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 (Iowa State). To achieve these means, Iowa State University dedicated the 2018-2019 season to pursuing innovative exhaust designs and specifically focused on a solution to reduce noise pollution. To accomplish this, the team designed a unique exhaust system that incorporates an additional muffler, a catalytic converter, and custom exhaust pipe work which accounted for unconventional bend angles, differences in tube diameters, and a large section of routing. The additional muffler was added to eliminate peak wave frequencies within a given range which was established during baseline testing in October of 2018 (Figure 24). The additional muffler was fabricated from 304 Stainless Steel and features a three-chamber reactive design, as well as a dual-walled shell which is filled with a 2300° F ceramic heat blanket to insulate the heat created by the engine. In addition to the exhaust system, the team also focused heavily on taking measures to improve the overall fuel efficiency of the snowmobile. To do so, the team incorporated additional bogey wheels mounted to the lower portion of the skid, as well as a custom 3D printed support arm with an additional set that applies an upward force on the track. A big wheel kit was also added to decrease the rolling resistance on the track and new graphite hyfax were added to the bottom of each skid plate in place of the stock polyethylene hyfax. Lastly, the team installed a new G4+ Link Fury standalone ECU in place of the stock ECU to allow for a custom tune, enabling the snowmobile to run off a range of ethanol from E0 to E85.

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 coordinates all sponsor visits and travel. The Technical 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 analyzers. 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" (Iowa State).

Timeline Management

At the beginning of the season, a meeting was held between the Project Director, Technical Director, and all Team Leaders to solidify a feasible timeline in which projects were to be completed. The timeline was mutually agreed upon and openly discussed until everyone felt certain that they would be able to uphold their responsibilities and meet their position-specific deadlines. Examples of a few of the team's critical deadlines are listed below.

- October 14th - Initial baseline testing completed
- October 20th - Begin innovation design and integration
- December 17th - Final design selected for additional team designed muffler
- January 19th - Begin ECU tuning
- February 3rd - All innovations fully integrated and tuned, sled is competition ready

To ensure that these deadlines were met, the team held weekly meetings on Tuesday evenings to discuss current and future initiatives, as well as organize team shop times for the coming Saturday and Sunday. During the weekly meetings, an updated projects list was presented to the team and individuals working on projects would present progress reports to keep everyone informed on what still needed to be accomplished as well as where additional assistance was needed. In addition to the organized team shop times, all members who completed the Iowa State University shop trainings were eligible to work in the shop as they pleased. This was highly encouraged as most projects required additional time outside of the weekend shop times to complete.

Team Outreach

In addition to Iowa State University focusing on developing new innovations for the 2019 SAE Clean Snowmobile Challenge, focus was also dedicated to participating in community outreach events. The first outreach event of the year was a tour of the team's shop space for the Saylorville Dam Snowmobile Club (SDSC), a local snowmobile organization and long-time sponsor of the team. Throughout the course of each season, members from the Iowa State team regularly attend their monthly meetings, and the team also participates in their annual grass drag event. The team's relationship with the SDSC also serves a functional purpose as they regularly provide valuable insight to customer concerns on a variety of sled related issues. Throughout the years, members have given innovative advice on numerous sled improvements that they themselves have made, some in which the team has integrated into their own snowmobile, such as the graphite hyfax, big wheel kit, and Link brand ECU. Pictures of the shop tour are displayed below in Figures 1 and 2. The next event that the team participated in was a local robotics competition put on by FIRST Tech Challenge (FTC). FTC is an international organization that presents middle-high school aged students with exposure to robotics and interactive problem solving. Each season, FTC assigns a singular task that must be completed by a robot. Similar to the SAE Clean Snowmobile Challenge, teams are given a year-long build period and then face off against each other in international competition. For the local competition held at Iowa State, members from the Iowa State Clean Snowmobile team volunteered to be team mentors where they worked one on one with the various teams by listening to their design presentations and providing feedback (Figure 3). In addition to the shop tour and robotics competition, the team also dedicated time to volunteering with two other on-campus organizations: Women in Science and Engineering (WISE) and the Society of Women Engineers (SWE). In working with WISE, members from the Iowa State Clean Snowmobile team volunteered to present at a conference that WISE hosted for local female K-12 students. The purpose of the conference was to provide female students interested in STEM with the opportunity to visit Iowa State and listen to presentations given by various on-campus engineering organizations, as well as participate in fun interactive problem-solving activities. The team presented on the unique opportunities that competing in the SAE Clean Snowmobile Challenge provides students, as well as some of the innovative solutions that the team has been able to create since their establishment five years ago. The next presentation that the team volunteered to speak at, was a presentation given to SWE. Similar to the presentation given at the WISE conference, the team once again spoke about that unique opportunities that the SAE Clean Snowmobile Challenge provides students. However, the team also took time to focus on recruitment as the they hope to better diversify their current demographic in the coming years.

Figure 1: Iowa State Shop Tour with SDSC

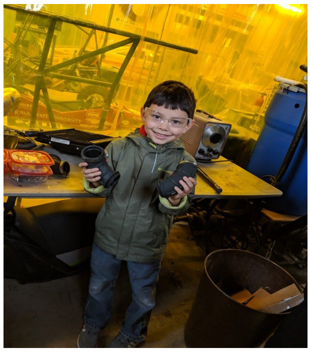


Figure 2: Iowa State Shop Tour with SDSC

Figure 3: Iowa State at FTC Event

Entry Description

- Chassis- 2018 Arctic Cat ZR 7000 Sno Pro
- Engine- Yamaha Genesis, 4 stroke, 1049cc, 3 cylinder
- Track - 129” Camso Ice Attak XT
- Muffler - Stock muffler plus additional custom designed 3 chambered reactive muffler
- Catalytic Converter - Aristo Global 3-way Catalyst
- Skis - Stock Arctic Cat ProCross 6”
- ECU - Link G4+ Fury standalone ECU

Baseline Testing

At the beginning of the season, baseline testing was conducted to determine how in-depth certain elements of the snowmobile would need to be modified in order to comply with competition guidelines. The baseline testing also provided the team with useful data which would enable them to justify their innovations after final testing was completed prior to competition. Due to the team not possessing all of the instrumentation needed to fully complete testing, Iowa State University and MTS Systems Corporation were contacted. The team was able acquire a Bridge five gas analyzer and sound meter, which helped them to ensure that accurate measurements were obtained for stock emissions and noise pollution. The results from the testing are shown below in Appendix A-1 and A-2.

Testing Procedure

For both, emissions and noise pollution, testing was conducted in accordance to the SAE standards and instructions listed in Sections 10.6.3 and 10.9.2 of the 2019 SAE Clean Snowmobile Challenge Rule Book (SAE).

Calculations

To determine the team's stock E-Score, lines of best fist for the collected data sets were drawn to identify values for CO, HC, and NOx. The team then took the averages of the identified values (listed below) and plugged them into the provided equation in section 10.6.5 of the 2019 SAE Clean Snowmobile Challenge Rule Book (SAE). From these calculations, the team's stock E-Score was 120.605. No noise calculations were needed to determine the range of emitted peak frequencies (Figure 24).

(CO)avg = 11.33 g/Kw-hr
(HC)avg = 225 g/Kw-hr
(NOx)avg = 266.67 g/Kw-hr (average of values taken at 60 seconds)

Analysis of Baseline Testing

After analyzing the calculated E-Score and the graph of the emitted peak frequencies, Iowa State University was able to determine that modifications needed to be made to their snowmobile in order to achieve an E-Score of at least 175 and a decibel reading of less than 67 db. Since both emissions and noise pollution presented areas of needed improvement, the team agreed that modifying their exhaust system would be the best solution to this problem. To do so, the team identified the most problematic frequency range: 31.5-1,000 Hz (Figure 24) and began designing a new exhaust system specifically targeting emitted frequencies from that range.

Cold Start Testing

In efforts to maximize the probability that Iowa State's snowmobile would be capable of completing the Cold Start event at this year's competition, preliminary testing was conducted to identify possible areas of weakness within the snowmobile at harsh environmental conditions. To simulate these conditions, Iowa State partnered with Danfoss to utilize their state of the art, cold testing cell which is capable of reaching temperatures of up to forty degrees below zero Fahrenheit. The team first met with Danfoss in late November to tour the facility and develop a test plan, which was solidified by mid-December, and testing began in the first week of February.

Original Test Plan

The original test plan stated: conduct three test runs for three consecutive days in which the snowmobile is to be cold-soaked overnight, started in the morning, and operated for five minutes at idle conditions where no acceleration will be applied. The five-minute period will provide the snowmobile with adequate time to reach optimal operating temperatures, and temperature readings will be collected for the oil, coolant, exhaust stream, and engine block. The first test run will be conducted at ten degrees Fahrenheit, followed by zero degrees Fahrenheit, and will conclude at negative ten degrees Fahrenheit. During the three day test period, the snowmobile will remain enclosed in the cold testing cell and started remotely by an externally hard-wired push button start. The push button start will ensure that the temperatures inside of the cold testing cell remain accurate as they will be manually adjusted by an external thermometer.

Actual Test Proceedings

Test run one was conducted on Wednesday morning after the snowmobile had been cold soaked overnight at ten degrees below zero Fahrenheit. It did not start that morning and it was determined later that afternoon that it was due to a faulty battery. Test run two was conducted Thursday morning after the temperature was adjusted to ten degrees Fahrenheit and a brand-new battery had been installed. The snowmobile started that morning and the data collected from the run is displayed in Figure 4 below. Test run three was conducted Friday morning after the snowmobile had been cold soaked the night before at zero degrees Fahrenheit. The snowmobile started that morning and the data collected from the run is displayed in Figure 5 below. Test run four was conducted on Monday morning after the snowmobile had been cold soaked over the weekend at ten degrees below zero Fahrenheit. The snowmobile started that morning and the data collected from that run is displayed below in Figure 6.

Analysis

Test runs one through four yielded that, with the stock battery installed, the snowmobile would ultimately fail to start at temperatures of ten degrees below zero or colder. After the failed start, the battery was tested, and it was revealed that it is was at 75% percent of its maximum charge and that it had also lost 30 of its original 310 crank amps. This confirmed the team's suspicion of problematic starting, as prior to the testing the snowmobile regularly required three to four engine firings before it turned over and started at room temperature. However, once a new battery had been installed, these problems were no longer experienced even at the low testing temperatures. Which, after cold soaking the snowmobile for nearly 72 hours at ten degrees below zero and then having a successful start, the team feels confident that they will be able to complete the cold start event if similar weather conditions are experienced.

Final Test Outcomes

Displayed below are test runs two through four. No data was collected for test run one as the snowmobile failed to start.

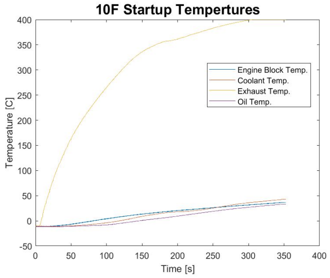


Figure 4: Cold Start Test - Run Two

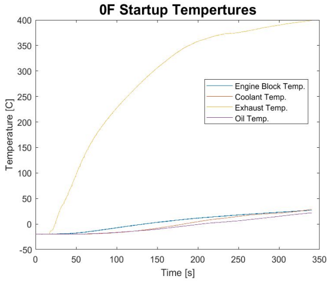


Figure 5: Cold Start Test - Run Three

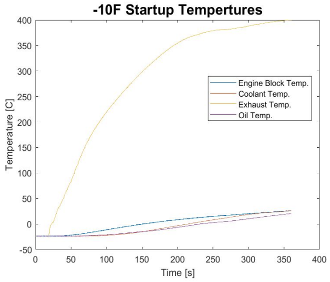


Figure 6: Cold Start Test - Run Four

Exhaust

Muffler Design

To maximize the reduction of noise pollution, Iowa State University designed a custom exhaust system which features two mufflers, one that is team designed and one that is stock. The stock muffler came standard with the team's 2018 Arctic Cat ZR 7000 Sno Pro, while the team designed muffler was developed after extensive research and flow simulations. The team designed muffler features a 304 Stainless Steel construction of a three-chambered reactive design, encased within a dual walled exterior shell that is insulated with a 2300-degree Fahrenheit ceramic heat blanket. The ceramic heat blanket also encases the interior portion of the muffler featuring three lengths of perforated pipe (Figure 7). The ceramic heat blanket was chosen for its ability to insulate the heat produced by the engine, and also for its material properties which allow it to absorb extremely hot temperature without igniting. The material properties of the ceramic heat blanket are displayed below in Figure 8.

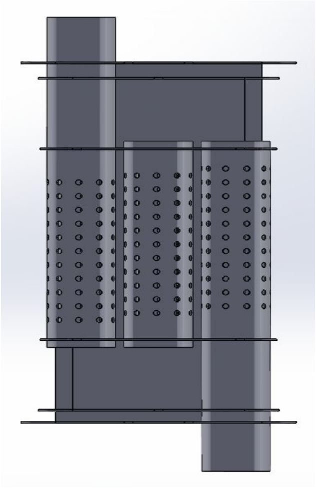


Figure 7: 2019 Iowa State Team Designed Muffler

Ceramic Heat Blanket Specifications	
Temperature Grade	2300 °F
Thermal Conductivity (BTU- in/hr * ft^2 * °F)	0.8 at 1000 °F
Density (lbs/cu*ft)	8
Thickness (inches)	1

Figure 8: 2019 Team Designed Muffler

Muffler Design Process

Iowa State University's muffler design process entailed four fundamental phases: research, design and modeling, simulation, and fabrication. The research phase entailed extracting useful information from online resources including SAE technical papers, journals, databases, and forums. During this phase, team members found two resources to be particularly useful; SAE.org and the Iowa State University Interlibrary Loan and Document Delivery system (ILL/DD). Through the ILL/DD, team members were able to gain full access to the wide variety of technical documentation on SAE.org without needing to pay for any of the material out of pocket. This greatly benefitted the team as it enabled them to obtain numerous documents relating specifically to muffler design. The next phase was the design and modeling phase. This phase entailed a collective effort by the team to design prototype mufflers with unique internal features, which were then modeled with ANSYS flow simulation software and analyzed to determine which features yielded the best results. Section views showcasing the internal features of several team designed mufflers are displayed below in Figures 9-13.

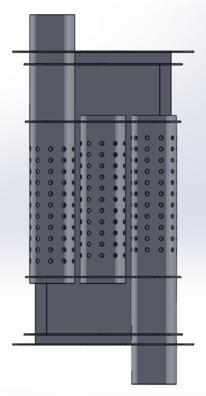


Figure 9: Muffler Design 1

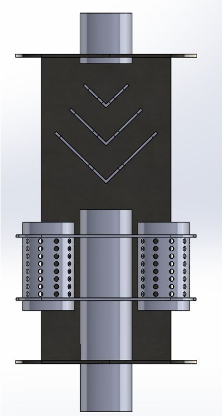


Figure 10: Muffler Design 2

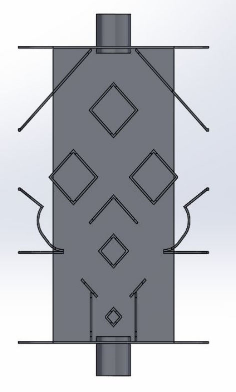


Figure 11: Muffler Design 3

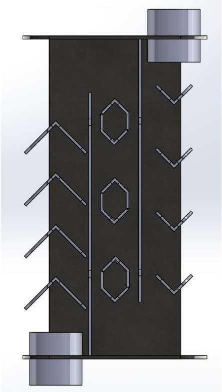


Figure 12: Muffler Design 4

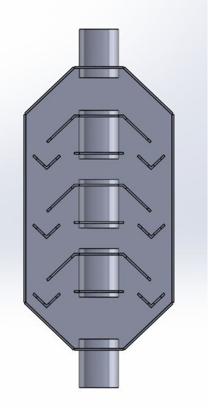


Figure 13: Muffler Design 5

The third phase of the process was simulation. This phase entailed importing the prototype mufflers designed in SolidWorks, into ANSYS to analyze their flow patterns, particle velocities, and noise frequencies. Unfortunately, during this phase the team faced unexpected difficulties mastering ANSYS' learning curve and ended up being unable to complete all of their intended simulations. That being said, the muffler designs that were modeled are displayed below in figures 14-16.

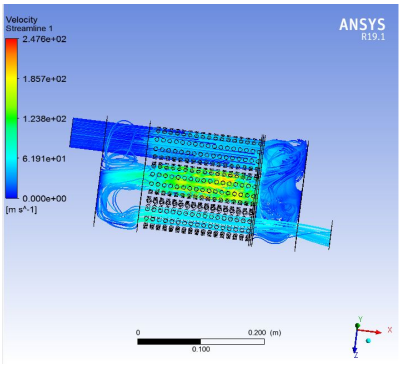


Figure 14: Muffler Design 1 Modeled in ANSYS

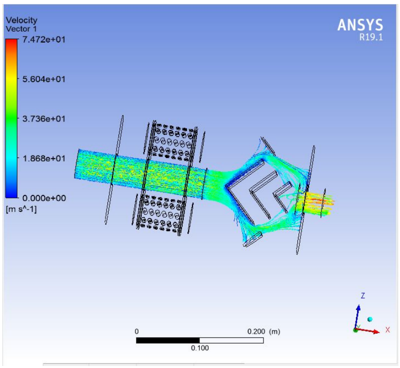


Figure 15: Muffler Design 2 Modeled in ANSYS

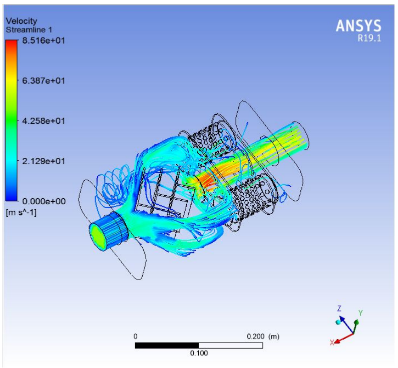


Figure 16: Muffler Design 2 Modeled in ANSYS With Baffles Rotated 180 Degrees

The last phase in the process was fabrication. This phase entailed having all components of the muffler cut out with a water jet and TIG welded to ensure a rigid air tight structure where the exhaust particles could not escape.

Muffler Selection Process

The team's original process for selecting the additional muffler design, that was to be incorporated into their exhaust system, closely correlated to their muffler design process and even included several of its steps (original selection process listed below). However, due to the experienced difficulties with ANSYS, the team was unable to completely follow the original process and ultimately deviated from it in order to maintain course and meet their deadline of having a final muffler design selected by December 17th.

Original Selection Process

1. Compile ten uniquely designed mufflers. Designs are encouraged to be hand drawn and can correlate with well supported research or hypothetical ideology.
2. Model each muffler in SolidWorks.
3. Import SolidWorks constructions into ANSYS.
4. Perform general, and Harmonic Vibration & Acoustic simulations on each construction.
5. Analyze simulations to validate/invalidate designs of each construction. Designs will be validated/invalidated based upon observed flow patterns, particle velocities, and noise frequencies which the mufflers are designed to cancel. The internal designs that render frequencies closest to those in the established range of the Arctic Cat ZR 7000 Sno Pro, from initial baseline testing this fall (Figure 24) will be selected for the final design.
6. Select a final design.
7. Recreate final design in SolidWorks. Identify any areas or geometries problematic to manufacturing.
8. Submit final muffler design to be cut out with a water jet.

Actual Selection Process

The actual selection process closely followed the original selection process up until step 4, where the team experienced a major timeline set back. This timeline set back ultimately forced the team to select a final design under far less informed circumstances than what they had hoped for in efforts to meet their December 17th deadline. Making the best of the situation, the team analyzed each of the three design options and made their selection based off of manufacturability and flow pattern. The muffler that the team selected (Figure 9), contained the fewest number of internal features that required cutting out by a water jet. It also did not feature any baffles or parts with excess tab material in which would provide a surface to weld to. Lastly, the team noted that the muffler selected presented them with the largest area in which to wrap the perforated tubing in the 2300° F ceramic heat blanket. The team also agreed that out of the three options, the selected muffler had the best flow pattern and presented the fewest number of potentially problematic areas.

Exhaust Routing

Significant exhaust routing was required to accommodate the placement of Iowa State's additional team designed muffler. The additional muffler, which is located at the very rear of the snowmobile, is mounted to the underside of the tunnel and sits perpendicular to its length. The overall exhaust system begins closest to the driver's foot on the right-hand side of the snowmobile and travels underneath the running board all the way to the tail end of the vehicle. The success of the routing was accomplished by making a modification to the stock muffler as well as by designing a custom, flange connected, multi-segmented length of angled and straight exhaust piping. The modification made to the stock muffler was the removal of its lowest two inches of exhaust piping. This allowed for the 90-degree mandrel bend, that sits directly after the exhaust exit on the stock muffler, to gain altitude in the positive z-direction, which in turn allowed the entire exhaust system to snug up against the running board. This was the desired outcome due to the fact that if the piping was positioned too close to the ground, any uneven element of terrain (log, rock, etc.) could collide with it and possibly cause damage.

Catalyst

To reduce the levels of harmful emissions exiting the snowmobile, Iowa State University incorporated a three-way oxidation catalyst into their exhaust system, as the Arctic Cat ZR 7000 Sno Pro did not come standard with one. The catalyst, which was developed by Aristo Intelligent Catalyst Technologies, has dimensions of 3.5 inches in length and 2.65 inches in outer diameter. It includes a proprietary inner coating and is located just before the stock muffler in the team's exhaust system. In addition to the proprietary coating, the catalyst is also wrapped in 2300° F ceramic heat blanket and ceramic fiber heat wrap, which is all enclosed underneath a full encompassing protective layer of metal heat shielding.

Catalyst Adapters

Due to the catalyst having a larger outer diameter than that of the exhaust piping, custom metal pipe adapters were designed to accommodate the differences in diameters so the team would not have to sacrificing a loss in useable surface area of the catalyst. The metal pipe adapters were fabricated from small elongated sections 2.65 inch OD 304 Stainless Steel exhaust piping.

Chassis and Suspension

Venting

To comply with competition guidelines, the team covered all openings in the body of the snowmobile larger than 12 mm to minimize the risk of injury. The team accomplished this by using Frog Skin, hexagonally patterned grill material, and 3D printed ABS plastic to cover problematic areas like the air intake and side panel vents.

Graphite Hyfax

To reduce friction on the track, the stock polyethylene hyfaxes were replaced with aftermarket graphite hyfax. Iowa State University chose to use graphite hyfax based off of data that was collected last year that showed an average of 20% decrease in force. The decrease in force results in a reduction in power lost through the friction force between the skid and track. This data can be observed in Figure 17.

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

Figure 17: Iowa State University's 2018 Hyfax Data (Iowa State)

Lower Skid Modifications

Additional modifications to the chassis were made by widening pre-existing holes in the rear portion of each skid plate to accommodate an additional bogey wheel to reduce track friction and improve fuel efficiency. The team was required to widen each hole to accept the slightly larger mounting bolts of the additional bogey wheels, and each hole was widened from 0.25 to 0.35 inches in diameter. To justify this modification, the team modeled one of the skid plates in SolidWorks and performed Finite Element Analysis (FEA) to prove that the modifications made to each plate did not compromise their structural integrity (Figure 18).

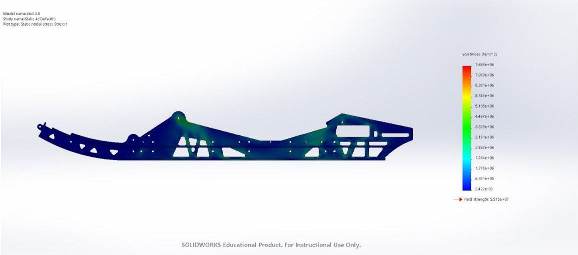


Figure 18: FEA Analysis of Skid

For the FEA analysis, 6061 Aluminum alloy was chosen for the skid plate material as the snowmobile's user manual confirmed that the skid plates were made out of anodized Aluminum but failed to specify the particular grade of the material. 6000 series Aluminum is one of the most commonly used alloys of Aluminum, and 6061 is commonly used for structural applications.

In conclusion to the FEA analysis, the widening of the holes in each skid plate did not compromise their structural integrity. In both of the simulations, similar stress values were recorded for the skid plate with 0.25 inch holes as well as for the skid plate with 0.35 inch holes. In each scenario the yield strength was 5.515e+7 N/m2 and the stress values throughout each plate remained sufficiently below that level.

In addition to the extra set of bogey wheels, a big wheel kit was also added to skid, changing the outer diameter of the two inner rear wheels from six inches to nine inches. This modification was made as bigger wheels increase the radius of the turn that the track has to make around the back half of the skid. This increase noticeably improves the efficiency of the power produced by the engine as the rolling friction is greatly reduced.

Upper Skid Modifications

To reduce vibrations and quiet the snowmobile, a mount was designed to apply an upward force on the track. The mount itself, features two bogey wheels and a 3D printed support arm (Figure 21) that attaches around a nut and bolt on each side of the upper portion of the skid (Figure 19). The support was manufactured using a Markforged 3D printer at Viking Pump, and the material that it was printed out of is a combination of chopped carbon fiber and reinforced fiberglass (Figure 20). The chopped carbon fiber material, called "Onyx" by Markforged, was chosen for its strength from the carbon fiber and its ability to flex and retain its shape from the nylon, allowing the support to act as a shock absorber. While Viking Pump was not able to obtain good strength data from their material tests, Markforged states that the fiberglass reinforced "Onyx" is roughly 8 times stronger than PLA plastic. This material was strategically placed around the mounting holes and the areas where the bogey wheels would attach to the supports. However, the material was not placed completely around the supports in order to allow it to flex when the rear suspension compresses.

Figure 19: Mounting Location (nut and bolt) for 3D Printed Support Arm

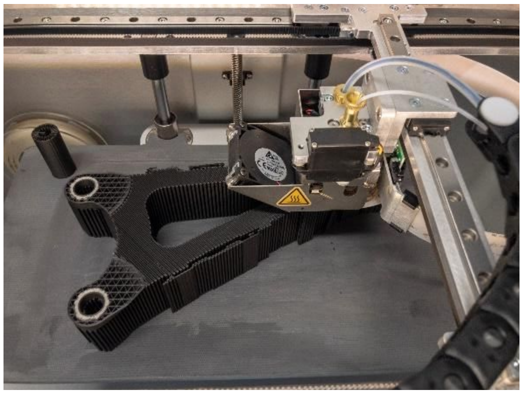


Figure 20: Mount Midway Through Manufacturing Process

Figure 21: Rendering Support Arm

To allow the upper bogey wheel support to function properly, some modifications had to be made. The first major modification was carving a channel in the lower support beam to allow for the suspension to travel through it when the suspension compressed. The team also had to widen the bogey wheel mounts to allow the bogey wheels to run in the proper place. This was done by creating new parts for the bogey wheels to ride on and fabricating shims to provide the proper spacing.

Rear Hitch Addition

Iowa State University's Arctic Cat ZR 7000 Sno Pro did not come standard with a rear hitch, which is a competition required feature that each team's snowmobile must include. To resolve this problem, a custom hitch was designed and manufactured to carefully follow the curvature of the rear bumper so that when welded, would produce the strongest bond to the chassis. This carefully followed curvature design was achieved by first prototyping the trailer hitch with cardstock as seen in Figure 22. The two side hitch supports were then machined by hand from ¼-inch-thick aluminum plate material, and a universal attachment point for any trailer was added to complete the assembly (Figure 23). The assembly was then TIG welded onto the bumper to ensure the strongest possible bonds between the three surfaces.

Figure 22: Prototyping Mounts for Rear Hitch (In hand)

Figure 23: Completed Rear Hitch Assembly

Line-X Sound Reduction

In 2017, Iowa State University collected data on the benefits of applying Line-X bed liner to the underside of the snowmobile's tunnel. From the data collected (Figure 24), it was evident to see that the Line-X bed liner did in fact reduce noise pollution levels, as reductions of up to 12 decibels were documented without the inclusion of Ensolite foam. Armed with this information, Iowa State University has once again chosen to incorporate this element into their snowmobile for the 2019 SAE Clean Snowmobile Challenge. The thickness chosen for this year's competition was ⅛ inch as it has been proven to yield the best results.

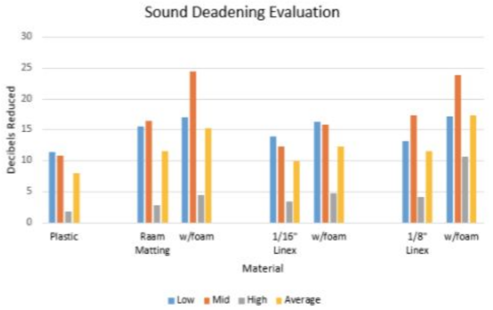


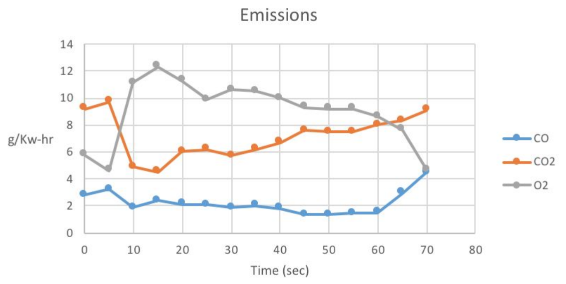
Figure 24: Iowa State University's Sound deadening data from 2017 (Iowa State)

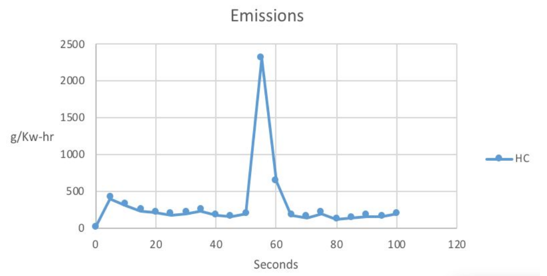
References

1.“Harmonic Vibrations and Acoustics.” *Simulation Capabilities | ANSYS Icepak*, ANSYS Inc., 2019, www.ansys.com/products/structures/vibrations/harmonic-vibrations-and-acoustics.
2. Iowa State Clean Snowmobile Team. *10_Iowa_State_Design_Paper*. Iowa State University, 2018, pp. 1–15, *10_Iowa_State_Design_Paper*.
3. SAE International. “2019_SAE_CSC_rules_FINAL_Draft_10.5.2018.Pdf.” SAE International, 2018.

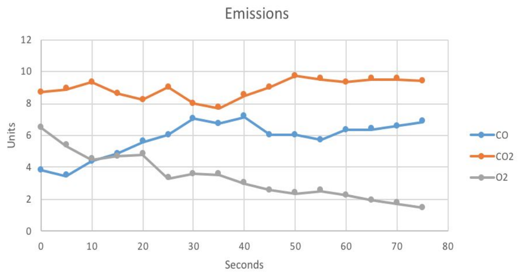
Appendix A-1

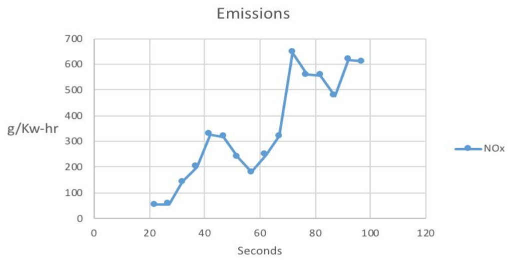
Test Run 1



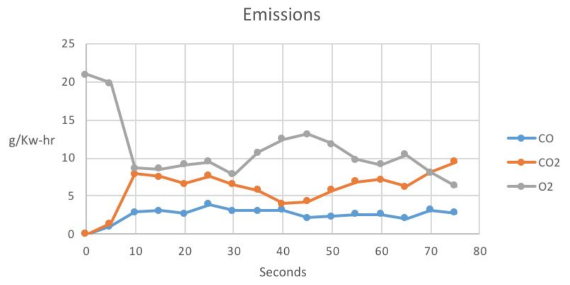


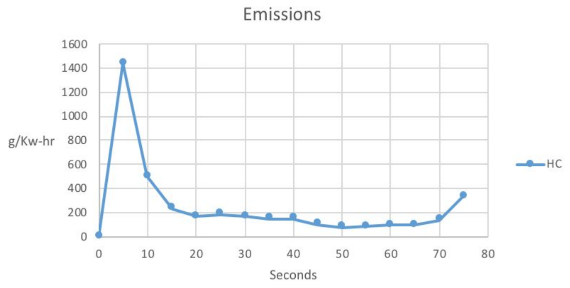
Test Run 3



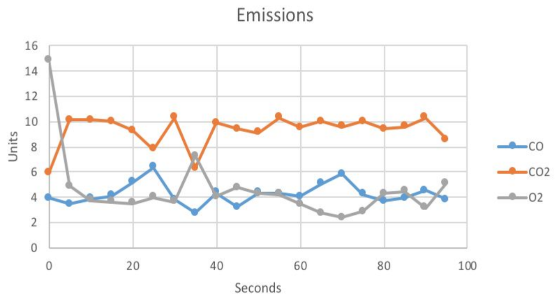


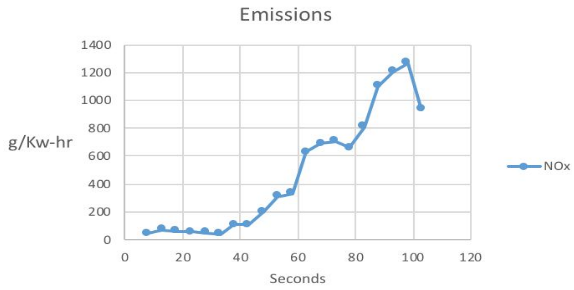
Test Run 2





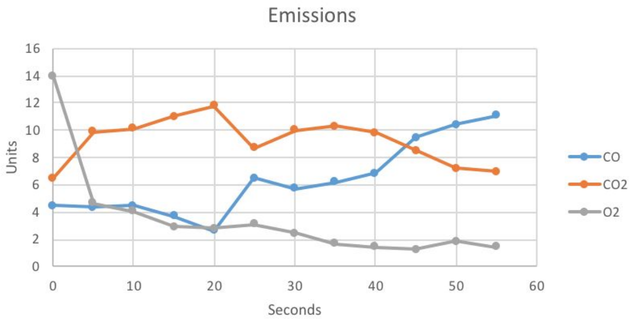
Test Run 4

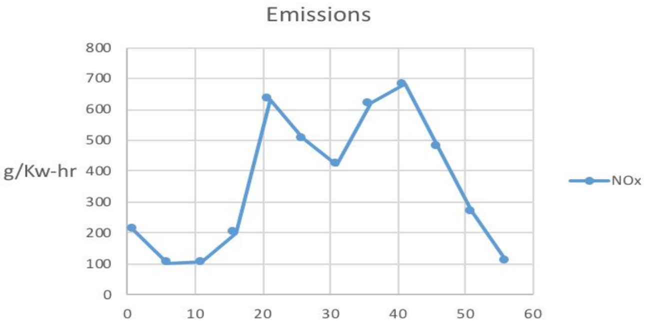




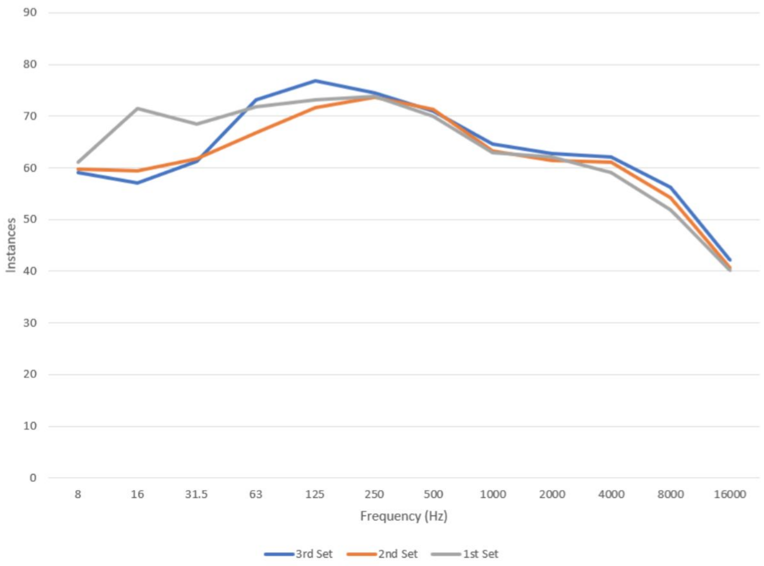
Appendix A-2

Test Run 5





Sound Meter Testing



NOTE: The Y-axis should be properly labeled as "Sound-Pressure Level-DB", not "Instances".