Iowa State Clean Snowmobile Challenge

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Abstract

Iowa State University's entry into the 2018 SAE Clean Snowmobile Challenge is a 2014 Polaris 800 Indy SP. The objectives of the competition are to improve fuel economy and reduce noise and emissions levels of a production snowmobile. The entry snowmobile was used as a base chassis and incorporated a MPE 750 Four-Stroke Turbocharged Weber Engine. This engine replaced the two-stroke, stock engine from the 2014 Polaris Indy in order to utilize the four-stroke's reliability and general design for pollution reduction. The engine swap required the design and fabrication of custom mounts for the engine as well as the oil cooler, intercooler and radiator. An analysis of the engine mounts was conducted to verify the support of engine load conditions. Original piping was mounted to accommodate the change in arrangement of the engine and assisting components. A custom, two chamber reactive muffler and three-way oxidation catalyst were added to the exhaust system to decrease noise and emissions. The muffler utilized both a reactive and absorptive style to reduce noise output, and material selection and manufacturability were considered during design. To further decrease noise, 1/8-inch-thick Line-x was applied to the underside of the tunnel. A 3-D metal printed downpipe was designed and manufactured in order to conform to the added complexity of the engine configuration. Graphite hyfaxes were implemented onto the snowmobile after testing confirmed their ability to reduce friction on the track. The use of a four-stroke engine along with the custom exhaust system and noise-dampening lining combined to produce a clean and quiet snowmobile without sacrificing the fun of riding.

Innovations

The Clean Snowmobile Challenge aims to build upon the work from production snowmobiles by innovating ways to extend fuel economy, reduce harmful emissions, and decrease noise pollution. To achieve these means, the team replaced the stock two-stroke Liberty 800 engine from the 2014 Polaris Indy and installed a MPE 750 Four Stroke Turbocharged Weber Engine. The replacement engine was able to produce more complete combustion which reduced NOx. Custom aluminum engine mounts were fixed to the chassis because of the material's low weight, corrosion resistance, and the FEA analysis evidence of support under load conditions. The engine's increased size led to custom brackets for the oiler cooler and intercooler/radiator stack to support the systems and ensure adequate air flow was achieved. Modifications were made to the exhaust system with the creation of a custom muffler. Made with 304 Stainless Steel, a two chamber reactive muffler with a ceramic fiber double-walled shell was able to insulate the heat created by the engine. Due to the increased size of the engine the down pipe from the turbo manifold had to be redirected to not interfere with the chassis. Using a 3-D metal printer, a custom down pipe made with 420 stainless and 40% bronze impurity was installed. Iowa State has produced a snowmobile to challenge what it means to run clean and quiet.

Team Organization and Time Management

Leadership Structure

The ISU CSC cabinet is composed of eight team leadership positions. The Project Director manages ISU CSC's affairs with ISU's SAE International Organization, maintains the overall team timeline, oversees purchasing, and upholds the team's standard work and documentation, as well as coordinating all sponsor visits and travel. The Tech Director is responsible for the engineering on the physical sled. This position holds final say on the overall design of the sled, detailing what modifications will occur and what the strategic direction of the sled will be. The remaining six leadership positions fall under the Tech and Project Directors. The Engine Team Leader serves as the specialist on all the intricacies of the engine. If there are any issues with the functionality of the engine, the Engine Team Leader and their team will troubleshoot and find solutions to the problem. The Exhaust Team Leader is in charge of routing the exhaust and designing a muffler that will muffle the exhaust noise without adversely affecting the engine performance. The Testing Team Leader is in charge of testing hardware such as the Land and Sea Dynamometer, and ISU's emissions analyzer. The team lead also documents the testing results and compares the data to past year's results. The Chassis and Suspension Team Leader's primary responsibilities are to ensure that the snowmobile has proper suspension travel and to research suspension improvements that can be made on the front skis or rear skid assembly. The Safety Officer monitors the shop space and verifies the design of test hardware to certify that the equipment is safe to use and no hazards are present.

Timeline Management

At the beginning of the season, the Project and Tech Directors decided when major milestones were due throughout the season. Examples of major deadlines throughout the season were:

- November 25th - Engine mounts manufactured
- December 9th - Weber engine fully mounted in sled
- January 27th - Weber engine is operational in Indy chassis
- February 10th - Sled is competition ready

After upper leadership finalized the major milestones, team leads were responsible for further detailing the projects that were required to complete each milestone, based on overall timeline priority. TeamWeek was used as a visual, interactive calendar, acting as a season-long Gantt chart to track deadlines and the actual progress made towards deadlines. The TeamWeek system allowed the tool to be accessed online, making it very easy to update and check if there was any confusion. Goals and deadlines were established for every team along with overall team goals. The team was rather successful at meeting the major deadlines set by the ISU CSC cabinet. The use of TeamWeek helped the team to easily plan out and manage their time effectively in order to achieve their goals in an efficient and effective manner.

Entry Description

Chassis – 2014 Polaris 800 Indy SP

• Engine – Weber Motor, Gasoline, 4-stroke, 750cc, 120 Peak horsepower (stock), turbocharged

• Track – Camoplast 1.25-inch Ripsaw II, Woody's Gold Digger 60 Degree Traction Master Carbide Studs

• Muffler – Custom, 304 Stainless Steel, 2 Chamber Reactive Muffler, Ceramic Fiber Shell

• Catalytic Converter – Aristo Global Three-Way Catalytic Converter

• Skis – Stock 06' FST skis with Dual Runners

• ECU – Standalone AMP EFI Mega Squirt 3 Pro Ultimate

Baseline Testing FST/Indy

The base engine selected for 2018 ISU Clean Snowmobile is the Weber 750 MPE. This turbo charged high-output engine replaced the 2014 Polaris Indy original two-stroke Liberty 800 engine. At the stock configuration, the Weber 750 MPE outputs 120 peak horsepower (Appendix C) compared to the Liberty 800's 150 peak horsepower. Baseline testing was conducted to compare these two engines to justify engine choice.

Apart from the Weber 750 MPE producing power under competitions horsepower limit of 130 peak horsepower (SAE International), the Weber 750 MPE produces better emissions data than the Liberty 800. At stock the Weber 750 MPE was found to produce an E-score of 176 (Rochester Institute of Technology). During the 2015 Clean Snowmobile Challenge Competition, ISU used a 2014 Polaris Indy SP equipped with a Liberty 800 that produced an E-score of 76**.** A catalyst was not implemented in either assembly, which allowed ISU CSC to justify implementing the Weber 750 MPE engine into their final assembly. Baseline emission testing was conducted on the Weber 750 MPE prior to catalyst installation to compare to the team's 2015 snowmobile (refer to Appendix A).

Baseline noise testing was conducted on the Weber 750 MPE with an average reading of 77 dBA using the Clean Snowmobile Challenge Competition's noise testing setup (refer to Table 1). This testing was done using an aftermarket muffler that was equipped to the Weber engine at purchase. This aftermarket muffler was said to be louder muffler than the stock muffler equipped on the 2006 Polaris FST. Even with the aftermarket muffler equipped to the Weber engine, noise results for the Weber were better than the Liberty 800's noise results for the 2015 Clean Snowmobile Challenge Competition. In the 2015 Clean Snowmobile Challenge Competition ISU's Liberty 800 engine was equipped with its stock muffler that resulted with noise testing result of 90 dBA.

Table 1. Baseline sound pollution testing

2017-18 Testing		
dBA	Configuration	Notes
75	Baseline	No snowfall present, FST chassis
80.4	Baseline	
77.1	Baseline	
76.6	Baseline	
75.9	Baseline	
77	Baseline (Average)	

Engine Swap

ISU's snowmobile, a 2014 Polaris Indy chassis, utilizes a Weber 750cc 4-stroke engine in this year's design. A four-stroke engine was chosen over a two-stroke for its reliability and general design; using its own lubrication system opposed to gas/oil mix providing lubrication to the cylinder walls causes it to produce less pollution than a two-cycle engine of equivalent size. The Weber 750 engine was specifically chosen for its use of a turbo charger, fuel injection, CVT output shaft and the fact that the engine is owned by a common manufacturer as the chassis it was placed into, Polaris Industries.

The engine swap ISU performed created many challenges in this year's design process. The Weber motor had originally come from a 2006 Polaris FST Switchback chassis which had a much larger engine compartment than the 2014 Indy chassis. Limited space made it a challenge to specifically mount the engine, radiator, oil tank, intercooler, and intercooler piping.

Engine Mounts

Through the processes of swapping the Weber four-stroke engine into its new chassis ISU faced a large challenge to design new engine mounts to hold the engine into place. The stock Liberty 800 2-stroke engine originally mounted in the chassis weighted around 80lbs including the clutch and recoil, excluding exhaust and throttle bodies. With the Weber 750 engine weighting 132lbs it was obvious heavy-duty mounts would need to be incorporated. The first step in designing the engine mounts was to attain a rough shape and size of what the engine mounts could look like. The most difficult, and arguably most important, aspect of mounting the Weber engine was to assure proper clutch alignment. With the Liberty 800 originally being mounted at the bottom of the engine case and the Weber 750 engine originally being mounted from its sides a plate style engine mount was designed to utilize both the side mounts of the 750 Weber and the bottom chassis mounts in the Indy. After significant measurements were taken engine mount plates were modeled in SolidWorks and eventually cut by water-jet machine on ISU's campus. Proper clutch alignment was attained using digital measuring devices and serval straight edges.

Figure 1: Shows use of wood to attain rough shape and size measurements of PTO side engine support.

Through the engine mount designing process several FEA simulations were conducted in SolidWorks. The first simulations tested static loading on the mounts. The simulations were set up using the aluminum properties for the type of Aluminum that was planned for the manufacturing process which was ¼" Aluminum alloy 3003. The plates were modeled into an assembly with a round cylindrical part representing the engine. The cylindrical part was set as rigid in the simulation process apply focus on the engine plates. Figure 3 shows a static load simulation with 300 lbf and 100 ft*lb torque applied to the cylindrical part representing the engine. With these values being approximately two times that of the actual engine and results showing a max point load 1/5 of the material yield strength, confidence was attained static load conditions.

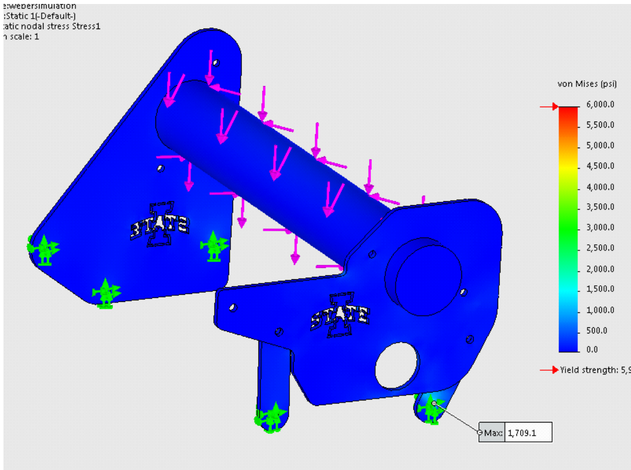

Figure 2: Static load (weight force and engine torque) test of realistic load on engine mounts.

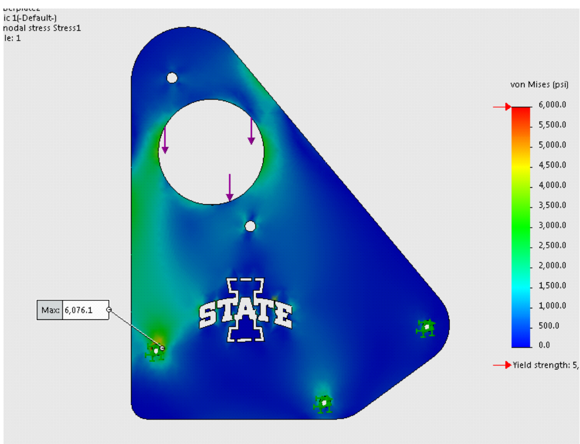

Figure 3: Showing static load test (1,400lbf) on exhaust side engine mount

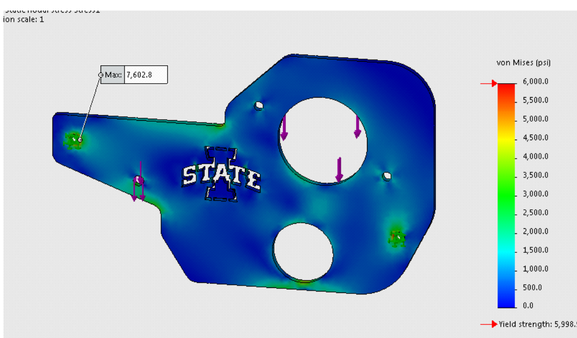

Figure 4: Showing static load test (1000lbf) on PTO side engine mount

Although the static load simulations showed good results a more important simulation needed to be tested to fully assure the mounts would be more than sufficient for the Weber 750 engine. This test was a frequency test to examine how well the mounts could handle vibrations produced by the 4-stroke engine. Through research it was found that firing frequency is the most disturbing mode present in an engine. For 4-stroke engines the firing frequency can be calculated by the following equation, F = (RPM * Number of cylinder)/ (2*60) *(Reference 3)*. Using the engines redline RPM our natural frequency was calculated to be 133.33 rad/s. This frequency is significantly lower than the values attained through the frequency simulation (shown in Table 2), meaning the mount plates are sufficient for the engine vibration.

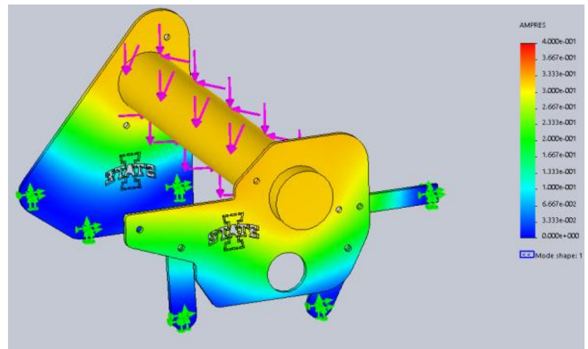

Figure 5: Showing frequency vibration test of engine mounts with load and torque applied

Table 2: Natural frequency of Engine Mounts

Study name:Frequency 1

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	493.66	78.569	0.012728
2	1875.9	298.56	0.0033494
3	4176.6	664.73	0.0015044
4	4469.2	711.29	0.0014059
5	6250.9	994.86	0.0010052

Intercooler/Radiator Mounting

Due to the size of the Polaris Indy's chassis, options for mounting the FST's factory radiator and intercooler were limited. In addition, the Indy's stock configuration did not use a radiator or an intercooler. The most viable option was to package both the radiator and intercooler together and lay them flat in the nose of the snowmobile, allowing cold air to enter through the bottom and heat to flow out of the top. To improve airflow, vents were strategically cut in the plastic lower section of the nose to direct air into the radiator/intercooler stack. The stock fan was left on top of the radiator/intercooler stack to pull the air through the system and further improve cooling. The radiator was mounted on the bottom under the intercooler due to the nose-cone geometry. This design allowed for the intercooler to be easily connected to the turbocharger and engine intake. In order to keep the radiator/intercooler stack from separating, a simple mount was designed to secure the pieces. A small metal bracket was also designed to mount the stack to the frame of the snowmobile.

Intercooler Piping

In addition to mounting the intercooler, several considerations had to be made when designing the piping connecting the intercooler to the engine intake and turbocharger. The space constraints of the Indy's chassis with the additional components of a turbocharged engine meant most of the lines were routed outside of the chassis, but still within the plastic body panels. Clearing the steering shaft posed a challenge as these components would move the most while the snowmobile is in operation. Flexible silicon couplings allowed the piping to be more forgiving in tighter spaces at the cost of additional potential for leaks. Aluminum was chosen for its light weight and readily available pre-bent sections of mandrel bent pipe. Using mandrel bent pipe decreases the fluid flow resistance in the piping by keeping the cross-sectional area of the pipe consistent throughout the bend. Silicon pipe couplers were used for added flexibility and an air tight seal.

Fuel System

The stock FST seat and gas tank assembly was retrofitted to ISU CSC's entry and a higher pressure external fuel pump was added, along with a pressure regulator. This was to ensure greater control over fuel system. The seat construction also proved to fit more effectively with the engine intake since the seat was originally designed to fit in tandem with the Weber engine, unlike the Indy gas tank and seat.

Exhaust

Muffler Design

1. The custom muffler includes the following features: 304 Stainless Steel housing and interior, two–chamber reactive design, dual-walled with a ceramic fiber filled shell (Figure 6). The 304 Stainless Steel increases durability and corrosion resistance for long-term use in a fluctuating temperature environment (*SSINA: Stainless Steel*). The two-chamber reactive design allows for better sound reduction versus absorptive styles, while maintaining adequate flow velocity to not diminish engine efficiency (*Potente, 2005*). In addition to the two-chamber reactive design, the muffler is dual walled and insulated with ceramic fiber to further dampen noise while providing heat protection at temperatures up to 2600 degrees Fahrenheit (Table 3).

Figure 6: Ceramic Fiber Blanket

Table 3: Ceramic Foam Insulation Properties

Ceramic Fiber Metrics	
Temperature Grade	2600 °F
Thermal Conductivity (BTU*in/cf/hr/F)	0.78 at 1000 °F
Thickness	0.5 inches

Muffler Design Process

The main parameters that were considered when choosing the final design included: muffler style, material selection, ease of exhaust flow, and manufacturability.

Two different muffler styles were considered; the two being reactive and absorptive. The two styles have unique tradeoffs. A reactive muffler is designed to reduce noise through destructive interference by utilizing expansion chambers that allow noise waves to partially cancel with each other. A down side to reactive mufflers is that they produce back pressure. Back pressures can have a negative effect on engine efficiency. On the other side, an absorptive muffler uses absorption to reduce noise by converting sound energy into heat energy. Absorptive mufflers create less back pressure but do not reduce noise as effectively as reactive style mufflers (*Potente*, *2005*). A reactive style muffler was chosen because they are better for noise cancelling applications.

Another parameter that was looked at was material selection. Aluminized steel and 304 stainless steel are two common options for mufflers and exhaust systems. Due to the extreme conditions snowmobiles face, in terms of heat fluctuation and corrosive environments, 304 stainless steel was selected. 304 stainless steel maintains durability and corrosion resistance in fluctuating temperature environments, thus making it an ideal choice for ISU CSC's design.

Ease of exhaust gas flow was another major concern. In order to maintain vehicle performance, it is important to maintain a steady exhaust flow while also providing some back pressure for the turbocharger. A reactive muffler allows for this slight generation of backpressure. Using ANSYS software, various muffler designs were analyzed to determine which would be best suited to maintain a desirable average flow. In general, good flow equates to the least possible disruption in exhaust flow (*Teja, 2016*). To achieve this parameter, it was important to develop a design that produces an average exhaust velocity similar to that of the entrance velocity (See Table 4).

Additionally, manufacturability was considered. Considering the timeline and availability of resources, the design that met the criteria mentioned (desired flow, reactive style) while maintaining ease of assembly was chosen for manufacturing. Choosing a design with less complexity helped to reduce cost and save time.

Figure 7: Muffler 1 flow analysis

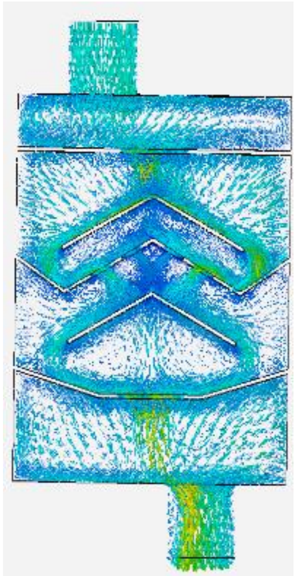

Figure 8: Muffler 2 flow analysis

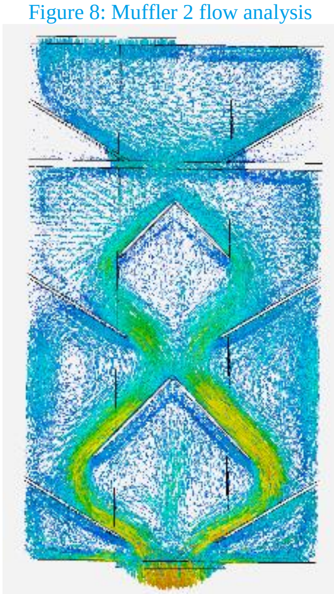

Figure 9: Muffler flow analysis (Final design)

Table 4: Reactive Muffler Flow Analysis with Data

Units in m/s	Muffler 1	Muffler 2	Muffler 3
Entrance Velocity	50	50	**50**
Maximum Velocity	103.63	121.71 m/s	**150.08**
Average Velocity	14.019	27.97 m/s	**41.253**

Figure 10: Final Muffler Design - Dual Wall Cutaway

Exhaust Routing

The 750cc Weber engine swap, into the 2014 Polaris Indy chassis posed a unique geometric constraint for designing the exhaust routing. The turbo outlet was rotated to allow room for the engine to sit properly in the chassis. Additionally, the exhaust system had a limited amount of room to accommodate the catalyst and the muffler before exiting the snowmobile. Custom components were designed and manufactured (downpipe, catalyst housing, and muffler) to ensure the system was efficient, clean, and safeguarded from potentially catastrophic thermal events.

3D Metal Printed Downpipe

A turbo downpipe was modeled and 3D metal printed in 420 stainless steel/bronze mixture. The downpipe had to be designed and fabricated in an unconventional way to accommodate for complex geometries while accommodating for a wideband sensor. The complex geometry of the part was unable to be manufactured using modern CNC technology. Ideally on a large scale the part would be mass produced as cast iron, similar to the stock downpipe. Due to a tight deadline, 3D metal printing was chosen as a quick and economical option. An additional flange was printed separately and TIG welded on with silicon bronze filler wire. This flange joins the downpipe with the rest of the exhaust system. Stainless steel bronze was chosen to accommodate for the high heat of the engine. Additionally, the material was certified by the manufacturer to withstand heat up to 900°C or 1652°F. See Appendix B for further details.

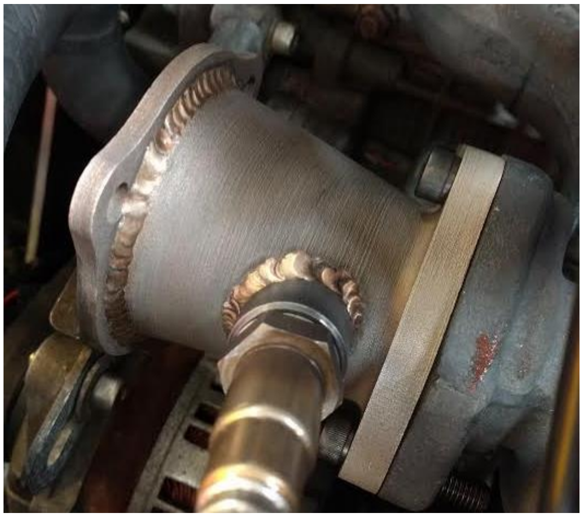

Figure 11: Downpipe Including Instrumentation

Catalyst

The exhaust system of the 2006 Polaris FST did not originally come with a catalyst. It has been shown through research that catalysts are a highly effective way to reduce emissions, burn off excess fuel and reduce the heat of the exhaust gasses. This is evident from government mandate (Clean Air Act) that states, "Under federal law, catalytic converters may not be removed and replaced with "converter replacement pipes' by any person..." (*US Government, 1990*). Catalytic converters are used to convert harmful exhaust gases into less harmful gases. A three-way catalyst focuses on reducing nitrogen oxides, carbon monoxide, and hydrocarbons. The three-way catalyst attempts to convert these harmful substances to nitrogen, carbon-di-oxide, and water. The three-way in the name refers to the three types of harmful substances converted. The team decided a three-way catalyst, developed by Aristo Intelligent Catalyst Technology. The catalyst selected has a cpsi of 200 and dimensions of 2.77" by 3.94". The catalyst is made up of a wash coat and precious metals. The actual content of the platinum group metals (pgm) is proprietary. The wash coat is made of rare earth oxides along with alumina. The catalyst is placed directly after the downpipe coming out of the turbo. It is placed in this position so the remaining fuel is burned off before entering the muffler. The catalyst being further up the exhaust stream gives the gases more adequate time to cool down.

Graphite Hyfaxes

Testing Process

For the hyfax testing the guide wheels were removed from the FST skid so that only the hyfaxes were in contact with test plate. The 48 pounds skid was then set on a ¼ inch aluminum sheet to simulate the hyfaxes interacting with the track clips. Next the skid with the stock polyethylene hyfaxes was pulled across the steel sheet using a Pelouze 7830 spring gauge at 1 mph. The force was measured after the skid had achieved 1 mph. After resetting the skid, this process was repeated 4 more times for a total of 5 trials. Next the stock polyethylene hyfaxes were removed and replaced with the new graphite hyfaxes. The skid with the graphite hyfaxes was pulled across the metal sheet at 1 mph using the spring gauge more 5 times.

Table 5. Hyfax Testing Data

Trial	Pulling Force (lbs) Old Polyethylene Hyfax	Pulling Force (lbs) New Graphite Hyfax
1	15	13
2	15	12
3	14	13
4	16	11
5	13	12

Findings

The results of the testing shown in Table 5 show that the skid with the graphite hyfax required an average of 3 pounds less or 20% decrease in force to pull across the steel sheet than the original polyethylene hyfax. The decrease in the friction coefficient the graphite hyfaxes provide will allow the track to rotate against the skid with less resistance.

Ventilation Strategy

Vents were implemented throughout the engine bay of the snowmobile in order to assist in the cooling of critical components on the snowmobile. The team was focused on delivering a supply of cool air onto the catalyst, along with the radiator and intercooler. Sections of the body panels were cut in strategic positions to introduce fresh air, without compromising the structural integrity of the chassis. On the front of the snowmobile, a vent was cut into the nose-cone and a slot was cut on the exhaust side panel. Both vents were covered by hydrophobic mesh and supported with an aluminum grill.

Analysis

The effectiveness of the front nose-cone vent system was evaluated using Ansys. For the analysis, it was assumed that the snowmobile would be moving at 45 mph, thus the air flow would be entering the vent at 20.1 m/s. In the Ansys model, the max air velocity seen in the engine bay would be 26.7 m/s. The physical nose-cone geometry was then modified to focus the entering air into the intercooler and radiator stack. As a result, the maximum velocity was increased to 60.3 m/s in the nose-cone.

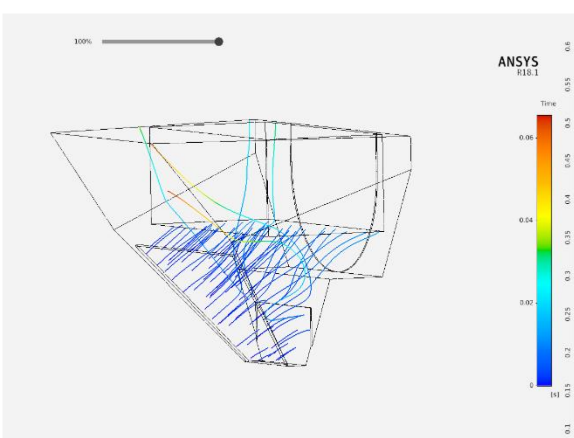

Figure 14: Nose-cone with vent and unedited geometry

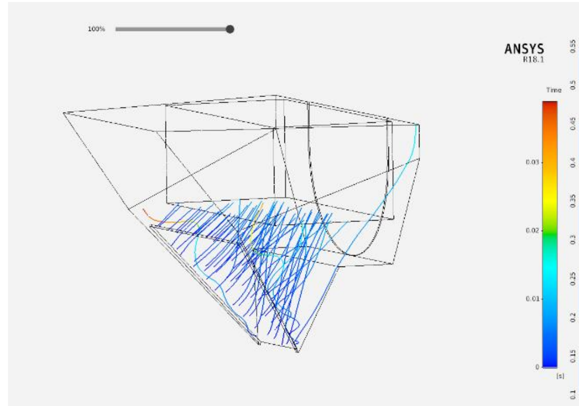

Figure 15: Nose-cone with vent and edited geometry

Sound Reduction

In order to reduce the sound pollution, 1/8-inch-thick Line-x was applied to the underside of the tunnel. Iowa State University chose to use Line-x based off of the data the team collected from the previous year. The test results from the previous year can be seen in the Figure 16. Iowa State University found that the combination of 1/8 inch thick Line-x with Ensolite foam provided the best average sound deadening. The Line-x also provides the added benefit of strengthening the sled since it is a tough, durable rubber.

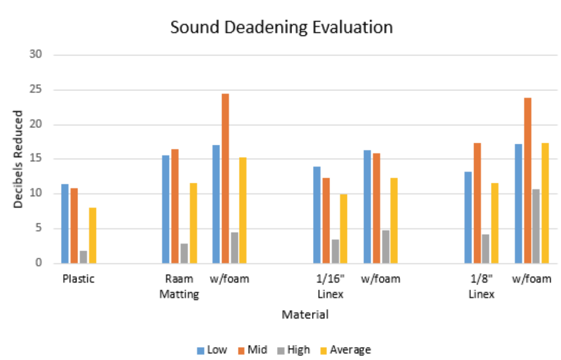

Figure 16: ISU CSC 2017's Sound Testing Data

Summary/Conclusions

Through extensive research, development, and innovation, the 2018 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:

1. Design for safety (ceramic fiber insulation around high heat components, extra engine bay ventilation, dual intercooling system, safety tether kill switch, fire extinguisher)

2. A quieter ride with the use of a two-chamber reactive muffler and Line-x coated tunnel

3. An emission reducing, three-way catalyst exhaust design

4. Custom component designs for superior vehicle performance and user interface. (dual intercooling system, reactive muffler, downpipe, instrument panel, quarter turn fasteners, graphite hyfaxes)

5. Cost effective (MSRP value of $13,496.98)

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 2014 Polaris Indy has been redesigned with intent to delve one step closer in achieving the ultimate snowmobiling experience. In collaboration with SAE International, Iowa State Clean Snowmobile Challenge's goal is to not only to compete to win but to come together as an eager society to engineer quieter, cleaner, and more enjoyable riding experiences for future riders.

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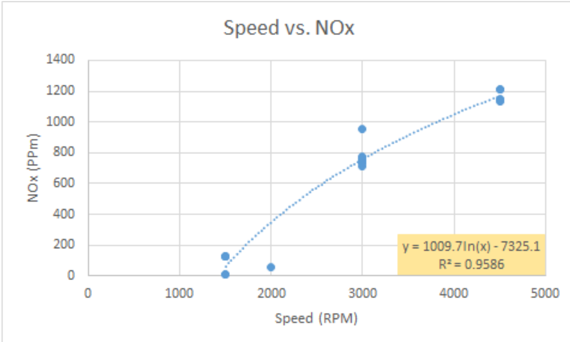
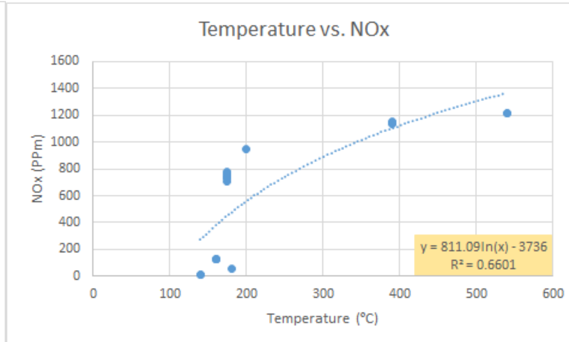
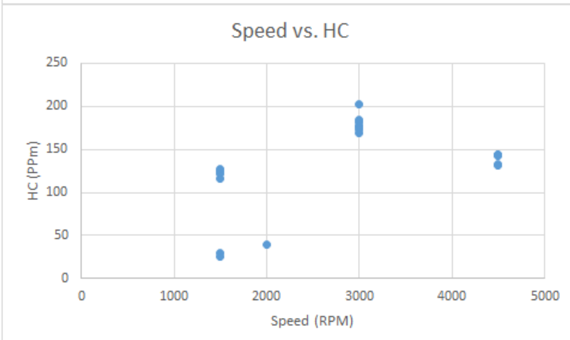
Definitions/Abbreviations

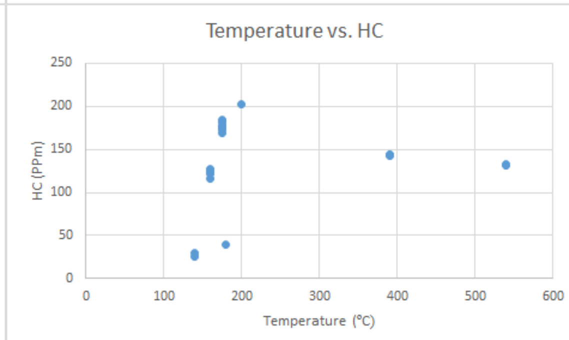
ISU	Iowa State University
CSC	Clean Snowmobile Challenge
Mph	Miles per hour
m/s	Meters/ second
FEA	Finite Element Analysis

Appendix A


Speed vs. NOx
NOx (PPm)
Speed (RPM)
0
1000
2000
3000
4000
5000
0
200
400
600
800
1000
1200
1400
y = 1009.7ln(x) - 7325.1
R² = 0.9586


Temperature vs. NOx
NOx (PPm)
Temperature (°C)
0
100
200
300
400
500
600
0
200
400
600
800
1000
1200
1400
1600
y = 811.09ln(x) - 3736
R² = 0.6601


Speed vs. HC
HC (PPm)
Speed (RPM)
0
1000
2000
3000
4000
5000
0
50
100
150
200
250


Temperature vs. HC
HC (PPm)
Temperature (°C)
0
100
200
300
400
500
600
0
50
100
150
200
250

Appendix B

Material Propertes	Test Method	420SS / Bronze	
		Annealed	Non-Annealed
Tensile Strength	ASTM E8		
Ultimate Strength		72 ksi (496 MPa)	99 ksi (682 MPa)
Yield Strength (0.2% offset)		62 ksi (427 MPa)	66 ksi (455 MPa)
Elastic Modulus		21.4 Mpsi (147 GPa)	21.4 Mpsi (147 GPa)
Elongation		7.0%	2.3%
Poisson Ratio		0.3	0.3
Hardness	ASTM E18	93 HRb	97 HRb
Fractional Density	MPIF 42	95%+	95%+
Density		0.284 lbs/in³ (7.86 g/cm³)	0.284 lbs/in³ (7.86 g/cm³)
Machinability		Conventionally machinable	Refer to ExOne for recommendations
Weldability		Use silicone bronze rod & TIG weld	Use silicone bronze rod & TIG weld
Thermal Conductivity	ASTM E1530	13 BTU/hr ft °F (22.6 W/m°K)	13 BTU/hr ft °F (22.6 W/m°K)
Specific Heat	ASTM E1263	0.114 BTU/lb °F (478 J/kg°K)	0.114 BTU/lb °F (478 J/kg°K)
Thermal Expansion Coefficient	ASTM E228	7.4×10^{-6}/°F (13.4×10^{-6}/°K)	7.4×10^{-6}/°F (13.4×10^{-6}/°K)

Material Properties for 420 Stainless Steel infiltrated with Bronze

Appendix C

Technical Specifications

Type	Four Stroke, Overhead Cam, Parallel Twin	
Displacement	750 cc	
Power	NA: 51 kW (70 hp)	TC: 88 kW (120 hp) @ 7500 rpm
Torque	NA: 65 Nm @ 7000 rpm	TC: 120 Nm @ 5000 rpm
Bore x Stroke/Compression	85 mm x 66 mm/9:1	
Alternator, Internal	750 W Nominal @ 12 V (55 A)	
Cooling System	Liquid Cooled	
Lubrication System	Dry Sump	
Starting System	Integrated Electrical Starter	
Fuel Delivery System	Map based, multipoint electronic fuel injection	
Aspiration	NA: Naturally Aspirated	TC: Turbo Charged
Fuel Requirement	Premium unleaded gasoline (95 ROZ / 91 R+M/2)	
Weight	NA: 52 kg/114 lbs	TC: 60 kg/132 lbs