cylinders to be monitored and tuned independently for greater accuracy to the target lambda values. The exhaust was designed with aid from Lotus Engine Simulator with a model of the 600ACE to give ideal parameters for the exhaust design. The model is illustrated below in Figure 4.

Figure 4- *Lotus Engine Simulation Model*

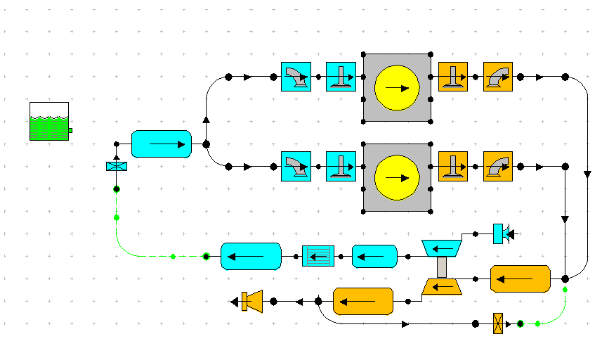


Figure 5 *- Header Pressure Profile when MAG Cylinder is on Exhaust Stroke*

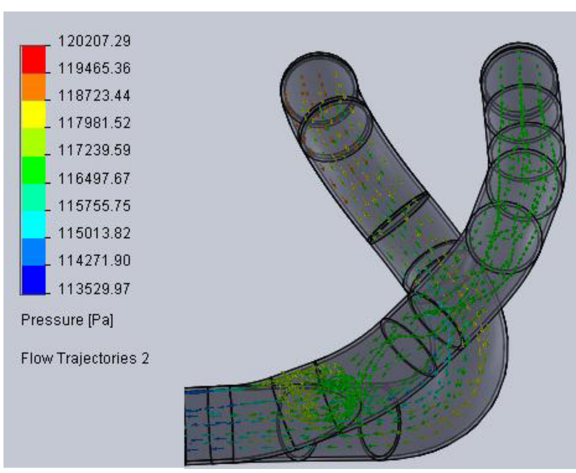
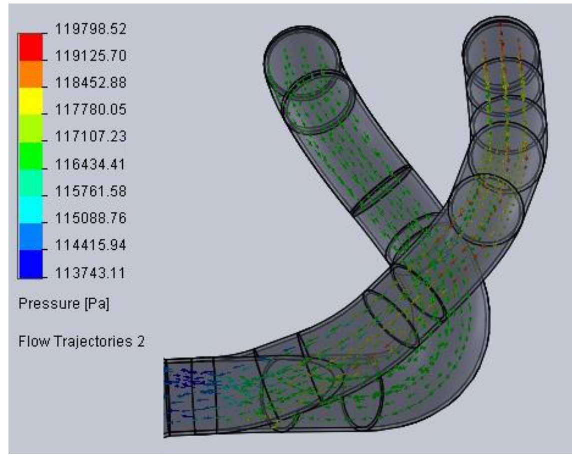


Figure 6 - *Header Pressure Profile when PTO Cylinder is on Exhaust Stroke*



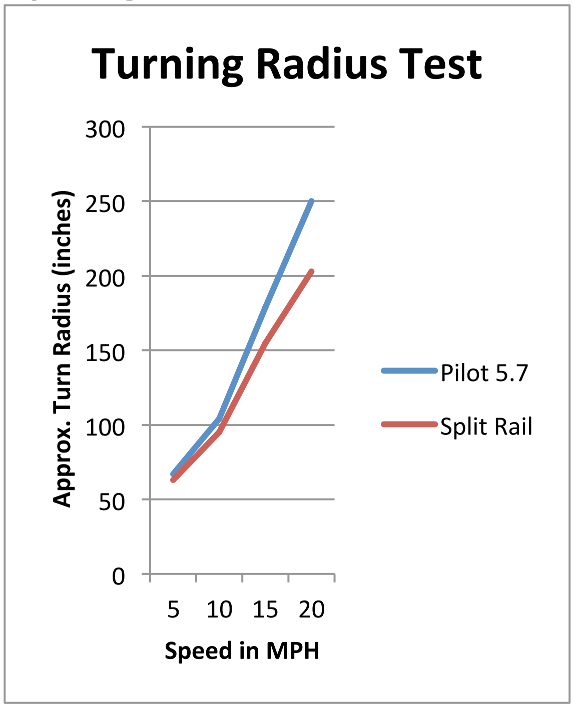
This year's design for the exhaust headers closely resembles last year's design in that the purpose is to reduce exhaust backpressure that was slightly increased by the integrated catalytic converter and turbocharger. This design reduced the average backpressure by approximately 2kPa (20mbar) on the PTO side header. For the MAG side it was reduced to about 1kPa (10mbar).

HANDLING AND TRACTION

The Ski-Doo MXZ Sport was partially selected as a base for our design based on the outstanding handling characteristics of the stock machine coupled with the lightweight 600ACE power package. In the interest of keeping this entry level machine competitively priced, the changes implemented would be both economical and easy production changes to the stock model.

To improve handling in this machine's native groomed trail terrain, skis from Split Rail were fitted. These not only replace the ski itself, but also the spindle with one of revised geometry optimized for the dual runner design. These skis "twist" into corners, allowing the outboard and inboard halves to flex and dig into the snow independently, giving improved grip in corners thus eliminating the tendency to "dart" or follow grooves left by other snowmobiles in the trail. These skis also improve track lubrication and cooling. The hollow center design serves to create a channel for snow that blows back into the track and tunnel while underway. The extra snow ensures the track and hyfax are well lubricated, helping minimize friction while at the same time improving cooling capacity of the heat exchangers on icy or marginal snow conditions. A test on a hard packed lake revealed the handling advantage of the Split Rail skis over the stock Pilot 5.7 skis, as illustrated in Figure 5 below.

Figure 5- *Split Rail vs Pilot 5.7 Skis*



With the additional power output from the turbocharging system, the stock .75" lug track would be overwhelmed and not adequately transfer the power to the ground resulting in excessive track-spin during acceleration and while riding in deep snow. To help improve traction in all conditions, trail, powder, and ice, a Camoplast Ice Attak XT pre-studded track was fitted, which features a more aggressive 1.22" lug height as well and molded in stud tips to provide extra traction and safety in icy conditions. The length of the track was not extended in the interest of keeping costs low and preserving the agile handling of a short track machine.

CLUTCHING

For the 2013 Clean Snowmobile competition, it is expected the snowmobile will produce approximately 90 horsepower, measured at the crankshaft. The stock engine was tested to match the manufacturer's claim of 60 horsepower. With this increase in power output, changes are needed to the continuously variable transmission (CVT) system both for efficient power transfer, and for safety. The stock snowmobile uses Ski-Doo's "E-Drive" primary clutch, which was specially developed for the 600ACE power package- and its stock power output. While this clutch could be modified to handle the additional power, to ensure the safety and reliability of the machine this clutch replaced using the new "E-Drive II" clutch. This clutch was designed for the MY13 Ski-Doo 1200 4-TEC power option, which produces 130 horsepower, well in excess of our target.

The goal of an effective clutch tuning setup is to optimize power delivery to the track in all conditions. To maximize both performance and efficiency, the setup must allow the engine to reach its peak power RPM under full throttle, but also quickly upshift under partial throttle to reduce engine RPM and raise efficiency. However, as a CVT is a torque-sensitive system, changes in engine power output require changes to the clutches to maintain performance. With our choice of the E-Drive II clutch, which is configured for 130 horsepower, modifications were needed for it to operate efficiently with our target of 90 horsepower.

The E-Drive and the E-Drive 2 primary clutches are similar in construction, both using the same spring and style of weights. The E-Drive uses six 32 gram weights, while the E-Drive II uses six 40 gram weights. With the spring rate constant, heavier weights will lead to an earlier engagement RPM and faster upshift, increasing the rate load is applied to the engine under acceleration. Using weights that are too heavy for a given power output will cause reduced acceleration performance and an unresponsive feel from the throttle. Using weights that are too light can cause over-revving of the engine and a loss of efficiency due to a lack of up-shift. In practical terms, more powerful engines need heavier weights, in a fairly linear relationship. All other factors held constant, interpolating power against weight values we determined that 36 gram weights would be ideal for our target power output. Testing demonstrated this gave a stock engagement RPM and overall similar feel to the stock machine, with good acceleration meeting the target peak RPM of 7200 while also shifting up to an efficient cruise ratio.

CONCLUSION

The 2012-13 Clarkson University Clean Snowmobile Team began by assessing what was successful and reliable enough to carry over from previous year's designs based on the 2011 Ski-Doo MXZ Sport 600ACE. The system for measuring and exporting a useable signal for ethanol content was simple, effective, and required no further modifications to function with the 2013 Challenge's criteria since the system is E0-E85 capable. A custom built Power Commander V accepts input from the oxygenate sensor, manifold pressure, throttle position, and RPM to make appropriate adjustments to fuel and ignition mapping to accommodate the compressor boost and ethanol content. Larger injectors were fitted to deliver the additional fuel demands. A main goal of our design was to preserve the stock appearance, something that would be appealing and affordable to a snowmobile consumer. The redesigned snowmobile will prove to be more powerful, more efficient and cleaner than the stock MXZ while still being appealing to purchase and fun to drive. For the 2013 CSC the Clarkson Winter Knights continue to defy conventional methods to display our passion for cleaner, quieter, and more efficient snowmobiles

REFERENCES

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Turbocharging Performance Handbook. St.Paul, MN: Motorbooks, 2007.

ABBREVIATIONS

SAE- Society of Automotive Engineers

CVT- Continuously Variable Transmission

BAT- Best Available Technology standard

cc- cubic centimeters

ACE-Advanced Combustion Efficiency

GM- General Motors

Exx- Ethanol Percentage in fuel

PCV- DynoJet Power Commander V

ECU-Engine Control Unit

RPM-Revolutions per Minute

USB- Universal Serial Bus

D.E.S.S.- Digital En Security System

HC-Hydrocarbons

NO-Nitrous Oxide

CO- Carbon Monoxide

ppm- Parts per Million

kPa- Kilopascals

mbar- Millibar

MAG- Magneto side

PTO- Power Take Off side

APPENDIX

Table 2

Percent Ethanol in fuel	Increased Percent of Fuel to account for more Ethanol to keep the stoichiometric ratio	New Flow Rate Required to account for increased Ethanol (cc/min)	Stock 600 Injectors Increased % Duty Cycle to Achieve New Flow Rate	1200 Injectors **Decrease** % Duty Cycle to achieve New Flow Rate
0%	0.0%	211.76	0.0%	36.4%
10%	4.0%	219.57	4.0%	34.1%
20%	8.4%	228.04	8.4%	31.5%
30%	13.1%	237.26	13.1%	28.8%
40%	18.3%	247.33	18.3%	25.7%
50%	24.0%	258.36	24.0%	22.4%
60%	30.2%	270.52	30.2%	18.8%
70%	37.2%	283.97	37.2%	14.7%
80%	44.9%	298.94	44.9%	10.2%
85%	49.0%	307.07	49.0%	7.8%
90%	53.5%	315.69	53.5%	5.2%
100%	63.2%	334.56	63.2%	-0.5%