2019 Ferris State University Clean Snowmobile Challenge Design Summary for a Two-Stroke Snowmobile Featuring EFI Tuning and Custom Exhaust

Buhrer, J., Fisher, A., Evans, C., Wiltshire A.
Ferris State University

Innovations Overview

2019 marks the second year of the Ferris State University SAE International Clean Snowmobile Challenge team. Thanks to the generosity of Polaris Industries®, the team is continuing with the donated 2017 Polaris 800 Switchback Assault 144 equipped with an 800 Cleanfire H.O.® two-stroke engine.

In order to reduce overall emissions, a catalytic converter was sized and installed in conjunction with a custom muffler/resonator. The muffler concept is driven heavily by packaging. The main restraint in packaging a catalyst in a sled with a two-stroke engine is the expansion chamber, which connects directly to the muffler, leaving no space for a catalyst. The solution is to place the catalyst before the muffler so the exhaust gasses can split flow into the two expansion chambers. The gases would then travel through fiber glass material and pipe baffles to help reduce the sound. The baffles and pipes have been through rigorous design modifications and simulations to maximize insertion losses of the system at high peak frequencies produced by the engine.

Team Organization and Time Management

The team in its current iteration originated as a group of sophomore students who wanted to be involved with a student organization that differed from the design teams that Ferris State University had already offered. This year, Ferris State has teams competing in SAE events such as Formula SAE, Formula Baja, and Formula Hybrid, as well as the ASME Human Powered Vehicle event. The Clean Snowmobile Challenge (*CSC*) provided a way to use engineering technology in production of snowmobiles and was a great addition to the engineering teams at Ferris State university. Our team has had help from students of all different programs at Ferris State, majors of students that have helped this team are Mechanical Engineering, Manufacturing Engineering, Welding Engineering, Information Security Intelligence, Plastics and Polymer Engineering, and more.

The returning team of students from last year's team formed together to continue to compete at the Clean Snowmobile Challenge. The three captains are Cameron Evans, Austin Fisher, and Joel Buhrer.

Various design groups were formed including Engine Control, headed by Cameron Evans (Captain), and Emissions/Muffler/Noise, headed by Austin Fisher (Captain).

Fabrication was done by Ferris Welding Engineering students who volunteered their time and welding expertise to assemble the muffler design that was created this year. We would like to thank Faurecia for sponsoring our team with baffled pipes and insulation this year. This helped in the manufacturing process and was only needed to be welded in the end. Once the muffler was finished, the catalyst was fitted to the top side of the muffler and heat shielding was installed to protect temperature-sensitive components.

Preliminary emissions and noise tests were performed in November 2017 using equipment from several departments within the College of Engineering Technology. The Mechanical Engineering Technology department was able to purchase a DYNOmite water-brake dynamometer. The dynamometer was completely functional, but we were unable to get our snowmobile started against the added resistance. The team will need a different way to start the snowmobile than a crank start to being able to dyno in the future years. To ensure that there were improvements made to the sled, the team continued to perform several tests which will be discussed in detail in the appropriate sections.

After emissions, efficiency and noise accommodations were made, performance was finally able to be considered. Our team selected flyweights that could maximize chassis performance and reduce our overall max horsepower rating needed for competition regulations.

Vehicle Description

The modifications were kept to a minimum to be sure we can complete the whole course of testing this year. Correcting problems from our previous year and qualifying for the challenge were held paramount. Due to this, the sled is mostly in its stock condition with additional modifications done to the engine, exhaust, and clutch. Below is a list of specifications for the competition sled.

Chassis:

- 2017 Polaris AXYS

Engine:

- Polaris 800cc Cleanfire H.O.
- Two-stroke gasoline engine
- Estimated stock horsepower of 160
- Unable to measure horsepower due to too much resistance to start snowmobile
- Horsepower will be limited using a Rev-Limiter tool in the DynoJet PowerCommander V if necessary
- Zeitronix Ethanol Sensor
- DynoJet PowerCommander V
- DynoJet AutoTune AFR Sensor

Track:

- Polaris, 15 x 144 x 1.35 Cobra
- Woody's Traction Control Studs

Muffler:

- A custom design incorporating an arrangement of perforated pipe baffles, packing material and tubing.

Catalytic Converter:

- MagnaFlow Three-Way catalytic converter

Skis:

- Stock skis
- Woody's Traction Control runners

Other:

- 62-gram Primary Clutch Flyweights

Chassis

The AXYS chassis is designed for endurance and mountain riding. It is one of the lightest chassis systems available on the market, and is factory stock on Polaris models between 2016-2019. The raised chassis is primarily aluminum, making it lightweight and durable, and the lift makes riding on hills easier. The AXYS chassis also gives the sled incredible balance and stability making it one of the best chassis on the market for mountain riding. No alterations were made to the chassis.

Engine

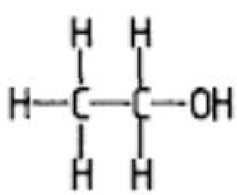
An 800 Cleanfire® H.O. two-stroke engine compatible with ethanol fuel mixtures has been utilized for the *2019 SAE International Clean Snowmobile Challenge*. This two-cylinder engine has 795cc of displacement, with 70mm of stroke. The manufacturer boasts a stock horsepower of 160 at 8250 RPM, which exceeds the maximum horsepower allowed at the *2019 SAE International Clean Snowmobile Challenge*, but conversion to ethanol fuel and modifications in fuel mapping are planned to bring power down to acceptable levels.

Impact of Ethanol Fuel

Ethanol fuel introduces a unique challenge that most production snowmobiles do not currently face; it is not chemically compatible with many rubbers and sealants used in fuel systems for primarily gasoline engines and, more importantly, requires significantly different mixtures of air and fuel to properly combust.

The air/fuel ratio required to completely combust fuel in the combustion chamber is called the stoichiometric (*stoich*), which is 14.7 parts air for every one part fuel in pure gasoline applications. As ethanol content increases, the stoich decreases linearly, resulting in a value of 9.87 for E85, meaning that it takes less oxygen to completely combust the same amount of fuel. This is a direct result of the fact that ethanol is an *oxygenated fuel*, meaning that the chemical makeup of ethanol contains oxygen atoms shown below.

Ethanol (Ethyl Alcohol) (C_2H_5OH)



Ethanol is 34.73% oxygen by weight, equating to a stoichiometric ratio of 9.00. A linear relationship from 9.0 to 14.7 can be interpolated to accommodate for any concentration of ethanol. A Zeitronix ethanol sensor is utilized in the return fuel line allowing the engine control unit to adjust air/fuel ratios accordingly.

Two Stroke Tuning Based on AFR

The main method of tuning engines used today is by editing the AFR (Air/Fuel Ratio). As previously stated, stoichiometric tuning involves an AFR of 14.7:1 for gasoline, meaning for every 14.7 units of oxygen there is 1 unit of Gasoline (Strub 2017). While this may be the perfect tune for burning off all of the gasoline, this AFR may not necessarily be what is best for the engine, or what is best for emissions. Running the engine *"Lean"* refers an AFR below stoichiometric, while running *"Rich"* refers to running an AFR above the stoichiometric. Changing the lean and rich mixtures at different throttle positions should create predictable levels of Hydrocarbons (HC), Carbon Monoxide (CO), and Oxides of Nitrogen (NOx).

The largest disadvantage to tuning for emissions in a two-stroke engine is the mix of exhaust gases with the Air/Fuel Ratio, leading to unburnt fuel being unaccounted for and wasted. This unburnt fuel increases the amount of pollution caused by two-stroke engines. Another difficulty that our team has to account for is the installment of a catalytic converter system. The catalysts can become clogged when flooded with unburnt fuel. The combination of the unburnt fuel and extremely high temperatures could lead to failure if the AFR is not properly tuned.

While it may seem simple enough to just constantly run lean to reduce unburnt fuel, running lean is not always the best option. Running lean increases the possibility of engine detonation, which is an unwanted spontaneous combustion, caused by high pressure or temperature in the combustion chamber. While running lean is optimal for creating less HC and CO emissions, running too lean will increase the temperature and pressure in the chamber so the team plans on only running 1%-2% leaner than stoichiometric in most of the stages of the tune. In regards to running rich, we plan on running 2%-4% richer than stoichiometric at idle and at full throttle to limit power and run cooler. We are willing to sacrifice some of the higher emissions at these stages to help the engine cool and keep us below the power restrictions set by the competition. The power restriction is something that has tied our hands considering we are using the 800 Cleanfire® H.O. two-stroke engine, which is widely considered as too powerful for an emissions based competition.

Fuel Mapping

The fuel map developed last year was used as a guideline for the map developed this year, and regions are categorized as follows:

Region 1: Rich Idle Position

- Low RPM and low throttle position
- Rich mixture to apply adequate oil to cylinders upon startup

Region 2: Lean Idle Position

- Slightly higher RPM than region 1
- Lean mixture to decrease warmup time

Region 3: Draw Bar Pull Test

- High throttle position and low RPM

- Rich mixture to increase power during draw bar test and acceleration events

Region 4: Optimal Trail Conditions

- Mid-level RPM and Mid-level throttle positions.
- Most commonly used region
- Lean mixtures maximize fuel efficiency and emissions

Region 5: High RPM

- RPMs above 8000
- Rich mixture to keep the engine cool and prevent thermal events at high RPM

We still believe this fuel mapping is the correct roadmap to a successful run, but after some failures at last year's competition, it has been determined that our percentage from stoichiometric were much too drastic and need to be tempered down. With some testing that is still to be done, we are hoping that this plan will be much more successful year.

Noise

Preliminary Testing

The OEM exhaust anatomy consists of an expansion chamber and resonator. The internals of the stock resonator are shown in figure 4, with a student-made custom muffler in figure 5.

Figure 1 Stock Muffler

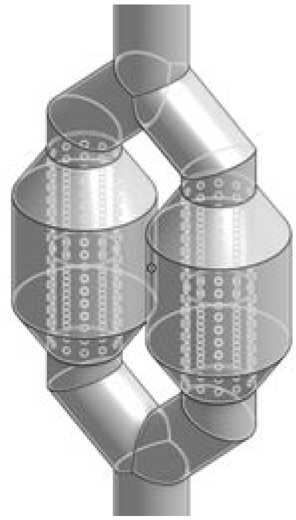


Figure 2 Student Designed Muffler

Initial sound levels were recorded with an octave band analyzer. dBA measurements were taken on each side of the snowmobile at five feet and then at 50 feet. Measurements were also taken at idle and then at a speed of 35 miles per hour to simulate testing conditions. Noise levels ranged from 70 dBA to 80 dBA. These are higher than the levels accepted at the Clean Snowmobile Challenge. Decibel levels were higher on both the left and right sides of the snowmobile leading us to believe most of the noise came from the engine.
A straight pipe test was conducted by removing the stock muffler and placing a two-inch diameter pipe at the end of the expansion chamber to get a baseline sound level of the engine. Results showed 80 dBA to 90 dBA levels at 250 Hz and above. Which our team will continue to use this test to design our muffler.

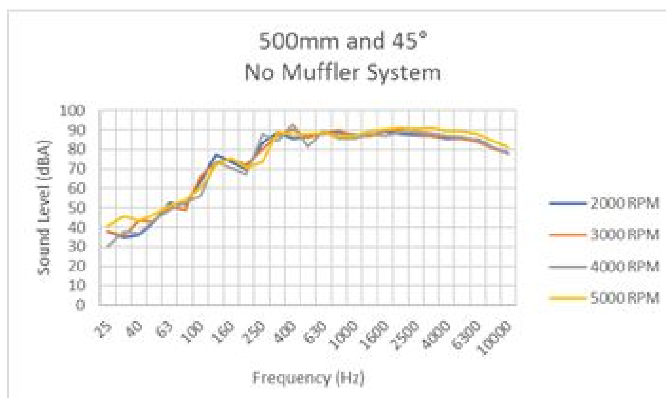


Figure 3 Straight Pipe Octave Band Analysis
Muffler Design

A new muffler was designed to make room for the addition of a catalytic converter. The two outside expansion chambers were designed to be able to give two separate chambers at the cost of space. While in our previous year we did not use packing material in our muffler design. With donated packing materials from Faurecia we were able to implement them inside this year's design. A plug was also placed inside the baffle pipe to be able to force sound in and out of the baffled pipe. The custom muffler contained different types of geometry to help attenuate engine noise including: Two large expansion chambers, two pipes with baffles, a center plug between both, and fiberglass packing.

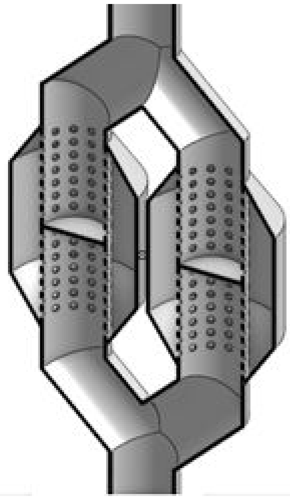


Figure 4 Student Designed Muffler 3D Model

The baffled features specifically the baffle sizes were simulated by Faurecia last year to predict the amount of insertion loss, or the amount of noise reduction each would have. An example of an insertion loss graph produced by these simulations is shown below. This graph suggests that perforations that were smaller, more restrictive perforates in the top baffle also showed higher insertion loss levels than bigger perforates. These features were selected again this year because simulations indicated higher insertion loss values at high frequencies, which tend to be an unpleasant sound. With these baffle sizes implemented with the packing material, we would hope to remove high frequencies and keeping lower frequencies down also. While also keeping a cylindrical body style for the muffler design.

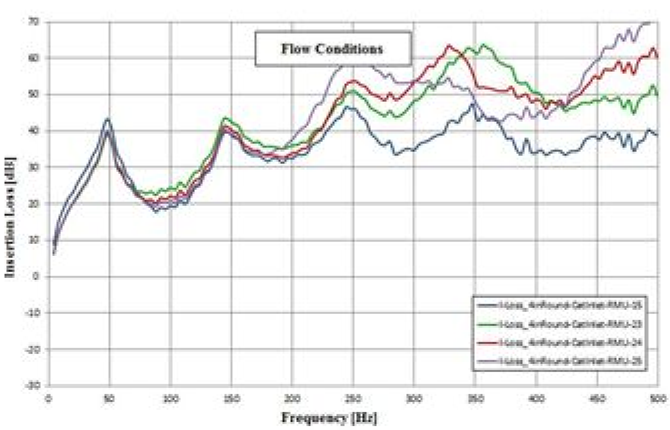


Figure 5 Insertion Loss of Variable Pipe Perforations Noise Results

A follow-up octave band analysis would soon have to be tested to show the dBA levels for the initial high frequencies target as RPMs increased to around 5000 RPM. These expected results should show the dampening of broad band higher frequencies. These lower levels are easier on human hearing and make the snowmobile more tuned for trails. The design, however, will hope to be able to tackle high frequencies, while also keeping the design small and compact for fabrication size constraints.

Preliminary Testing

Last year the stock system was tested to give benchmark numbers for exhaust flow rate, emissions content, and flow restriction. Instruments such as a Pacer Instruments Volume Flow Anemometer model DA10, a HORIBA Automotive Emissions Analyzer MEXA-584L were used to get exhaust gas samples on the factory sled. The results are shown in Figures 6 & 7.

Exhaust Summary		
Stock System		
Average Velocity	1818.3	FPM
Volume Flow Rate	44.76	ft^3/min
Density	0.078	lb/ft^3
Mass Flow Rate	3.474	lb/min

Figure 6 Stock Exhaust Flow Characteristics

Exhaust Gas Content						
	Speed (mph)					
	Idle	10	15	20	25	30
RPM	1750	3300	3750	4100	4300	4450
%CO	1.49	2.73	3.23	2.5	2.71	3.95
%CO2	2.52	3.68	4.16	5.26	6.68	5.82
%O2	15.73	12.63	11.55	10.91	8.5	8.44
%HC	0.561	0.66	0.662	0.486	0.491	0.534
%NO	0.0048	0.0065	0.0081	0.0032	0.003	0.0067
%Air	79.694	80.294	80.390	80.841	81.616	81.249
Percent Emissions	20.306	19.707	19.610	19.159	18.384	18.751

Figure 7 Stock Exhaust Gas Content

We were not able to test our numbers further with a new fuel map or our new muffler and catalyst system. We are hoping to see improvements on these results with a catalytic converter and new fuel map.

Catalyst Selection

To reduce the overall emissions of the snowmobile, a three-way catalytic converter was added parallel to the custom muffler design. The data gathered from the previous year's competition determined that it was a good option and will be utilized again.

Figure 8 Previous Student-Built Design
with Chosen Catalytic Converter

The three-way catalyst chosen by the 2018 Ferris Clean snowmobile team will continue to better reduce the overall emissions due to the basic oxidation and reduction reactions that take place, shown below. The data received from last year's team with the catalyst design is shown in figure 9 below.

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

$$C_xH_y + O_2 \; CO_2 + H_2O$$

$$2NON_2 + O_2$$

Keeping the surrounding components cool while letting the catalytic converter operate efficiently was a key problem we ran into during last year’s competition. As the catalytic converter was hot enough to have a thermal event during last year competition. We eventually burned our pull cord and it was too close to its surroundings of cooling and gas lines. Heat shielding considerations have been made around the panel, around the muffler and catalytic itself to give appropriate protection of surrounding components. While the movement of some lines have been placed to the opposite side of the snowmobile to ensure that things will not be melted during competition. This was also a rule for competition that we never changed last year. We have accounted for the heat of the catalytic converter by not keeping the catalytic converter enclosed by the muffler itself. The catalytic will have room to channel air inside to the surface thru the snowmobile panel, in hopes to keep it and the surrounding cool while running.

Stock Emissions with Flex Fuel					
RPM	%CO	%CO2	HC (ppm)	NO (ppm)	%O2
1750	1.94	2.14	5580	99	15.69
3000	3.19	4.32	7440	154	11.65
4000	3.17	4.84	6630	193	10.53
5000	3.29	8.96	3950	208	5.61
6000	2.69	9.86	2980	203	4.54
7000	4.67	8.84	2470	177	4.28

Emissions Test with Flex Fuel and Catalytic Converter					
RPM	%CO	%CO2	HC (ppm)	NO (ppm)	%O2
1750	5.47	7.34	573	10	6.01
3000	5.82	8.26	506	21	4.08
4000	5.51	9.34	423	21	2.83
5000	3.43	10.56	314	27	3.82
6000	3.14	12.22	266	32	1.7

Figure 9 Effects of Catalytic Converter on Emissions

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Contact Information

Ferris State Clean Snow
Swan First Floor
49307 Big Rapids, Michigan
ferriscleansnow@gmail.com