Analysis and design of the 2017 Iowa State Clean Snowmobile: A 599cc two-stroke utilizing a redesigned clean and quiet exhaust system.

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Abstract

Iowa State University's entry into the 2017 SAE Clean Snowmobile Challenge is a 2015 Polaris 600 Rush Pro-X. The objectives of the competition are to improve the fuel economy, noise levels, and emissions of a production snowmobile. The exhaust system was modified by utilizing a dual catalyst setup with Aristo Global® two-way oxidation catalysts in conjunction with a redesigned muffler for substantial noise reduction. Noise levels were additionally reduced by using Line-x® spray-on bedliner and Ensolite foam. With the use of a Dynojet Power Commander V in series with the Polaris engine control unit, the ignition timing and fuel curves were adjusted to improve emissions and horsepower by allowing the motor to perform under a lean burn condition. With these changes, Iowa State University has produced a clean and quiet snowmobile for use in the most environmentally sensitive areas while sustaining the "fun to ride" aspect of the sport.

Introduction

For many years, snowmobiling has been a great opportunity for winter recreation and sport. Snowmobiles often are ridden in Yellowstone National Park and other environmentally sensitive areas where the negative effects of a snowmobile can be substantial. Typically, snowmobiles tend to be loud and release harmful exhaust emissions, with having poor fuel economy. As a way to counter these potentially negative impacts of snowmobiles, a competition was created for colleges around the world to redesign, modify, and fabricate a clean and quiet snowmobile.

The SAE International Clean Snowmobile Challenge was introduced as a collegiate design competition to combat the detrimental effects that power sports can have on the environment. Throughout the years, this challenge has provided an innovation center for sustainable modifications from which the snowmobiling industry has benefited greatly. Teams are tasked with developing a snowmobile that excels in three main categories: emissions, noise levels, and fuel economy. The 2017 Clean Snowmobile Challenge requires teams to have a "flex-fuel" design, accepting ethanol fuel blends ranging from 0% - 85%.

The following report goes into detail how the Iowa State University team has prepared a snowmobile for acceptability in areas such as national parks and reserves. This year, many of the design changes that were made revolved around noise reduction and exhaust treatment.

Snowmobile Selection

For the 2017 competition, Iowa State University chose to enter a 2015 Polaris Rush 600. The selection was made based off of market research surveys conducted by the team, the preferred power-to-weight ratio of a two stroke, and the better handling ability of the Rush model. Market research surveys were given to members of Iowa snowmobile clubs as well as students at Iowa State University. The surveys recorded fifty-four unique and anonymous responses to two basic questions.

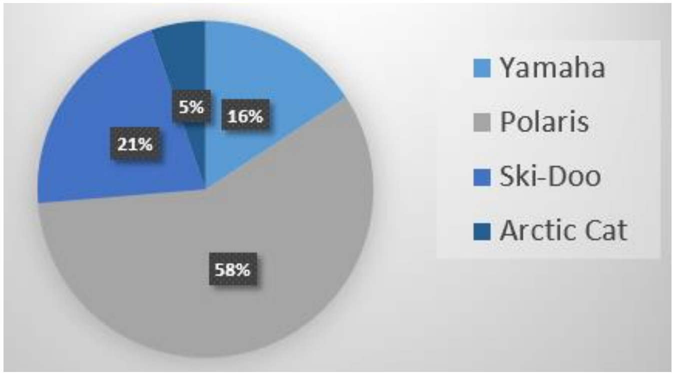

Figure 1: Response breakdown when a group of riders were asked which brand is owned or preferred.

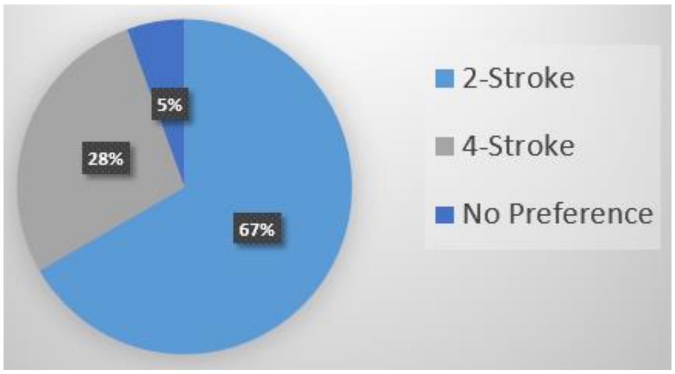

Figure 2: Response Breakdown when a group of riders were asked which engine style is preferred.

As shown in both Figure 1 and Figure 2, the most preferred sled was a Polaris with a 2 stroke motor. The market research survey only used fifty-four responders, but a noticeable trend in snowmobiler preference was clearly formed. When asked about brand preference, Polaris was the preferred manufacturer for 58% of responders. It was also shown that the 67% of riders preferred using a sled with a 2-stroke motor over a 4-stroke motor. The goal for the ISU team was to create a clean, quiet, and fuel efficient snowmobile without decreasing the snowmobile's performance.

The 2015 Polaris Rush Pro-X uses the Axys® chassis, which features a carbon-fiber structure and aluminum handlebars. This chassis design allows for centralized vehicle mass, more power with less weight, and better rider balanced control than previous models. With the new Axys® chassis, the rider's feet are moved 2" forward, and the knees, seat, and hands are all moved 4.5" forward compared to the previous Pro-R models. This moves the rider into a more balanced position. This sled also features the Pro-XC rear suspension system, which is both lighter and stronger than previous models. This suspension system utilizes Active Pitch Control, which has the ability to control the pitch with suspension geometry instead of just simply a high spring rate. The dry weight of the stock Polaris Rush Pro-X was 435 lbs., which was lighter than most models that Polaris offers as shown in Figure 3.

	Weight (lbs.)	Percent increase from ISU sled
2015 Indy SP 600	449	3.20%
2015 Switchback Pro-S 600	447	2.70%
2015 Switchback Assault 600	460	5.70%
2014 Rush Pro-R 600	464	6.70%

Figure 3: Weight comparison between a few similar Polaris models and difference from the 2015 Polaris Rush 600 Pro-X

The engine choice for the ISU team was a 599cc Cleanfire® engine with semi-direct injection. This initial engine choice was based on the market survey for two stroke engines over four stroke, and the need for better fuel economy.

Chassis Improvements

Track Selection

The main audience for the Polaris Rush Pro-X are typically trail riders or extreme riding in ditches and ungroomed trails. To address this preference, Iowa State University chose to select a track with an appropriate lug length for better bite with off-trail use and performance for on-trail use. The stock track that typically comes with the Pro-X chassis is the 120 x 1.75" Backcountry X track but ISU team chose to use a 120 x 1.25" Ripsaw II track. The Ripsaw track has shorter lugs than the Backcountry and has better grip or bite into groomed trails. This track has excellent traction on loose, less compacted snow as well, making it very versatile and efficient.

The Iowa State clean snowmobile challenge team set a goal of creating a performance driven and ecofriendly snowmobile.

To improve performance, the team chose to use 1.325" 60˚ carbide tip Gold Digger studs from Woody's Traction in a 96 single pattern. ISU's 2016 acceleration data for a 60-foot distance is shown in table 1. In this test, the rider accelerated from rest to full throttle. This year, the team decided to use 42 studs rather than 84, to reduce weight while still improving acceleration. The snowmobile will have better traction control resulting in better efficiency.

Trial	Time for unstudded (seconds)	Time for studded (seconds)
1	1.97	1.83
2	2.08	1.88
3	2.13	1.91
Average:	2.06	1.87
Improvement:		9.06%

Table 1: Acceleration times due to unstudded or studded tracks.

Noise Mitigation

The two sound deadening materials, Raam Matting and Line-x spay-on bedliner were evaluated to determine which was the most effective. Raam Matting was used last year by the team and had minimal noticeable results. Line-x was chosen as a test subject because it is a tough, durable rubber that would strengthen the sled, while reducing sound pollution. Since lower frequencies tend to travel farther distances than high frequencies, the team aimed to neutralize a range of lower frequencies. A range of 200-1000Hz was measured due to past data, where readings of 1000 Hz or below had the highest variation. Figure 4 shows Iowa State University's past sound deadening data.

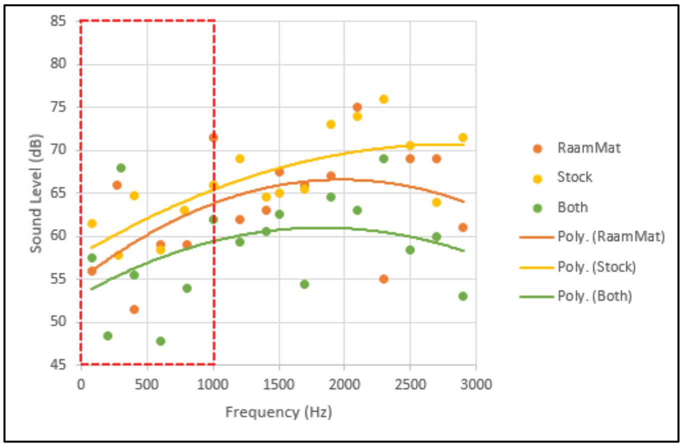

Figure 4: Frequency vs. Sound Level graph for sound deadening material.

Ensolite foam was also evaluated as a complimentary layer to further dampen high frequency sound pollution. To test the materials, a control group was measured by placing a bare plastic sheet over a wooden box with an enclosed speaker, and measuring decibel readings at high (1000 Hz), mid (600 Hz), and low (200 Hz) range frequencies. Both products were applied to a similar sheet of plastic and evaluated using the same testing set up as the control group. Two treatments of Linex were tested, one treatment at 1/16" and another at 1/8" thickness. A layer of Ensolite foam was added onto each treatment of Linex and Raam Matting, and the test was repeated. The results were compiled into a graph shown in Figure 4.

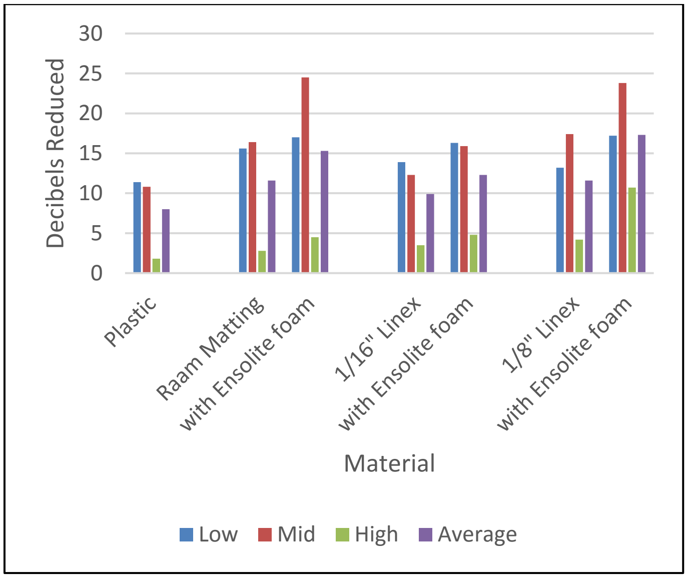

Figure 5: Sound deadening test results with different materials.

Iowa State concluded that the 1/8" thick Line-x with the layer of Ensolite foam had the best average sound deadening qualities for the range of frequencies measured, and would be suitable to use on the snowmobile. Based on these results, a 1/8" thick layer of Line-x was applied to the interior of the side panels and the underside of the tunnel. Ensolite foam was added to the side panels' interior, however Iowa State chose not to apply the foam to the tunnel since the foam is not durable enough to survive during running conditions.

Emission Control

Analysis of 2-Cycle Oil

The constituents of exhaust emissions in a typical 2 stroke motor are carbon monoxide and unburned hydrocarbons. The main source being unburned fuel and oil. In order to minimize this effect, ISU tested five commercially available 2-cycle lubricants:

1. Amsoil Dominator
2. Amsoil Interceptor
3. Polaris VES Gold
4. Green Earth Technologies G-Oil
5. Klotz Super Techniplate

Each oil sample was connected to the oil system using a clean external container. The oil system was then bled between every trial to ensure all passageways contained the oil being tested. Emissions were collected while carrying out a stepped dyno run. The five step run started at 3000 RPM and ended at 5000 RPM with each step increment of 500 RPM lasting twenty seconds. Additionally, two seconds between each interval were given to allow engine RPM to balance, resulting in a test duration of 110 seconds. The fuel (E70) and tuning map were held constant for the entirety of the test, which was performed prior to catalyst installation and exhaust treatment.

Since Carbon Monoxide and hydrocarbons are naturally very high in 2 stroke, the team used CO % and hydrocarbons (ppm) as the metrics for this test. With increased environmental safety being the goal, lower levels of CO and fewer hydrocarbons are preferred. The team computed the definite integral, representing the area under the curve, in order to quantitatively compare the oil specimens tested. The smallest integral value corresponds to the cleanest burn. The emissions data graphs can be found in the appendix.

Oil Tested	Definite Integral (Cumulative % over 110 seconds)	Percent Increase Compared to Lowest
Interceptor	191.884	N/A
Polaris VES	202.515	5.25%
Dominator	203.008	5.48%
Klotz	229.758	19.74%
G-Oil	205.375	7.03%

Table 2: Definite integral calculated using the midpoint method for carbon monoxide emissions vs. time for the tested oil.

Oil Tested	Definite Integral (Cumulative % over 110 seconds)	Percent Increase Compared to Lowest
Interceptor	601,577	N/A
Polaris VES	662,111	10.06%
Dominator	780,694	29.77%
Klotz	629,608	4.66%
G-Oil	644,463	7.13%

Table 3: Definite integral calculated using the midpoint method for hydrocarbon emissions vs. time for the tested oil.

The Amsoil Interceptor proved to have the best emissions results for both carbon monoxide and hydrocarbons. Polaris VES, Amsoil Dominator, and Klotz Super Techniplate all were within 5.5% of Amsoil Interceptor in one of the two metrics, however, each of these three lubricants tallied over 10% more emissions than Interceptor in the other emission measurement. Green Earth Technologies G-Oil produced slightly over 7% higher emissions than the interceptor over the span of the test in both categories. From these results, it is clear that the Amsoil Interceptor produces the most favorable and environmentally friendly emissions. These results made for an easy decision when choosing lubricants to use for the competition.

Catalyst Utilization

A major project and goal for the 2017 competition was to greatly reduce emissions while sustaining a "fun to ride" two stroke snowmobile. Two stroke engines tend to have high levels of hydrocarbons and carbon monoxide in the exhaust gas. Carbon monoxide appears in the exhaust gas due to insufficient oxygen to convert all the carbon in the fuel into carbon dioxide. Hydrocarbon emissions result from the presence of unburned fuel in the exhaust gas [8]. Iowa State took a couple steps to help combat this issue. The team is running the engine at a lean air-fuel ratio. This will mostly help reduce hydrocarbon emissions by decreasing the amount of unburned fuel in the combustion chamber. The biggest change was installing two catalytic converters onto the exhaust system. The team worked with Aristo Global to choose two three-way catalysts to reduce harmful emissions. Three-way catalysts provide a solid surface for chemical reactions to take place. The catalysts are coated with Palladium and Rhodium, which react with the harmful emissions to create environmentally friendly gases. The chemical reactions that take place are detailed in the equations shown below [8]. Equations (1) and (2) are oxidation reactions and work best under lean conditions. These reactions remove carbon monoxide and hydrocarbons. Equations (3) and (4) are reduction reactions and remove the majority of nitrogen oxides.

$$2CO + O_2 \rightarrow 2CO_2 \qquad (1)$$

$$C_xH_{2x+2} + \left[\frac{3x+1}{2}\right] O_2 \rightarrow xCO_2 + (x+1)H_2O \qquad (2)$$

$$NO + CO \rightarrow \frac{1}{2}N_2 + CO_2 \qquad (3)$$

$$NO + H_2 \rightarrow \frac{1}{2}N_2 + H_2O \qquad (4)$$

In order to minimize the back pressure that the catalysts put on the engine, the team elected for a high-flow type catalyst where the cell density is 200 cells per square inch. The team decided to incorporate two catalysts on the new muffler in order to retain a high level of emissions treatment. Last year, Iowa State used one catalyst with a density of 400 cells per square inch, which was too restrictive. This year, one catalyst was installed at the top of the muffler and the second one at the end where the gases will meet the atmosphere. Each catalyst has an outer diameter of 2.9 inches and a length of 3.94 inches. Emissions data was not yet available prior to design paper submission to show the result this catalyst had on emissions. With this installment, Iowa State University is confident that the 599cc Polaris Rush will perform with greatly improved emissions.

Figure 6: Picture showing the density of the catalyst.

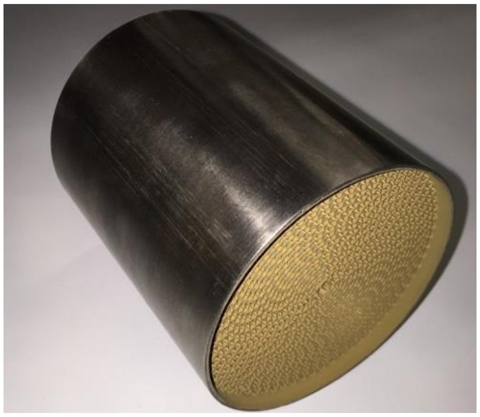

Figure 7: Picture showing size and shape of the catalyst.

Muffler Design

In addition to implementing a catalyst into the exhaust system for the 2017 competition, Iowa State designed and manufactured a muffler to work in conjunction with the catalysts to reduce sound pressure levels created from exhaust gases. A reactive style muffler was chosen due to its ability to greatly reduce sound. Last year, Iowa State utilized an absorptive muffler and sound was a major issue. An absorptive muffler uses perforated tubes and sound deadening material to cancel sound waves. A reactive muffler uses engineered chambers with plates or tubing to isolate and diminish harsh engine tones [4]. The following images show Iowa State's design and engineered chambers

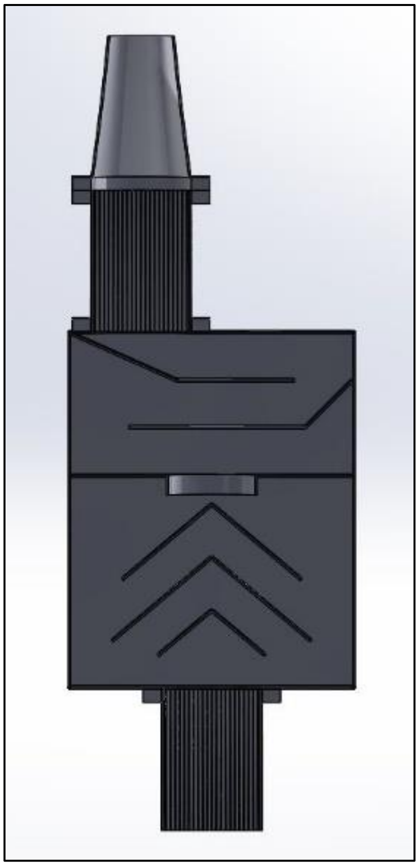

Figure 8: Split view showing muffler chambers.

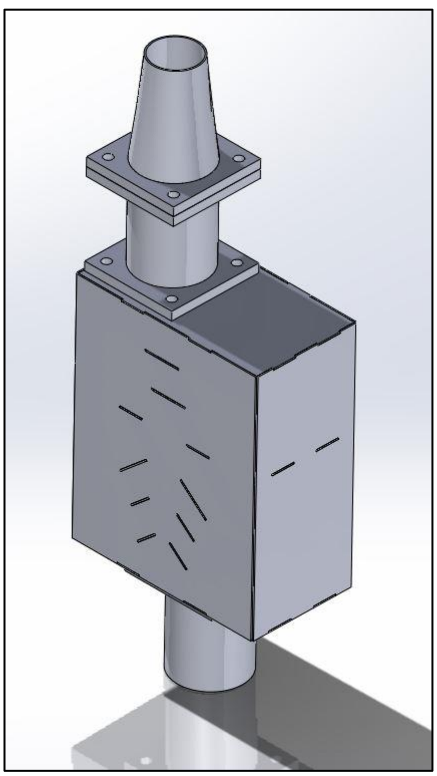

Figure 9: Three dimensional model showing muffler and catalyst design.

Due to space constrictions, Iowa State was only able to incorporate two chambers into the design. The top chamber includes two plates that guide the exhaust gases side to side and down the muffler. This allows the gases to bounce off the wall and creates destructive interference between the sound waves, drastically reducing the sound pressure levels. The second chamber includes three delta plates. The function of these plates are to split the incoming sound waves and when they come back together at the bottom, the like frequencies will cancel each other out. The muffler was fabricated with 302 stainless steel and TIG welded together. The plates were water-jetted and included tabs to make welding easy and ensure a perfect fit.

Before manufacturing the muffler, a flow simulation (Figure 10) was conducted to ensure non-restrictive flow and validate exhaust gas velocity. With the additional back pressure already being introduced to the exhaust from the catalysts, it was very important to have smooth and consistent flow through the muffler.

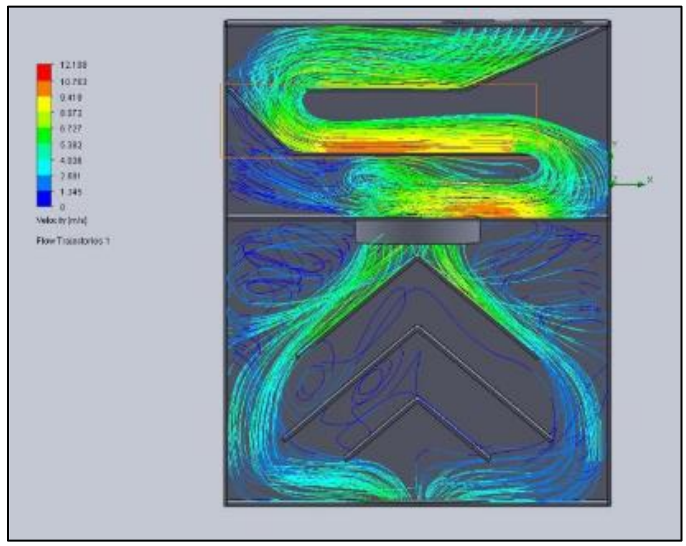

Figure 10: Flow simulation showing trajectories throughout the muffler.

Designing a custom muffler allowed Iowa State University to not only significantly reduce emissions by incorporating a catalyst in the exhaust, but also effectively attenuate exhaust noise by more efficiently reducing sound pressure waves from exhaust gases.

Engine Modifications

The 2017 Iowa State University Clean Snowmobile Challenge team chose to use the Liberty 599cc two-stroke engine. This decision was based on the power-to-weight ratio, efficiency, and reliability that the 599cc Liberty motor offered over other options. Another large advantage of utilizing a Polaris Liberty 2-stroke is the addition of Cleanfire® Technology, using semi-direct injection, which increases efficiency while lowering emissions. The factory specifications are shown in Figure 11.

Engine:	
Engine Brand Name	Liberty™
Engine Type	Horizontal In-line
Cylinders	2
Engine Stroke	2-Stroke
Cooling	Liquid
Valve Configuration	Reed Valve
Bore (mm/in.)	77.3 / 3.04
Stroke (mm/in.)	64 / 2.52
Displacement (cc/ci	599 / 36.6

Figure 11: Engine specifications

Engine Management System

To make adjustments for the blended fuel mixture, ISU installed a Power Commander V (PCV) Fuel Injection Module. This system is a popular addition to snowmobiles and is built specifically for use in power sports applications. Using this system with a 600 Rush engine control unit (ECU) allowed for adjustments of fuel amounts of up to 100% leaner and 250% richer, only constrained by injector volumetric flow limits. This unit is also able to adjust ignition timing allowing for advancement and retardation of spark by 20 degrees. In addition to the Power Commander V, ISU installed a Dynojet POD- 300 Digital Display that will make viewing critical engine parameters possible. The 5V signal input on the PCV was employed by ISU for the addition of a fuel sensor to monitor ethanol content of the fuel. This sensor was used alongside a wideband O2 sensor to analyze the air-fuel ratio in the exhaust stream which is also viewable on the POD-300 display. Utilizing this Power Commander V with additional sensors has allowed Iowa State University to modify the fuel and ignition while producing a truly flex fuel capable vehicle.

Adjustment to Ethanol

For the 2017 Challenge, the Iowa State University team was given the task to run an ethanol-gasoline blend ranging from 0-85%. There are many pros and cons with the use of ethanol. The biggest positive is that ethanol is extremely resistant to knocking, better known as detonation, where there is ignition of the fuel in the cylinder at undesired times [5]. This resistance to detonation allows the tune to be more aggressive, making more power while maintaining engine reliability. Ethanol also is very environmentally friendly and produces significantly less greenhouse gases, saving our irreplaceable atmosphere for another generation [6]. One of the negatives includes the decreased fuel economy due to a lower energy content compared to gasoline. Ethanol requires 30% more fuel to be equal to the same power as gas. This is because E85's specific energy is 33.1 MJ/kg and gasoline's (average 10% ethanol 90% gasoline) specific energy is 43.52 MJ/kg. The decrease in fuel economy along with ethanol's smaller availability are the biggest disadvantages facing a successful ethanol industry. With the positives being far greater than the negatives, ethanol is a suitable replacement to other gasoline additives and can contribute to lower emissions for future fuels.

Flex Fuel Sensor

In most commercially available flex fuel automobiles, a dielectric sensor is employed to monitor alcohol levels in the fuel in order to adjust fueling and ignition accordingly. The ISU Clean Snowmobile Challenge Team implemented a commercially available flex fuel sensor, a Continental 13577429, into the fuel return line to monitor ethanol levels. This sensor provides a frequency based signal which most engine control units are capable of reading, however, the Power Commander V installed does not have this capability. In order to overcome this issue, a Zeitronix Ethanol Content Analyzer (ECA) was used in conjunction with the sensor. This ECA provides a single 0-5V linear signal to the Power Commander, shown in figure 12 [7]. From these readings, the Power Commander V is able to interpolate fuel and ignition adjustments accounting for changes in ethanol amounts. Using this easily accessible part along with proper engine adjustments, Iowa State University was able to produce a snowmobile that is able to run ethanol blends from 0% to 85% without any further user input.

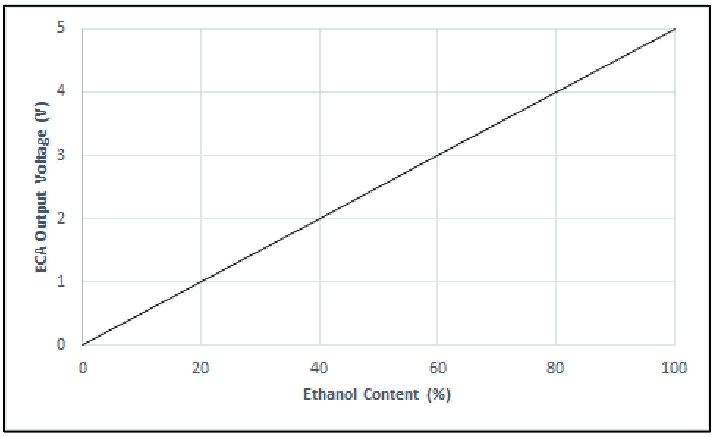

Figure 12: Graph of relationship between ethanol content percentage and ethanol analyzer output.

Clutch

For the 2017 competition, ISU decided to use an aftermarket set of clutch weights along with a different primary spring to shift the power band to a lower, more useable RPM. The spring combination that was chosen was the Polaris red/white spring along with heavier weights over the Polaris OEM black/green spring. Shown in figure 13, the red/white spring requires a lighter force to engage and produces a smoother, more horizontal power band.

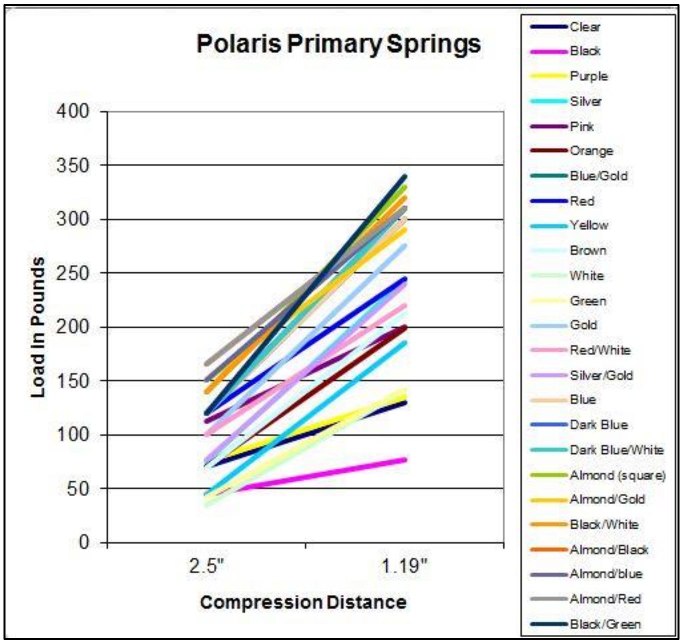

Figure 13: Graph showing Load (pounds) vs. Compression Distance (Inches) for Polaris primary clutch springs

With this change and heavier weights, the rider is able to receive a quicker throttle response with more predictability along the power band, as well as more power in the low RPM's for quick acceleration along trails.

Tuning Strategy

The Iowa State University CSC team decided to run a lean burn strategy for the 2017 competition in order to decrease emissions while increasing the power. All tuning was based on lambda values in order to quantify the air to fuel ratio. A stoichiometric level for lambda is 1.0, indicating the chemically balanced ratio of fuel and air. In order to run an effective lean burn, Iowa State University targeted lambda values around 1.1 throughout the tune. These measurements were taken using a Bosch wideband O2 sensor installed before the catalytic converter. After the use of the stoichiometric lambda level for tuning a safe map, the team slowly pushed the motor a little bit leaner until they hit a max efficiency with a combination between lambda and emissions.

To begin tuning the 599cc Liberty motor, the team started by increasing the overall fuel percentage by 20% across the fuel map (a table of fuel adjustments based on engine RPM and throttle position). The 20% increase gave the snowmobile a good baseline but further adjustment was needed. These next adjustments were made by indexing the throttle position while mounted to the dynamometer system explained above. The throttle positions indexed from 10% to 100% throttle by steps of 10%. The tests were run in a stepped RPM from 2000 to 8000 by increments of 500 RPM. The target lambda value through these tests was 1.1. This lean air-fuel mixture is attainable while on ethanol because of the extreme knock resistance of the fuel. An example fuel map is shown in figure 12, as the tuning had not officially been completed prior to design paper submission. The numbers shown indicate a percentage increase over stock fuel delivered to engine. After completion of the fuel map, ignition was adjusted to retard timing in the low RPM range while advancing ignition on the top end. This allowed the sled to produce plenty of power while ensuring the most complete burn of the fuel.

		Throttle Position (% open)									
		0	2	5	10	15	20	40	60	80	100
Engine Speed (RPM)	0	0	0	4	8	8	8	8	8	8	8
	500	5	5	4	8	8	8	8	8	8	8
	1500	6	6	6	8	8	8	8	8	8	8
	2000	7	7	8	8	8	8	8	8	8	8
	2500	8	8	12	14	14	15	16	18	22	20
	3000	10	12	12	20	24	27	26	26	25	21
	3500	16	18	18	22	23	25	26	25	23	20
	4000	18	18	18	22	23	25	26	25	24	21
	4500	18	18	18	22	23	27	26	25	24	21
	5000	18	18	18	22	23	25	26	25	24	20
	5500	18	18	18	22	23	25	26	25	24	18
	6000	18	18	18	22	23	25	28	27	24	16
	6500	18	18	18	22	23	25	26	25	24	16
	7000	18	18	18	22	28	25	25	23	21	19
	7500	18	17	18	18	28	25	23	23	21	19
	8000	19	16	17	18	28	25	23	22	21	19
	8500	19	15	16	17	28	25	23	22	21	19

Figure 14: Example fuel map showing percentage increases over stock.

Conclusion

Through extensive research, development, and innovation, the 2017 Iowa State University CSC team has produced a clean, quiet, and fuel efficient snowmobile without reducing the "fun-to-ride" aspect of snowmobiling. The snowmobile that the ISU team has provided fits the description of the ideal sled that trail-riders want, as well as increasing the effort to create a cleaner environment. With the modifications that were done over the year, this snowmobile accommodates many positive qualities including:

- A quieter ride with the use of a reactive muffler and sound deadening material
- Emission controlled exhaust that utilizes a dual catalyst system
- Lightweight (dry weight: 435 pounds) and rider balanced control and positioning
- Cost effective (MSRP value of $12,768.28)

The intent of the competition is to develop a snowmobile that is acceptable for use in environmentally sensitive areas such as our National Parks or other pristine areas. This modified 2015

Polaris Rush has been redesigned to be part of a solution that will keep snowmobiling around for many generations.

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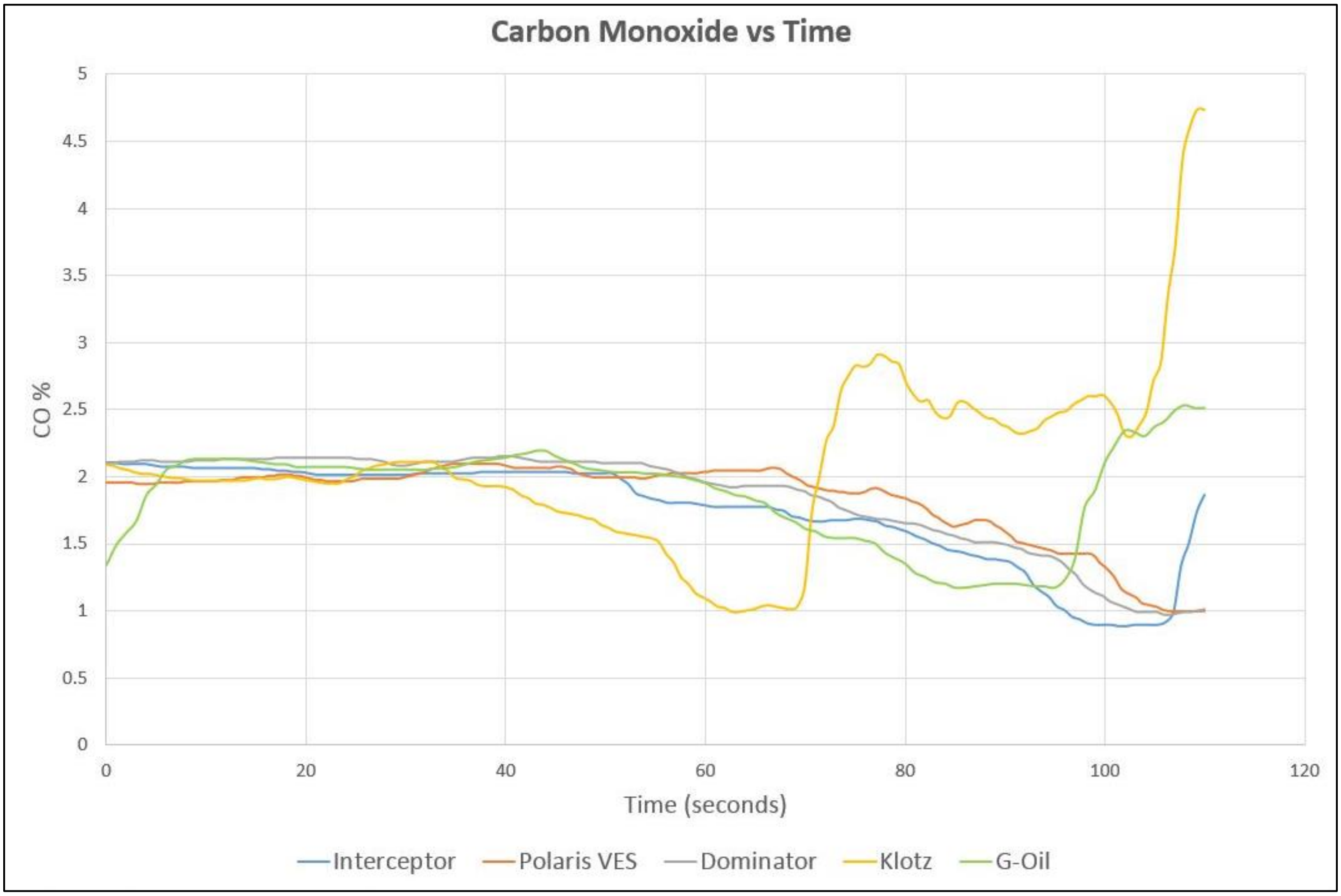
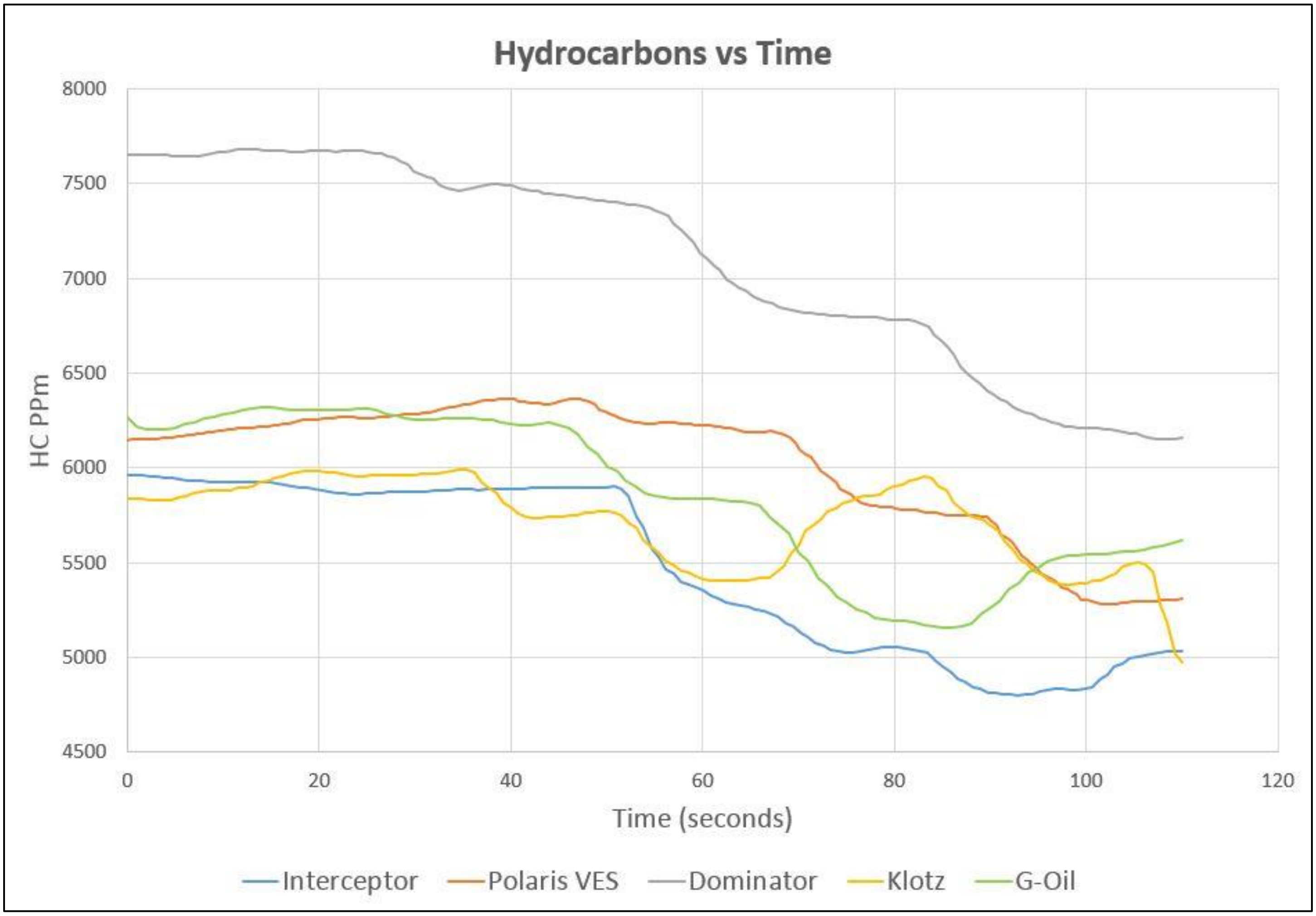
Definitions/Abbreviations

CO	Carbon Monoxide
CSC	Clean Snowmobile Challenge
dB	Decibel
ECU	Engine Control Unit
ECA	Ethanol Content Analyzer
Hz	Hertz
ISU	Iowa State University
ppm	Parts Per Million
PCV	Power Commander V
RPM	Revolutions Per Minute
SDI	Semi-direct Injection
SAE	Society of Automotive Engineers
TIG	Tungsten Inert Gas

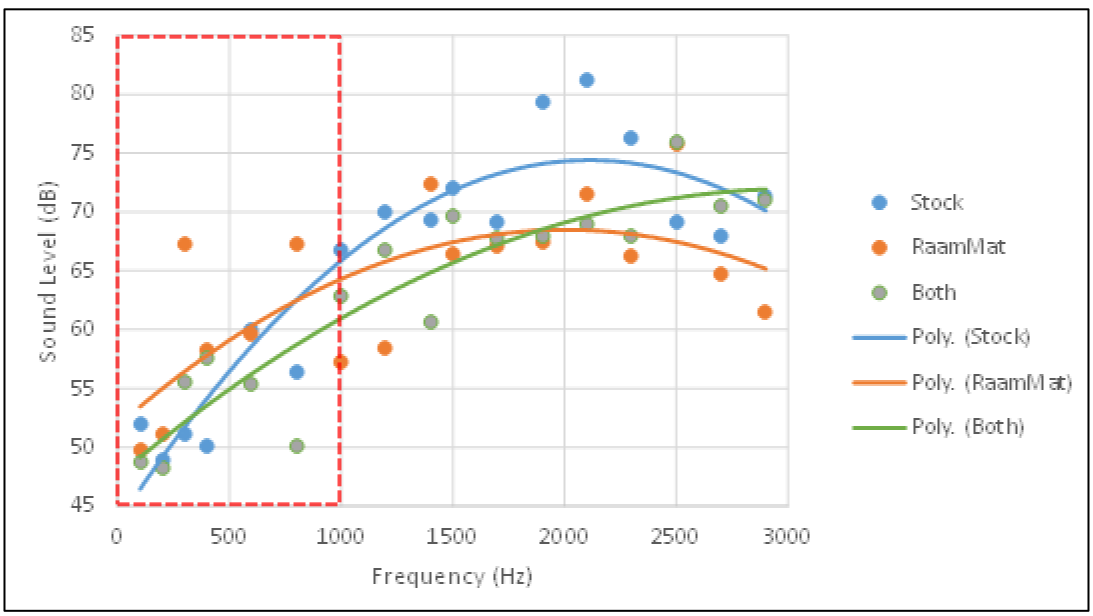
Appendix



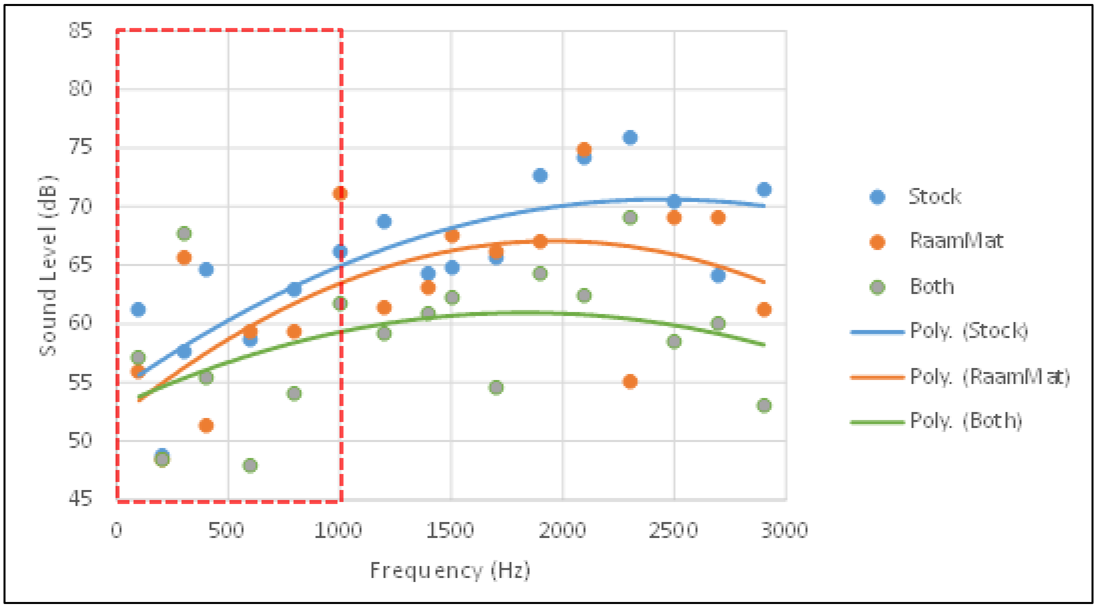
Appendix 1: Results from emissions testing, plotting carbon monoxide vs. time.



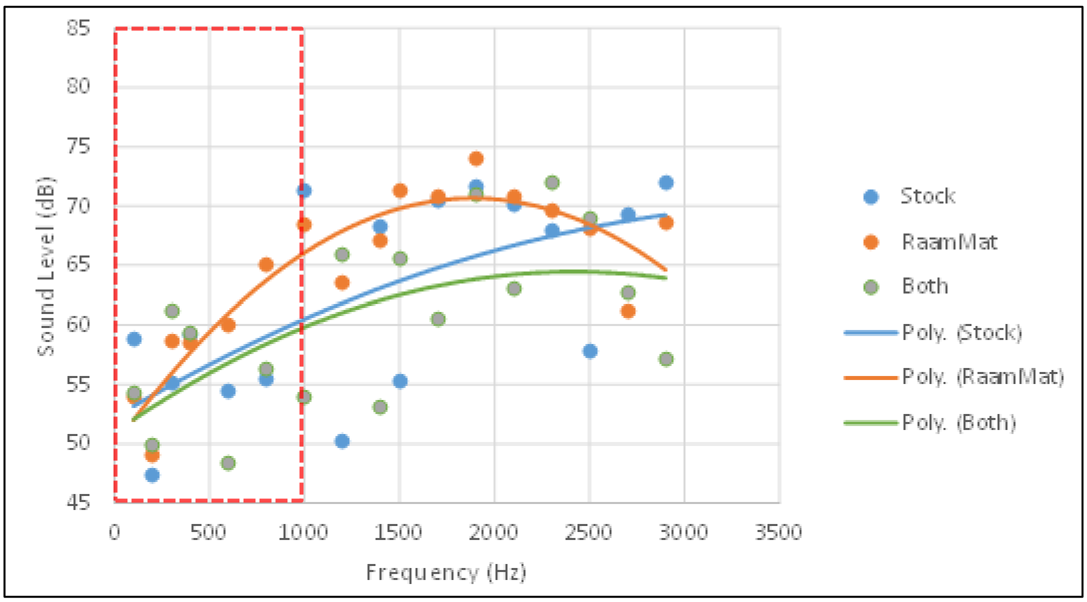
Appendix 2: Results from emissions testing, plotting hydrocarbons vs. time.



Appendix 3: Sound level data measured from front of snowmobile, with 0-1000 Hz range noted.



Appendix 4: Sound level data measured from left side of snowmobile, with 0-1000 Hz range noted.



Appendix 5: Sound level data measured from right side of snowmobile, with 0-1000Hz range noted.