University of Waterloo Clean Snowmobile Design Paper

Barry Crosswell, Geoff Dijkema, Alec Espie, Carter Hilliker, Madelaine Liddy, Peter McClure, Atif Mian, Amir Panahi, Kristen Sperduti, Wesley van Barneveld

2010/2011 University of Waterloo Clean Snowmobile Team

ABSTRACT

The design mentality of the UW Clean Snowmobile Team for 2011 is to start with a lightweight and powerful yet efficient combination. This is achieved by mating a 2009 Ski-Doo Rev-XP chassis with a 2005 Arctic Cat T-660 engine. The difficulties involved in this engine swap proved mainly to be packaging issues – offering a chance for the team to redesign essential components, improving their performance while focusing on efficiency and cleanliness. The 2011 snowmobile features completely redesigned intake and exhaust manifolds and a custom built lightweight aluminum muffler with a catalytic converter. All of these redesigns allow the team to achieve the same – or improved – levels of performance as the stock systems.

INTRODUCTION

BACKGROUND – The focus on more environmentally friendly snowmobiles started in the late 1990's when a study in Yellowstone National Park found that snowmobiles contributed up to 90% of hydrocarbon emissions and up to 68% of carbon monoxide emissions yet only accounting for 6% of the total vehicles entering the park annually (1). Pollution was so bad that snowmobiles were actually banned in the park.

Due to the prohibition of snowmobiles from the park, manufacturers have been diligently working towards a cleaner yet still fun-to-operate solution. The two main methods for reducing emissions were borrowed from the automotive industry: installing four stroke engines coupled with catalytic converters.

The Clean Snowmobile Challenge takes this environmentally friendly push one step further by using an ethanol blend of fuel. The 2011 snowmobile is capable of running on fuels comprised of 0% to 85% ethanol. Ethanol burns much cleaner than gasoline yet still provides enough power to make snowmobiling enjoyable. The UW Clean Snowmobile team plans to implement all three emission reducing technologies towards creating a clean, enjoyable snowmobiling experience.

CHALLENGE – The main challenge faced when trying to develop a clean and quiet yet powerful and fun to drive snowmobile is that the concepts are, at first, mutually exclusive. Creating a sled that is extremely powerful with complete disregard for noise or emissions is easy. Creating a sled that is environmentally friendly is easy as well. Creating something that harnesses the best of both situations is not. This is where the team must innovate and figure out a way to make the sled cleaner and quieter without sacrificing any stock performance.

The biggest challenge faced by the team this year is the fact that the engine and chassis chosen are from two different manufacturers, each employing their own design strategy. The team needs to integrate the engine, chassis, and all required subsystems – it is for this reason that most of the stock subsystems needed to be redesigned. During the redesign, the systems were re-evaluated and improved upon.

DESIGN STRATEGY – The objective of the competition is to create a quieter, more fuel efficient, and cleaner snowmobile without sacrificing any stock performance characteristics. The design strategy employed by the University of Waterloo Clean Snowmobile Team for the 2011 model year is similar to the previous year, except with a new chassis and engine – minimize weight and maximize performance. The chassis is one of the lightest on the market, and the engine is small, yet efficient and powerful allowing the team to achieve a lightweight starting point with a high power-to-weight ratio. Using a four stroke engine and converting the engine to run on ethanol also greatly helps to reduce emissions. This combination of power, efficiency, and cleanliness is the objective of the team.

DESIGN CRITERIA – To ensure the most effective design, all decisions are weighted based on the design criteria outlined by the design team during the preliminary planning phase of the project. These design criteria are:

- Maximize performance of the snowmobile.
- Minimize emissions of carbon monoxide and unburned hydrocarbons.
- Minimize noise.
- Minimize weight of installed components.
- Minimize overall cost.

DESIGN CONSTRAINTS – The design must meet the design constraints outlined below in order to be considered successful.

- Designs must ensure safety of the rider.
- Snowmobile must run on ethanol flex fuel ranging from an E20 to an E29.
- All components must be ethanol flex fuel compatible.
- Snowmobile noise must not exceed 78 dBa.
- The engine must start within 20 seconds and move 100 feet within 120 seconds without stalling.
- Maximum horsepower of 130HP

PERFORMANCE AND EMISSION CONTROL

CHASSIS – The chassis selected for the 2011 competition is a 2009 Ski-Doo Rev-XP chassis, which at the time of manufacture, was lighter than any chassis on the market (2). The Rev-XP is also very ergonomic, which is important for every day drivability. Low weight is extremely important when aiming for performance and fuel economy, so the Rev-XP is a good fit with the UW design mentality. In order to keep costs down, the chassis was purchased second hand.

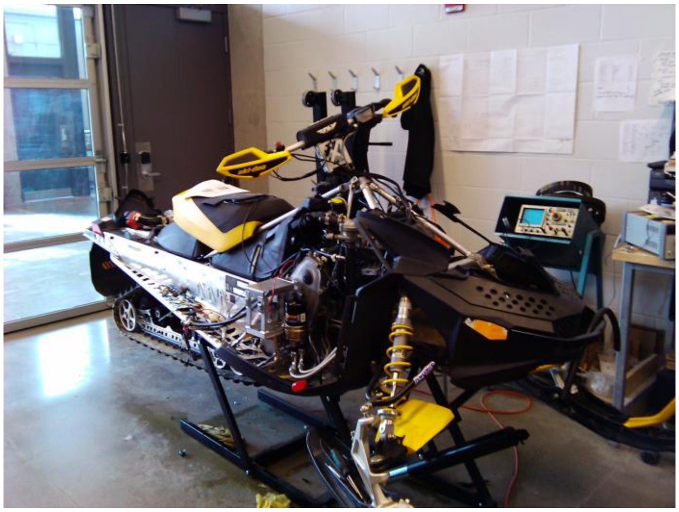

Figure 1: The 2011 Ski-Doo Rev-XP chassis.

ENGINE – The same criteria (low cost, low weight) applied to the purchasing of the engine, and in the end, it was decided that a 2005 Arctic Cat T-660 engine would power the 2011 sled. The T-660 is a 660 cubic centimeter, three cylinder, four stroke, turbocharged engine. Many snowmobiles come equipped with two stroke engines which produce much more harmful emissions due to the fact that oil (for lubrication) and gasoline must be mixed and sent into the combustion chamber. Four stroke engines have independent lubrication and gasoline loops which results in less harmful emissions and more complete combustion. One downside to four stroke engines is that they produce less power than their two stroke counterparts due to the fact that the two stroke engines produce power every two revolutions of the crankshaft, whereas four strokes produce power every four revolutions. To combat this effect, the T-660 is turbocharged and rated at 110 horsepower. This is under the 130 horsepower cap enforced by the competition rules. The combination of a lightweight chassis and lightweight, yet clean, powerful and efficient engine provides an excellent starting point that is in line with the team and competition objectives.

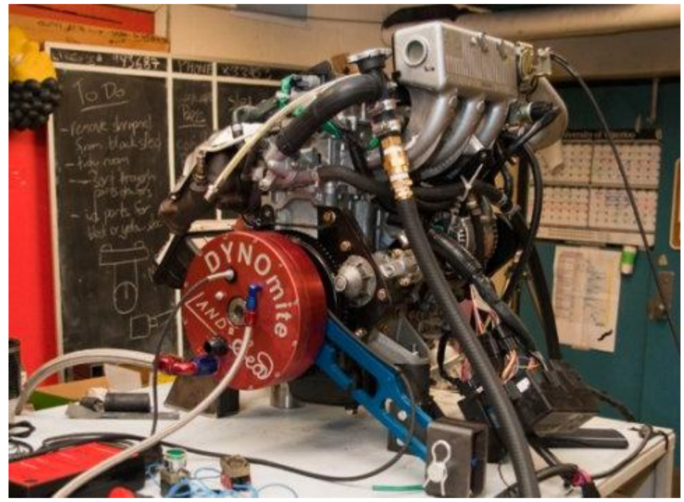

Figure 2: The Arctic Cat T-660 on the test stand, hooked up to the dynamometer.

ENGINE MOUNTING – There was no straight forward way to install the Arctic Cat engine into the Ski-Doo chassis. The approach that the team chose was to bend a plate of stainless steel in the shape of the bottom of the engine bay and bolt this directly to the chassis. This will help to improve structural rigidity because steel is stronger than aluminum. Flanges were cut and welded to this plate to create four mounting points for the engine. The four engine mounts are made from aluminum to reduce weight, and were custom machined. The engine will be soft mounted to the chassis via these mounts.

AIR INTAKE SYSTEM – Due to the fact that the stock intake system is much too large to successfully integrate with the chassis, it needed to be redesigned. A picture of the stock intake can be seen below.

Figure 3: Stock intake manifold.

In order to maintain stock performance, a quantitative approach was taken: an increase in airflow will improve performance. This is a reasonable assumption because engine performance is closely linked to the amount of air (and therefore fuel) entering the cylinders. More air/fuel into the engine results in more power out. This is important in maintaining stock characteristics. The redesigned intake system can be seen below.

Figure 4: Redesigned manifold attached to the engine, in the chassis.

The area of the inlet port on the engine was measured, and this became the diameter of the runners. The flange was created in Solidworks and then created via a CNC machine, so there is a smooth transition from the circular cross section of the runners to the oval cross section of the intake ports which is important to keep the air/fuel mixture moving into the cylinders instead of swirling around at the transition, resulting in a loss of power. The final plenum design has a capacity that is 1.6 times greater than the capacity of the engine meaning that there will always be air available to flow into the engine. It is important to have a significant amount of air in the plenum and runners because they are pressurized due to the fact that the engine is turbocharged, therefore the air inside (at about 16 psi) will flow quickly when there is an opening in the system such as the intake valve opening. The throttle body has also been mounted in the centre of the plenum, as opposed to the end. This will provide a more even distribution of air to the runners, ensuring consistent power delivery. Another assumption employed by the team is that since the intake system is pressurized, it will overcome any flow interruptions and maintain stock performance. At no point did any of the geometry get smaller, and this is why the team believes that there will be no performance hit with the newly designed intake system. The entire air intake system is made from aluminum to keep weight to a minimum.

FUEL INJECTION SYSTEM – A new fuel injection system was designed for this sled for two main purposes: first it was converted to peak & hold injectors in order to improve fuel economy and avoid wasted fuel. Second larger injectors were needed to add more fuel to the cylinders in order to supply additional fuel to compensate for the ethanol.

Peak and Hold injectors are more fuel efficient since less fuel is wasted. They are also called low impedance injectors and therefore they take less voltage to open and close. This means that the injectors can open and close more quickly, compared to high impedance injectors which need a little bit of ramp time to fully open and fully close. At higher RPM these ramp times start to overlap since the cylinders are firing so quickly. With the low impedance injectors, they are only open while the valves are open and therefore much less fuel is wasted.

The peak and hold injectors are rated for a much higher volume than would be needed for a normal combustion of this size. Since the ethanol in the fuel has a different Air-to-Fuel ratio than straight gas, as well as less power per volume; more fuel is needed to maintain stock performance. It would be possible to use smaller injectors, however, it is not recommended to run higher than 80% duty cycle, and the engine is getting close to that already without adding extra fuel for the ethanol. Going over this 80% mark would see dramatic reduction in fuel efficiency.

EXHAUST HEADER – The stock exhaust manifold is unacceptable for a number of reasons. First and foremost, it will not fit in the chassis and needs to be redesigned. Second, it is a very restrictive design and this will be accounted for in the redesign. A picture of the existing exhaust manifold can be seen below.

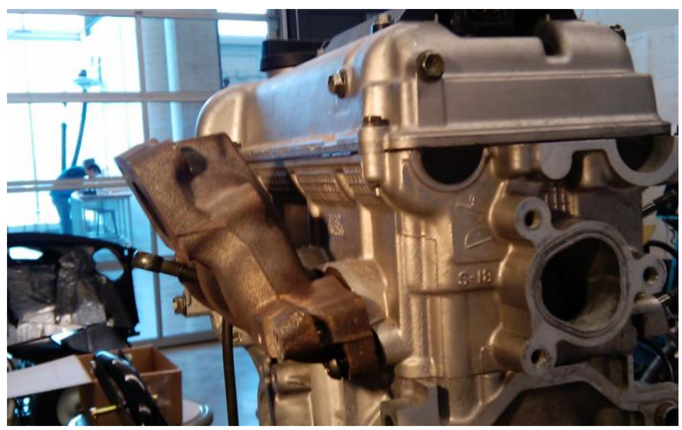

Figure 5: Stock exhaust manifold attached to the engine.

Note how the exhaust gases will turn 90° immediately exiting the engine. This is not a smooth transition, and can create a higher pressure at the exit which can hinder performance by not allowing exhaust gases from the cylinders escape efficiently. The first step in designing new headers is to determine the inside diameter. This is done by analyzing the engine at its top speed and calculating the flowrate of exhaust gases escaping. This diameter is determined to be 1.5”. The collector is where the three header pipes meet, and this has to mount to the turbocharger, therefore the diameter was determined. Once the diameters were determined, the length of the headers needed to be found. This was done using the speed and volume of the cylinders (which corresponds to how much gas is exiting the engine) and also on valve overlap – the length of the headers should be such that when exhaust gas from cylinder 1 reaches the collector, exhaust gas from cylinder 2 is just entering the header. This creates an efficient method of drawing the exhaust gases out and away from the engine. The headers are also required to be equal length. Once the length and diameters were calculated, a Solidworks model was created in order to determine how the final design should look. The final design needs to integrate with the sled properly without causing any interference, and must also allow the turbocharger to fit within the engine bay. The Solidworks model can be seen below that outlines the final design.

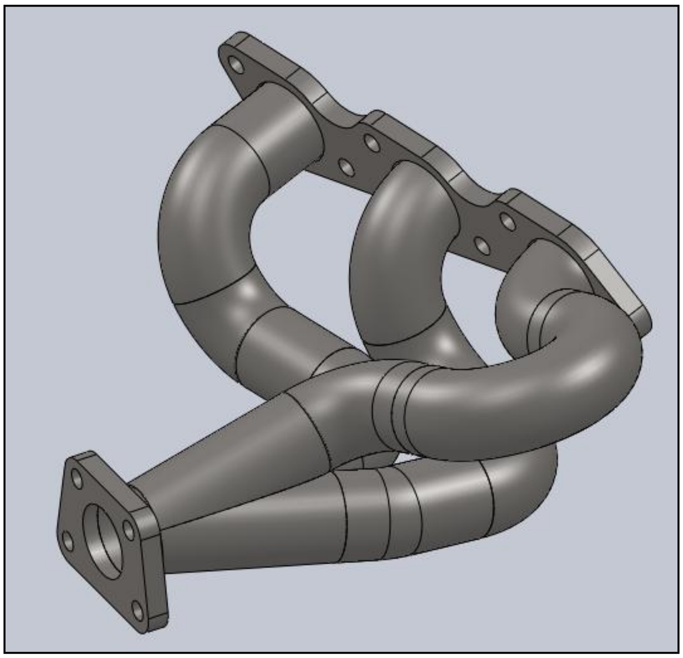

Figure 6: Solidworks model of the exhaust manifold.

The system has also been ceramic coated on the inside to reduce heat losses to the engine bay. This helps in two areas: it keeps the exhaust gases hot, which helps them to flow easier and evacuate the headers, and also reduces the heat released to the engine bay which contains many hoses and liquids that will not function properly if heated too far. In addition to determining the fit of the exhaust manifold, Solidworks was used to determine the factor of safety of the system because it is cantilevered to the engine bay, and the turbocharger is on the end. The factor of safety is sufficiently high (more than 15) and therefore will be safe to operate. The newly designed exhaust system is superior to the stock system because it provides a much smoother transition for the gases reducing backpressure. According to the same assumption made for the air intake system, an increase in airflow will increase performance. The final exhaust can be seen below compared to the stock system, and although it is much larger than the stock exhaust manifold, it weighs slightly less due to lighter components being used.

Figure 7: Stock exhaust manifold (top) versus redesigned manifold (bottom).

CATALYTIC CONVERTER – One of the main objectives of the competition is to make a snowmobile cleaner, and while a four stroke engine helps to reduce emissions, a catalytic converter is just important. Adding a catalytic converter also adds weight, but it is a necessary sacrifice in order to achieve a low emissions design. The main aspects considered when selecting the catalytic converter were type and heat shielding to apply. The optimum type of catalytic converter chosen is a cerium additive type because it provides the greatest reduction in emissions compared to air injection and also using two separate catalytic converters. The cerium additive is the most compact design that adheres to the criteria, and is the best fit within the system. Three different types of heat shielding were considered: fiberglass wrap, a solid shield, and ceramic coating. The fiberglass wrap is the cheapest solution, although it is also the poorest performing. A solid shield is more expensive than fiberglass coating, but will provide more heat protection because it is physically separate from the tube (eliminating conduction gains) and will therefore operate at a lower temperature than fiberglass wrap. Ceramic coating is superior to both the aforementioned, although it is quite expensive. Ceramic coating was discussed in the exhaust header section (as they are ceramic coated) but the objective is to keep the heat in the gases instead of the surrounding so 1) the gases can flow more freely and 2) heat is not transferred to the surroundings. Due to the fact that the convert will reach extremely high temperatures, the ceramic coating and solid shield were picked. The increased performance that these options provide justifies the cost, as they will both help to reduce emissions and improve performance. Fibreglass wrap will be used on the piping because the piping won't get as hot as the converter and therefore doesn't need to be shielded as much. The catalytic converter is relatively easy to locate and connect to the existing components as it is joined by pipe which comes in all shapes and sizes.

OIL SYSTEM – Due to the engine/chassis mismatch, the stock oil pan does not fit. It is too deep, and there is not enough space to raise the engine since it would interfere with the frame. The solution is to redesign the oil pan to make it shallower, while retaining the stock oil capacity.

First, the original pan was cut horizontally in order to keep the footprint that bolts to the engine block and about one inch of the original sides. The new pan is much wider in both directions, yet shallower so it is still able to fit in the chassis. The new oil pan is made from 18 gauge mild steel which was welded to what was left of the stock oil pan after removing the bottom and most of the sides.

The oil pickup needed to be modified as well since it was designed for a deeper pan. This was quite simple as some cross pieces were welded on first to keep the brace and seal in the same relative position. Then about 1 inch was cut out of the pipe, and the pickup end was welded back on.

The one issue with a wider and shallower oil pan is that there is a much higher chance of the pickup sucking air while cornering. This is because there is a lot more room for the oil to slosh about, and the oil level wouldn't be as deep in the first place. To prevent the starving the engine of oil, baffles were put in place to prevent this sloshing of oil. The oil pan was divided into three compartments of equal size, by two dividers perpendicular to the crank. Each divider contained a small hole with a trap door. This door only opens into the middle compartment where the pickup is located. This way when the sled takes a corner, the door on the outside of the corner is closed to the oil cannot leave the middle compartment, while the inside door opens so that the oil flows into the center.

ELECTRIC START SYSTEM – The T-660 includes an electric start system, so this has been kept stock. The only change is that a new mounting bracket needed to be fabricated due to space requirements.

FLEX FUEL MANAGEMENT SYSTEM – In order to make the sled compatible with ethanol, there is an ethanol sensor as well as a piggyback ECU system in place to detect the ethanol content and compensate for it, since the ethanol has a different octane rating and different power output. The sensor is taken from a GM vehicle and is manufactured by Siemens. The sensor outputs an alternating current; with the frequency transmitting the ethanol percentage and the pulse width of the signal transmitting the temperature of the fuel.

This signal then has to go through a frequency to voltage converter before it can be used by the piggyback ECU. Preliminary calculations and trial and error were used to get the correct values for the ranges required. While designing the converter, a signal generator was used to calibrate and verify the signals. The actual sensor was also connected to the converter and known concentrations of ethanol were used to do more calibration and to determine the exact values that we would be using for the piggyback ECU.

The ECU that is being used is a Combustion Management Device (CMD) manufactured by DynoJet Research. This unit was selected for the options and features required. The unit needed to be able to adjust the fuel tables based on the ethanol content, which would be inputted to the unit via a 0-5 V signal. The fuel table are adjusted based on the input signal, and they can be adjusted by +/- 100% of the input signal. There are two ways of controlling the boost, via percentage adjustment like the fuel tables, or it is possible to control boost from an absolute point.

The CMD is very easy to set up. All it requires is the interception of the three fuel injectors, as well as tapping into a few other sensor signals (i.e. TPS, MAP, and RPM). The unit comes with the Master Control Center software for the PC, which can be used to adjust the fuel and boost tables as well as record and view a variety of engine stats, such as RPM, duty cycle %, throttle position %, and boost pressure. Adjusting the fuel and boost tables is as simple as typing a new number into the corresponding box, and clicking another icon to send the new, modified map to the CMD unit via USB cable.

UNDER-COWL THERMAL PROTECTION SYSTEM – The turbocharger attached to the system produces a significant amount of heat when in operation. It is for this reason that any important components be properly shielded from the heat. The exhaust tubes running to and from the turbocharger are all ceramic coated, which helps to keep the heat inside the tubes and keep the gases flowing out of the engine bay. These exhaust pipes will also be covered with heavy duty fiberglass wrap, further ensuring that heat stays inside the tube and does not contribute to heating the engine bay. Lastly, there will be aluminum heat shields to protect from the radiation heat gains. In addition to protecting from heat gains via physical means, there will also be a reasonable air flow through the engine bay when in operation, due to holes in the bodywork (these holes are stock) that allow air to pass through and over the engine, helping to reduce temperatures.

NOISE REDUCTION

EXHAUST SILENCER – Another crucial area in the design of the snowmobile and scoring at the competition is an effective exhaust silencing system. The design that was chosen was an aluminum and stainless steel construction with parts being purchased and fabricated. A custom dual diffuser with side resonator as one unit will be connected to a side absorption silencer. The diffuser works by cancelling sound waves that are travelling in the direction of the pipe as seen below.

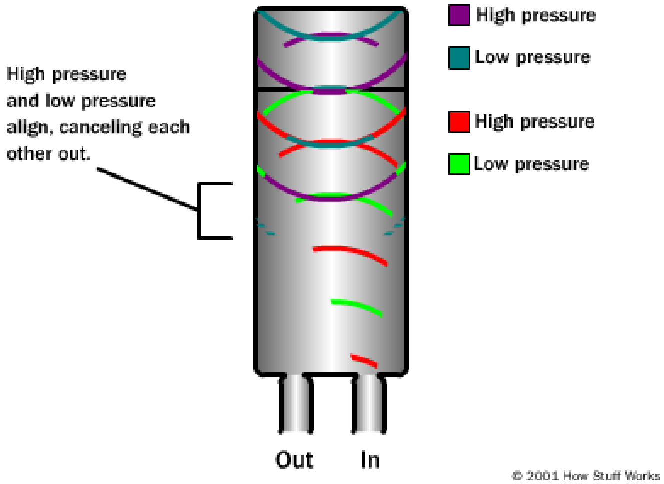

Figure 8: Waves cancelling inside a simplified muffler (3).

The diffuser targets specific frequency zones and this is the reason that a dual diffuser was chosen: to target more than one frequency zone. The side resonator works in a similar manner, except it works on sound waves travelling in the radial direction. The sound zone chosen to focus on is between 50 – 200 Hz. This is based on the firing rate of the cylinders over the engine's rpm range. The figures below shows the variables involved in analyzing the diffuser and side diffuser.

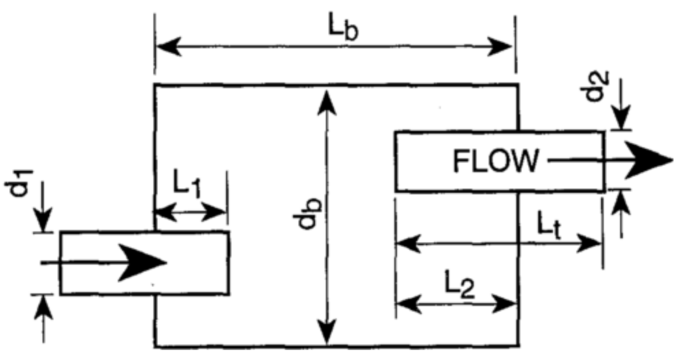

Figure 9: Schematic of a diffuser used in a muffler.

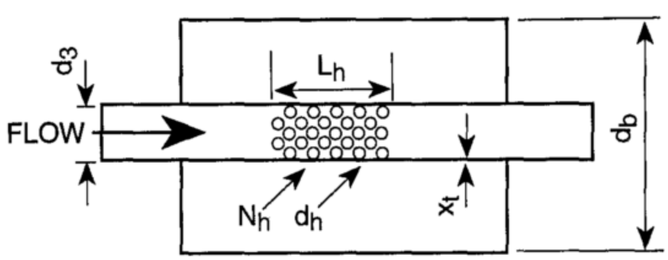

Figure 10: Schematic of a side resonator used in a muffler.

The approach taken was to determine the optimum performance based on the dual diffuser components, and then design the side diffuser to attenuate any missed frequency bands. Anything missed by all three diffusers will be caught by the absorption silencer. The absorption silencer is difficult to analyze, and is omitted from the calculations, but it is known to be effective at absorbing any leftover frequencies.

The results of the total attenuation by the silencer design can be seen below.

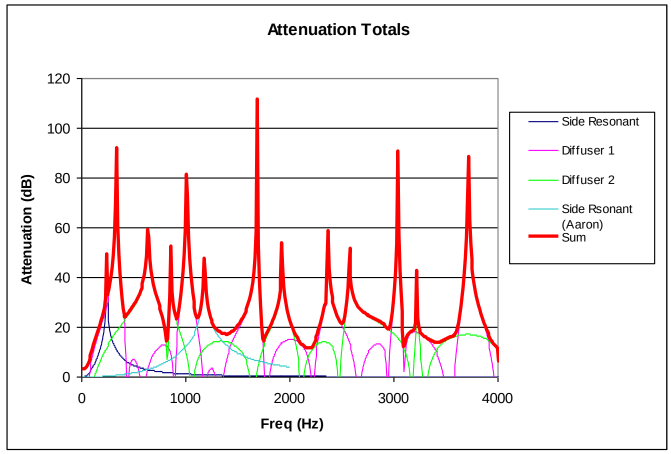

Figure 11: Muffler attenuation capability.

This graph shows what the diffuser is capable of over a range of frequencies. This graph also includes much more than the operating range of the sled (50 – 200 Hz). The below graph shows the expected sound level through the exhaust system if the assumed engine noise is 100 dB at all frequencies.

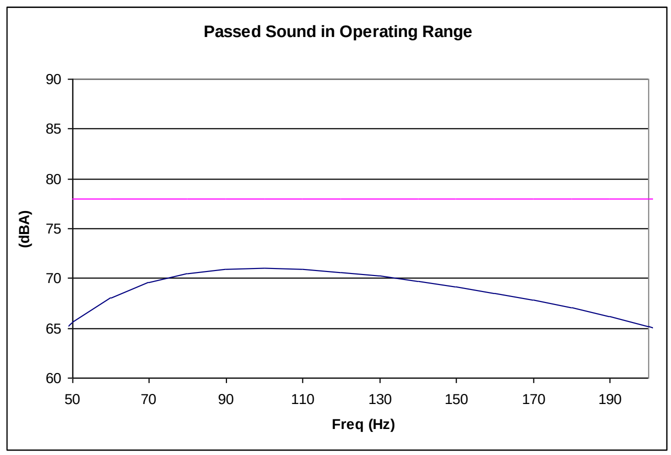

Figure 12: Expected sound level through muffler assuming 100 dB.

The constant line is the competition requirement (78 dB) and the curve is maximum at around 71 dB. This result is excluding the absorption silencer. Based on the analysis, this design adheres strictly to the competition requirements and is also procured in the most cost effective manner (a combination of custom made and purchased parts). The final design can be seen below.

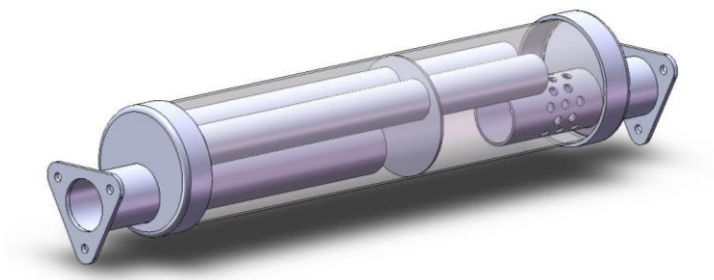

Figure 13: Isometric view of current muffler. Not including absorption silencer.

ENGINE COMPARTMENT SILENCING – Most of the engine compartment silencing comes in the form of insulating foam. It is applied wherever there is room in order to minimize sound coming from the engine compartment.

CONCLUSION

A quiet, clean and efficient snowmobile can still meet the performance requirements of the general public. The UW Clean Snowmobile Team has demonstrated this and has come up with a solution that can be easily implemented and marketed. The biggest solutions to the snowmobile pollution problem can be addressed by switching from a two stroke to a four stroke engine and adding a catalytic converter. Further improvements with regards to pollution can be addressed by converting the snowmobile to run on a gasoline/ethanol blend of fuel. The final product is a snowmobile that hasn't lost performance despite being environmentally responsible.

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CONTACTS

Peter Teertstra
Faculty Advisor
Department of Mechanical
Engineeringpmt@mhtl.uwaterloo.ca

ACKNOWLEDGMENTS

The University of Waterloo Clean Snowmobile Team would like to thank all our sponsors; if not for them this innovative design could not have been possible.

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