University of Waterloo Clean Snowmobile Design Paper

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2009/2010 University of Waterloo Clean Snowmobile Team

ABSTRACT

The University of Waterloo's innovative new internal combustion clean snowmobile provides exceptional performance while reducing harmful atmospheric emissions and overall noise. This innovative snowmobile combines a lightweight Bombardier MXZ chassis with a more environmentally conscious four stroke Yamaha Genesis 120hp engine. The flex fuel variable fuel system, the addition of a catalytic converter and a custom designed exhaust silencer provide emission and noise reduction in conjunction with the nature of the competition.

INTRODUCTION

BACKGROUND – The push for more environmentally friendly snowmobiles began in May of 1997 when environmental groups filed a lawsuit against the National Park Service for failing to comply with environmental regulations regarding Yellowstone National Park and two other national parks [1]. The controversy surrounded the use of snowmobiles within national parks because of their negative effect on air and water quality within those pristine national parks.

In response to these allegations, the National Park Service and the snowmobiling community in general are determined to develop solutions to lower emissions to ensure that snowmobiles may be permitted entrance into these scenic national parks. The strategy is two fold; improve snowmobile engine technology and improve the use of fuels and lubricants [1].

The automobile industry has reduced emissions through two major advancements that can be translated to the snowmobile with relatively low difficulty: the 4-stroke engine and the catalytic converter. These two technologies combined with the newer ethanol flex fuel (E20-E29) requirement outlined by the rules of the 2010 Clean Snowmobile Competition (CSC) provide three significant measures in meeting the goal of reduction in snowmobile emissions.

CHALLENGE – The challenge faced in designing an environmentally friendly snow machine is the competing desire to ensure high performance. As recreational vehicles, snowmobiles are expected to perform to a certain level. Catalytic converters that are used to reduce gaseous emissions and exhaust silencers that are used to reduce noise cause restrictions in the exhaust flow which reduce the overall power of the snowmobile. Therefore, taking a stock snowmobile and installing a catalytic converter and an exhaust silencer is not a satisfactory design choice, as a large drop in performance would be witnessed. Additional measures must be taken to ensure that the rated performance does not decrease to make the snowmobile attractive to potential consumers. The challenge lies in the apparent inverse ratio between high performance and low emissions and noise.

DESIGN STRATEGY – The design philosophy engraved in the minds of the design team of the UW clean snowmobile is to maximize performance while ensuring a reduction in both emissions and noise while meeting the rules set for the 2010 CSC. This philosophy is grounded in the decision to combine a lightweight chassis from a two-stroke snowmobile and replace the engine with a larger, more environmentally friendly, four-stroke engine. From this strategy stems the resolution to include custom intake and exhaust manifolds with switching the originally carbureted system to fuel injected to increase fuel efficiency and to minimize any power loss due to flow restrictions that may result from the addition of a catalytic converter and exhaust silencer.

The strategy also forces evaluation of components with their applicability to a flex fuel snowmobile. This flex fuel requirement would require a new fuel system, a programmable engine control unit with a ethanol flex fuel sensor, and a cold start system capable of starting the engine with a relatively low blend of ethanol fuel.

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 main selection criteria considered during chassis selection was low weight and cost. Selecting from the available chassis in the region, the chassis from the 2005 two-stroke Bombardier MXZ was selected as the most effective in terms of cost and weight. The MXZ chassis also provides an aggressive style that complements the strategy followed by the UW design team. The overall chassis is shown in Figure 1 below.

Figure 1: 2005 Bombardier MXZ chassis

ENIGINE – The Bombardier MXZ chassis is normally equipped with a two-stroke 600cc engine. The two stroke engine provides a better power to weight ratio because it completes the thermodynamic cycle every two strokes rather than every four strokes as in a four stroke engine. However, this comes at the cost of higher emissions because lubrication oil is mixed with the fuel and goes unburned during the combustion process [2]. Therefore, in an effort to reduce emissions, the design team opted for a four-stroke engine. However, this reduction in emissions comes at the cost of reduced power for a similar displacement engine. Thus, in order to preserve the power obtained from the two-stroke 600cc engine, the design team decided on a high displacement four stroke engine that was below the 130HP limit based on the CSC 2010 rules.

The three-cylinder Yamaha Genesis 120 engine as shown in Figure 2 was selected as the most effective higher displacement four stroke engine (973cc) available on the market. This double overhead cam 12-valve engine is light, narrow, and has a low centre of gravity which centralizes the weight closer to the centre of the chassis for improved handling [3]. Its conservative specific output of 120 hp also provides excellent fuel economy and a broad and flat torque curve ideal for touring sleds [4].

Figure 2: 2006 Yamaha Genesis 120 engine

Mounting – The large four-stroke Yamaha engine in a MXZ chassis made for a two-stroke engine made engine mounting a challenge. The engine was mounted as low and far back as possible for two reasons: allow space for other required components and centralize the weight of the engine for better handling. A single mounting plate was designed for the right side of the chassis whereas two plates were used to mount the engine on the left side to avoid interfering with the continuously variable transmission.

FUEL INJECTION SYSTEM – The Yamaha Genesis120 engine selected for the UW clean snowmobile is used in conjunction with a carbureted system. Carbureted systems are relatively cheap and simple to design, however, they do not provide good control of the air to fuel ratio when compared to a fuel injected system. A fuel injected system provides lower emissions through two methods: the capability to precisely control the amount of fuel injected (which in turn provides cleaner burning of the fuel), and optimizes the effectiveness of the catalytic converter by allowing more accurate control of the oxygen concentration in the exhaust gas [5].

The challenge in implementing a fuel injection system for the Yamaha Genesis 120 engine was the lack of industry available kits. Therefore, an innovative intake air and semi-direct injection system was designed, developed and fabricated for purposes of the 2010 CSC.

Intake Air System - Over the course of the development of the snowmobile, there was a redesign of the intake system. Originally, the design of the intake system included three throttle bodies that were acquired from a

1991 Polaris snowmobile. The purpose of utilizing a throttle body for each engine cylinder was to enhance the engine response with throttle changes. This would improve the acceleration and overall performance of the snowmobile. The original intake system design was modeled using SolidWorks and is illustrated in Figure 3 below.

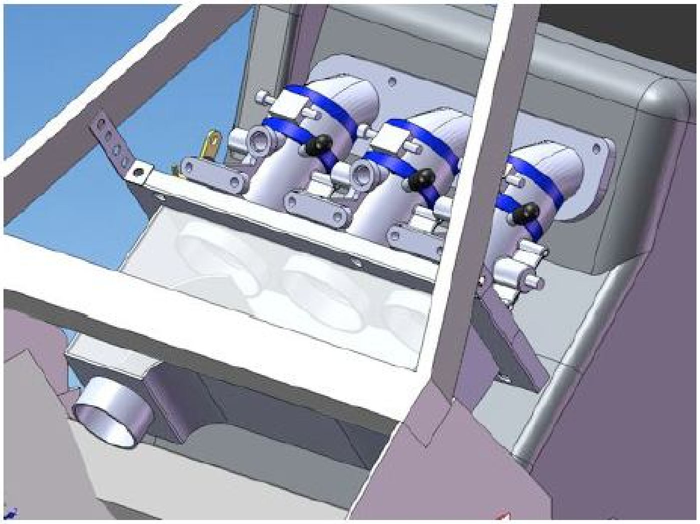

Figure 3: Original intake air system design

Due to a potential safety concern of the throttle body linkage, which connected and controlled all three throttle bodies, a new design was formulated to meet the design constraint of ensuring the safety of the rider. The new design incorporates an intake flange with integrated fuel injection ports that are orientated to allow for semi-direct fuel injection into the engine intake ports. The original design consisted of utilizing the existing fuel injector ports on the throttle bodies, which were not orientated in such a way to allow for semi-direct injection. The new design will allow for increased fuel economy and overall performance compared to the original design. The new intake system design is illustrated in Figure 4 below.

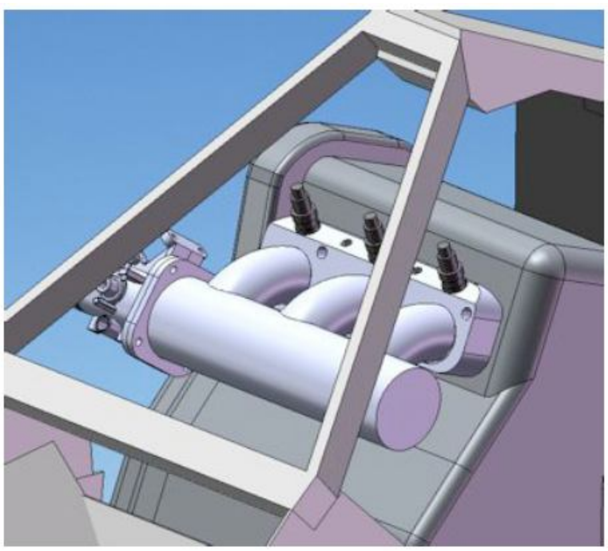

Figure 4: New intake air system design

The new design includes only one of the three throttle bodies to control the flow of air into the engine. This change will reduce the engine response compared to the original design, however the potential safety concern of the throttle linkage binding is avoided and the overall size of the assembly is reduced. The plenum size has also been reduced slightly in respect to the original design to further reduce the overall size of the assembly.

This size reduction greatly aids in providing space for adjacent designs, as the available space on the snowmobile chassis is minimal due to the integration of the large Yamaha engine. The air intake volume capacity is 1.58L for the 973cc engine, which is slightly above the minimum recommended for this application. The flow of the air through the plenum was modeled using ANSYS. The results of the CFD analysis are illustrated in the following images labeled Figure 5 and Figure 6.

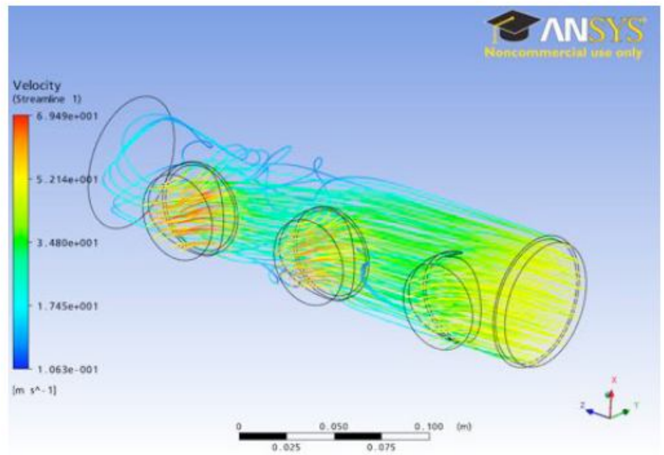

Figure 5: Isometric view of velocity stream profiles in custom plenum

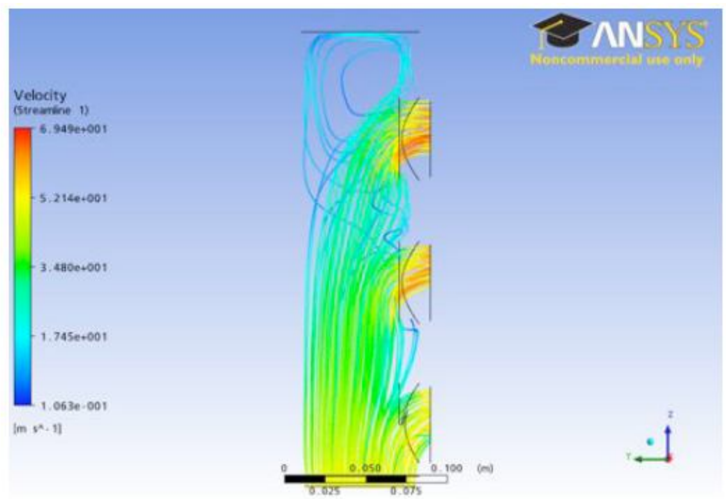

Figure 6: Velocity stream profile at plenum entrance and exits

The CFD analysis initially illustrated that the flow of air to the runner adjacent to the plenum intake port received minimal air. The configuration of the runner was adjusted to help capture more air into this port to create a more uniform flow distribution between the three runner ports.

As a result, the CFD analysis illustrated in Figure 5 and Figure 6 above demonstrates a large improvement in flow distribution and thus the fabricated intake system has included this modification. Figure 7 below shows the as machined plenum, the as fabricated engine intake flange and the complete as welded assembly.

Figure 7: As-welded final air intake assembly with fuel rail mounted

To further improve the performance, a 3 bar manifold absolute pressure (MAP) sensor was installed. This sensor provides the ECU with air densities so that airflow rates into the engine can be calculated and correlated to the necessary amount of fuel to be injected.

FUEL INJECTION SYSTEM – The fuel injection system makes use of three 59 lbs/hr @ 60 psi fuel injectors and a peak and hold driver in order to better control the pulse width and response time of the injectors. These injectors are mounted to the engine intake flange at an angle allowing for semi-direct fuel injection. Semi-direct fuel injection was preferred for two reasons [5]. Firstly, it allows for more precise control over fuel metering and injection timing, which in turn improves fuel economy. Secondly, the location of the injector produces an optimal spray pattern, where larger shear forces act on the fuel droplets increasing atomization, resulting in better combustion of the fuel. This has the benefit of reducing emissions and increasing power per unit of fuel. Fuel is fed to the injectors through a custom designed fuel rail made from aluminum and coated for protection against ethanol-induced corrosion. The fuel injection system is shown in Figure 8 below.

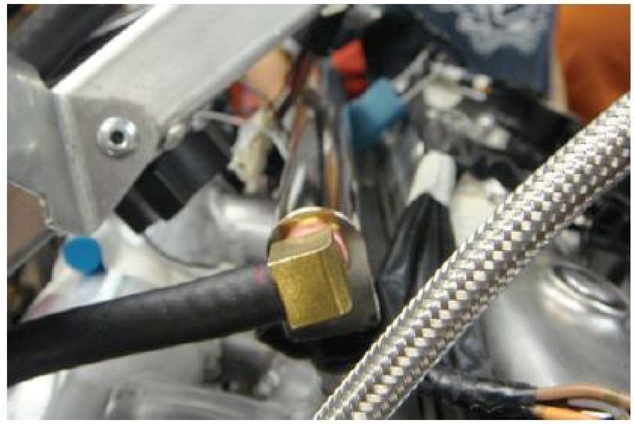

Figure 8: Fuel injection system (looking down fuel rail)

EXHAUST HEADER – The stock exhaust system which goes with the Genesis 120 motor is designed to route directly under the gas tank and seat. However, the 2005 Bombardier MXZ was not designed for this and so it was not possible to reuse the stock Yamaha exhaust header. A new tuned, equal length header and downpipe were designed to route exhaust beside to the engine and through the bottom of the sled as shown in Figure 9. Additional models of the manifold can be seen in Figure 10 and Figure 11.

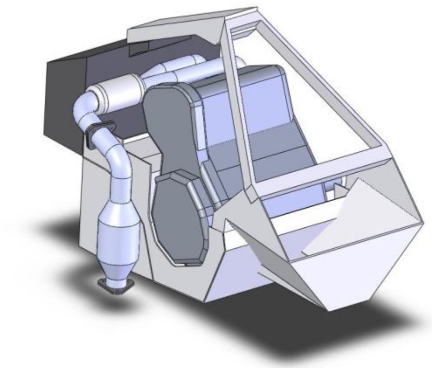

Figure 9: Exhaust Routing Through Bottom of Sled

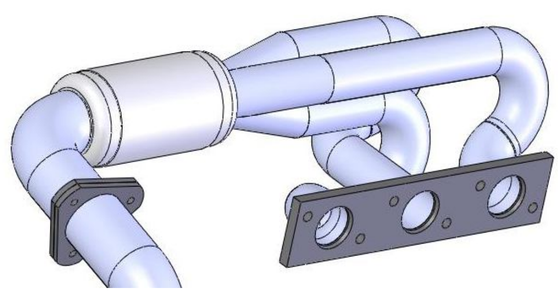

Figure 10: Exhaust Manifold Model Front

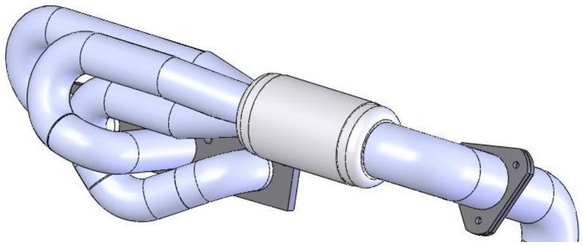

Figure 11: Exhaust Manifold Model Rear

Background - When the exhaust valves open, pressure pulses are created in the pipe with a high pressure head and low pressure tail. Travelling at the speed of sound, these pulses reach the collector and are reflected back up the pipe towards the engine. Ideally, the negative pressure pulses reach the head just as the exhaust valves reopen. This helps evacuate the cylinder, and create vacuum to draw in fresh air and fuel. As engine speed changes, the amount of time between exhaust pulses changes. Since the speed of sound in the exhaust gas is fairly constant, the pipe length directly affects how long the pressure pulses take to return to the head. Therefore, the manifold must be designed to optimize the timing of exhaust pressure pulses (and therefore torque) at a particular engine speed [6].

Unfortunately, the exhaust gas properties needed to calculate the proper pipe dimensions are quite difficult to obtain. Since the Genesis 120 motor already has good torque/power curves and both stock Vector clutches are being used, it was decided that Yamaha's stock pipe dimensions would be kept. The stock Yamaha exhaust header had pipe lengths of about 17.75" and internal diameter of about 1.375" so these were the targets for the new pipes. Equal pipe lengths mean that exhaust gas pulses will reach the collector at evenly spaced intervals. This minimizes interference of the pulses which can result in increased backpressure. It will also result in a smooth exhaust sound since combustion noises will leave the exhaust pipe and be heard at even intervals.

The stock MXZ exhaust exited the front of engine far away from the fuel tank. However, due to the design of the Genesis 120 motor, the exhaust must exit towards the fuel tank. To maximize rider safety, the header was designed to give at least 2" of clearance around the fuel tank to permit installation of heat shielding (Figure 12). It is also wrapped with heavy duty fiberglass exhaust wrap.

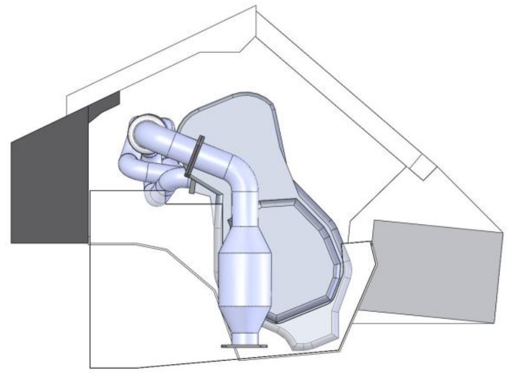

Figure 12: Side View of Engine Compartment Showing Exhaust Clearance

For construction of the header, T304 Stainless steel was chosen for its fairly light weight, availability, and resistance to corrosion.

CATALYTIC CONVERTER – The purpose of installing a catalytic converter on the UW clean snowmobile is to reduce emissions of carbon monoxide, unburned hydrocarbons and nitrogen oxides. This is accomplished through a reduction catalyst and an oxidation catalyst.

Sizing - Catalytic converters are generally not found on snowmobiles because they are not governed by the same regulations as automobiles. This generates a challenge in sizing catalytic converters for snowmobiles. Catalytic converters in automobiles are sized based on weight and engine power among other variables. The snowmobile weight (being much less than that of automobiles) results in standard sizing methods not being applicable. The challenge is therefore sizing a catalytic converter that will provide an optimal reduction in emissions while ensuring as little flow restriction as possible to minimize a loss in performance. To overcome this challenge, three selection criteria were outlined to determine the most effective catalytic converter for this particular application:

- Minimal spatial volume requirement.
- Maximum rated effectiveness of catalyst.
- Sized for automobile with similar exhaust flow rate.

The catalytic converter which best meets these criteria is a Vibrant Performance Universal High Flow Ceramic Core Catalytic Converter. They are designed to increase horsepower by reducing back-pressure while still meeting all E.P.A. and C.A.R.B. emissions control requirements. Vibrant's High Flow Cat (HFC) increases flow capacity and allows the engine to perform better with less restrictions. This particular HFC utilizes a honeycomb design to induce turbulent flow and allow for more chemical reactions. The flow rate can be increased either by increasing the overall cross section of the honeycomb or widening the passages. Vibrant's HFC does not sacrifice effectiveness for greater efficiency or performance, making it the ideal candidate for this snow mobile application.

OIL SYSTEM - The Yamaha engine's oil system comes factory configured as a dry sump system, which allows for lower engine placement (i.e. lower centre of gravity), cooler oil operating temperatures, less oil starvation and less crank losses due to viscous drag from oil churning when compared to a wet sump configuration. Combined, each of these advantages translate into greater overall performance and efficiency, which is why dry sump oil systems are used for most high performance applications.

Due to size and location constraints in the snowmobile, the original OEM tank could not be used in this setup. Also, improvements to the OEM tank were desired. The previous oil system did not have an oil/air separation mechanism and it also vented crankcase hydrocarbons to the atmosphere. This results in the storage of emulsified blow-by vapors in the engine oil and harmful hydrocarbon emissions. During an engine's compression stoke, a small amount of gases from the combustion chamber escape past the pistons [7]. These blow-by vapors end up in the engine's crankcase and contain moisture as well as combustion by-products and unburned fuel vapors, approximately 70% unburned fuel [7].

In order to address the crankcase ventilation issue, a positive crankcase ventilation (PCV) system was utilized, which uses the vacuum pressure of the pressure difference between the crankcase and the intake manifold to route the vapors into the intake manifold here they can be re-burned in the engine [8], rather than venting the vapors to the atmosphere. However, some blow-by vapors still get emulsified in the engine oil which can lead to sludge formation.

The emulsification of air into oil was dealt with by incorporating an oil/air separator into the dry sump oil tank design which, in theory, greatly increases the proportion of blow-by vapors that are vented to the intake manifold for re-combustion, resulting in greater fuel efficiency and an overall reduction in unburned hydrocarbon emissions. In order to separate vapors from engine oil, oil flowing into the oil tank first enters a cylindrical shaped inner surface. Shown below in Figure 13, the oil flow tangent to the separator wall at high velocity, thus creating a centrifugal action as it flows around and downwards. The centrifugal action increases the effective force of gravity and thus the buoyancy forces which greatly increases the rate of separation of emulsified vapors from the more dense liquid oil. As the vapors separate from engine oil, they rise to the top of the tank and are vented back to the intake manifold for re-combustion.

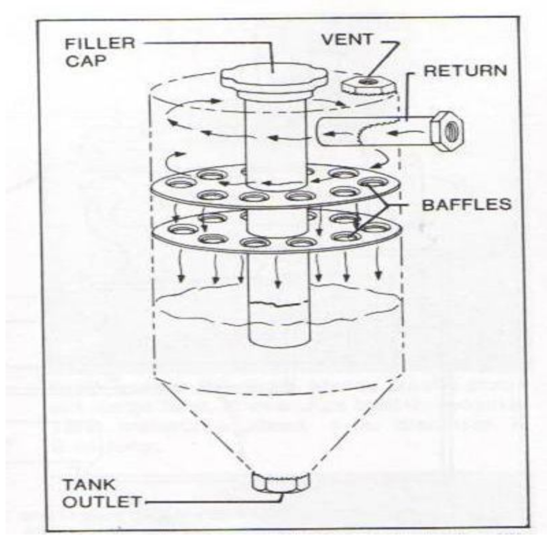

Figure 13: Air / Oil Separation Tank Diagram [9]

ELECTRIC START SYSTEM – The electric start design was one of many phases. During preliminary design, a simple electric start system was chosen over more complex options. The chosen design included: a single absorbed glass mat (AGM) battery, a voltage regulator in order to regulate the recharge voltage to the battery, and diodes to rectify the AC signal to the battery and convert it into DC. Both the diodes and regulator were supplied with the engine and did not need to be redesigned for the sled. Prior to battery type selection for the preliminary design, a technological analysis was completed on existing battery technology. This analysis showed that an AGM battery was the best option for the team, due to its low maintenance, high power density and solid-state operation. An AGM battery will not leak, even if broken and because they are immune to freezing damage, as they contain no liquid. For an environmentally clean snowmobile the sealed nature of the battery is a plus as it is non hazardous and allows for mounting in any position. Furthermore, AGM batteries have a very low self-discharge (approximately 1 to 3 % per month) and as such can sit in storage for long periods without charging. AGM batteries can also withstand shock and vibration better than any standard battery.

The electrical analysis revealed that the highest possible current draw from the electric start system would be 159A while the regular steady state current draw was 31.7A. The supply current from the magneto was tested to be 35A, meaning that enough power is produced by the magneto in order to meet all of the ‘grid’ power needs. The current draw over a range of RPM is shown in Figure 12 below.

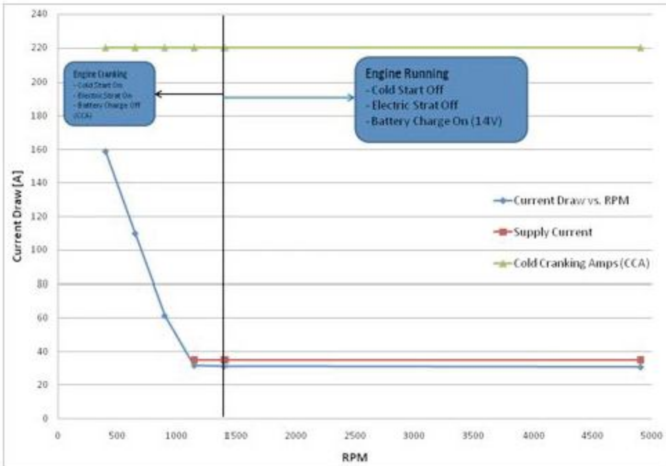

Figure 12: Current draw of electrical system

Based on the electrical analysis and experience obtained through previous competition the Exide Select Orbital (Part #: ORB78DT-84) was chosen for use in the team's sled. The Exide Select Orbital is a 12 Volt, Absorbed Glass Mat (AGM) battery. The Exide Select Orbital's 770 cold cranking amps, 3-5 second rating and relatively low price made it a superior choice when compared to other similar batteries on the market. An image of the battery can be seen below in Figure 14.

Figure 14: Exide Select Orbital Battery

In terms of mounting the battery to the sled, a box had to be manufactured to meet the SAE regulations. The regulations state that the battery, regardless of type, must be sealed in a vented, non-conductive box. The design materials selected were Polycarbonate sheet and Aluminum. Polycarbonate sheet was selected due to its toughness, machinability, and desired operating temperature range. Pull down catches were used to secure the lid instead of screws as the catches allow for easy access to the battery, which is desirable during competition. Aluminum sheet metal was used as a shroud for the Polycarbonate box to provide support against lateral loading. Figure 15 below shows a 3D model of the final design used on the team's sled.

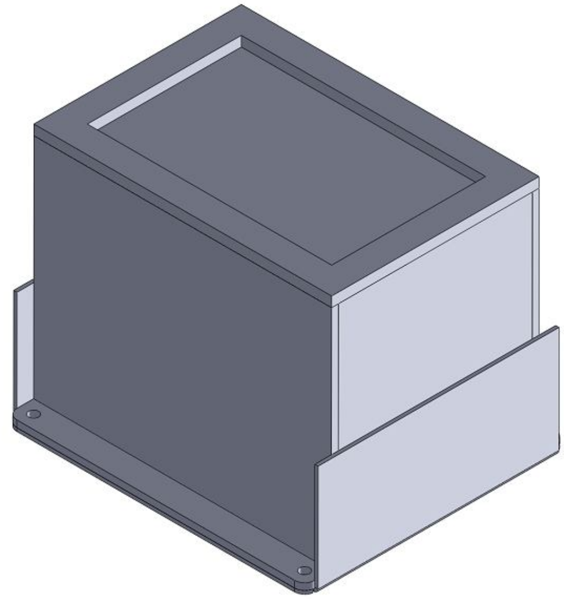

Figure 15: Battery Box Final Design

COLD START SYSTEM – The purpose of the flex fuel cold start system is to improve the rate of fuel vaporization to enable cold start of a range of ethanol blend from E20-E29 within 20 seconds, and enable the snowmobile to move 100 feet within 120 seconds without stalling as per the SAE CSC 2010 rules.

Background - Combustion requires that the fuel be atomized and mixed with combustion air. Forcing fuel through a small opening and under high pressure breaks the fuel into a fine mist, which results in fuel atomization. When the engine is cold, the compression stroke and addition of a spark may not be enough to raise the temperature of the air to the point where the air-fuel mixture is ignited. The fuel injector serves to atomize the fuel into small droplets, and when atomized fuel comes into contact with warm enough air, the fuel instantly vaporizes. [2]

The combustion of ethanol can then be improved through two separate methods; improving fuel atomization and increasing the rate of vaporization. Good atomization requires high fuel pressure in the injector, small injector hole size, optimum fuel viscosity and high cylinder pressure. The rate of vaporization of the fuel is then dependent on fuel droplet diameter, velocity and volatility, as well as combustion air temperature and pressure. Good atomization leads to very small droplets with large surface area, which promotes energy transfer during combustion, however, it also promotes heat loss to the surroundings during injection.

Normal operation of the engine results in two heat inputs and two heat losses. During the compression stroke of the engine, the air within the compression chamber is pressurized resulting in an increase in temperature. A spark is then produced to provide additional heat input and ignite the air-fuel mixture. The air-fuel mixture during start-up is at ambient temperature conditions and thus reduces the heat input to the process. The engine block of the Yamaha Genesis 120 is an aluminum electroplated ceramic composite material with a designed purpose of removing heat from the combustion chamber during regular operation [4].

Based on the variables that can effectively and easily be changed to improve fuel atomization and the rate of vaporization, increasing the temperature of the air-fuel mixture is the most attractive solution. This design complies with the design criteria and constraints by ensuring maximum performance while ensuring the safety of the rider.

Design – The solution to cold start a variable ethanol blend internal combustion engine borrows from the concept of combustion air pre-heating used by large diesel engines. Tests conducted by the Ford Motor Company demonstrate that a flex fuel vehicle operating with a winter blend E85 (equivalent to an E70) is capable of cranking over in 4 seconds at a temperature of -10˚F [10]. The record low for Houghton, Michigan, in the month of March is -23˚F [11]. Therefore, combustion air at ambient temperature would have to be raised by 13˚F in order for engine starting to occur. Allowing for a safety factor of 2.0 for possible differences between fuel temperature and composition, engine capability and heater accuracy, a total temperature change of 26˚F in 10 seconds is required to ensure engine cranking within the allowable 20 seconds specified by the 2010 CSC rules. This logic is based on using an E70 blend where in fact only an E20-E29 blend will be used. The lower percent of ethanol will only increase the factor of safety for a more reliable cold start.

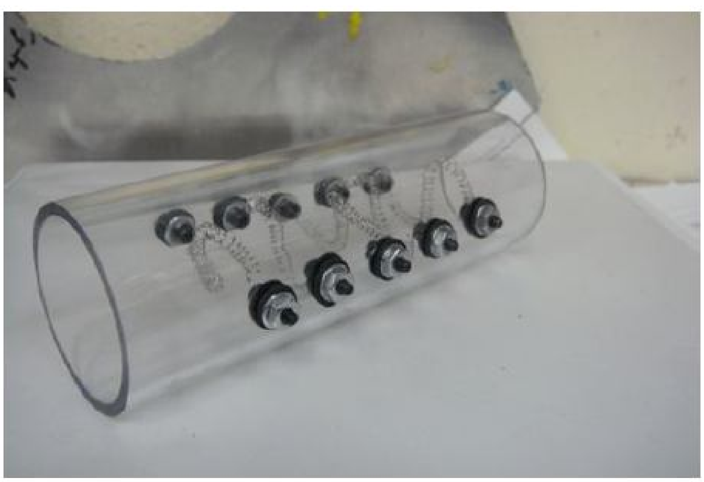

Figure 16: Flex fuel cold start system

The final cold start system design, shown in Figure 16 above, has at its heart a 2” polycarbonate tube located after the intercooler and prior to the main throttle body in order to minimize heat loss to the surroundings. Within this tube, five coiled in-flow Nichrome wires dissipate a total of 215 Watts of heating energy, providing a combustion air temperature increase of approximately 2.6˚F/s during engine cranking at 500 rpm based on feasibility of design testing. The Nichrome wires are connected in parallel to the battery and are limited to 20 seconds of operation through the use of a one-shot normally open contact timed relay.

FLEX FUEL MANAGEMENT SYSTEM – The requirement for flex fuel compatibility and the use of variable boost control to alter the compression ratio based on fuel ethanol content requires a new method to control process variables. The flex fuel management system designed for the UW snowmobile is one such method and combines a programmable engine control unit (ECU) with a flex fuel sensor and ethanol compatible fuel pumps and lines.

Programmable Engine Control Unit – The modifications made to the snowmobiles fuel distribution system and the variability in the fuel type requires the use of an aftermarket ECU to manage the fuel injection system. The team has opted to use the S60 Pro ECU from DTA FAST. This ECU has extensive capabilities such as comprehensive start up fuelling options that are time and temperature dependent as well as air, coolant and manifold pressure compensation maps. In addition, it logs extensive engine run time data at different load and speed conditions providing an effective method for tuning the engine to enhance performance and reduce emissions.

Flex Fuel Sensor – A flex fuel sensor is needed to exploit the capabilities of the ECU in terms of effectively managing the fuel injection system based on the ethanol content of the fuel. The selected sensor is compatible with the ECU and is used in General Motors flex fuel vehicles. The sensor operates by measuring the conductivity, temperature and the dielectric constant of the fuel and sends a duty cycle to the ECU. The frequency of the signal increases as the ethanol content increase. In order to insure an accurate reading, the sensor is mounted as close to the injectors as possible so as to measure as precisely as possible the content of the fuel that is being injected. The mounting of the sensor is shown in Figure 17 below.

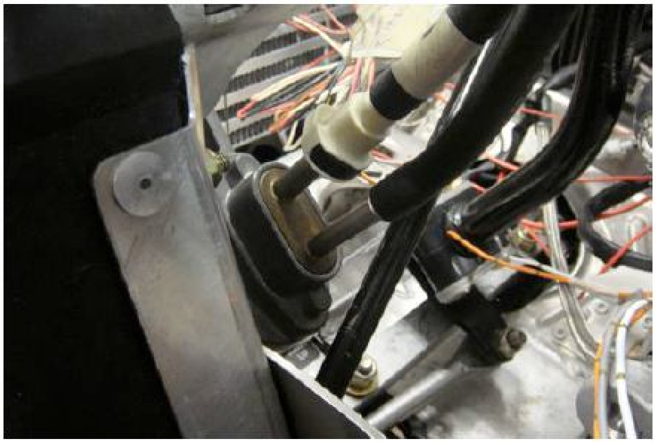

Figure 17: Flex fuel sensor mounted in location

Fuel Pump and Line Modifications – In order to ensure compatibility of the fuel management system with an ethanol fuel blend, testing and component modifications were undertaken. The first modification was to upgrade the high pressure electric fuel pump from the stock pump to an ACCEL 75706 in tank fuel pump in order to ensure compatibility with E85 fuel and in order to fulfill fuel flow requirements. Secondly, the fuel tank, o-rings, rubber gaskets and other components of the fuel management system were tested for E85 compatibility. The test consisted of submerging samples from each component in E85 for 15 days, followed by a comparison of the weight and surface appearance. No change in weight or surface appearance was observed; therefore no preventative measures were taken. The final system is shown in Figure 18 below.

Figure 18: Fuel pump and regulator installation locations

UNDER-COWL THERMAL PROTECTION SYSTEM - Due to the installation of a catalytic converter within the engine compartment and the larger engine, the running temperatures beneath the cowl are expected to be significantly higher than those experienced using stock components. Also, with the installation of a four-stroke engine, exhaust gases now exit to the rear of the engine rather than forward of it. The problem with this configuration lies in the fact that the plastic fuel tank is in close proximity to the exhaust side of the engine and that the turbocharger is installed roughly between the engine and the fuel tank.

A low estimate of the heat output from the exhaust pipes alone is roughly 4 kW. This value is based on an expected surface-to-air temperature difference of 280ºC. Naturally, as the engine and its components heat up, so will the cowl air. Additionally, at elevated temperatures such as those experienced by the exhaust manifold, radiant heat will become a problem. In close vicinity of the engine, there exist a number of plastic or rubber components, including hoses, wires, and the fuel tank. These will require thermal protection in order to avoid softening or melting. Thus, it is necessary to implement some means of reducing the effects of both convective and radiant heat transfer within the cowl.

In order to deal with convective heat transfer, several components will be utilized. The exhaust pipes and catalytic converter are to be wrapped using heavy-duty fiberglass exhaust wrapping. This will help to reduce heat transfer into the cowl air. A large intake fan, rated at 1500 CFM (0.708 m#/s), is already located at the front of the cowl for forcing air through the external cooling radiator.

The resultant airflow will be directed over the hot surfaces by means of shrouds. Most of the shrouds will be constructed of sheet aluminum; however the portion nearest to the fuel tank will be light gauge stainless steel. The shrouds will also act as radiant heat shields, and all hoses and wires will be kept behind them to prevent softening. The steel portion will be backed with fiberglass insulation, and will protect not only the fuel tank, but fuel lines and fuel pump as well. Finally, the fuel tank surface itself has been covered with a reflective coating to further protect against radiant heat.

Based on heat transfer calculations and assuming fuel and outside air temperatures of 0ºC, this thermal protection system is expected to maintain the fuel tank surface at a very safe temperature of about 3ºC. The temperatures of other sensitive surfaces such as hoses and wires will also be kept at similarly safe levels.

Figure 19 and Figure 20 below illustrate the effects of time and airflow (respectively) on cowl temperature. These plots do not take into account the fact that the engine and its components take some time to reach running temperature; instead they assume a constant heat output from hot surfaces. This can be noted from the very short time interval required for the cowl air to reach steady-state temperature. Note that the fans will not be running during cold start, as the cowl air temperature will be much lower than the thermostat set value. Also note that Figure 18 assumes an airflow of 750 CFM rather than 1550 CFM. This is to allow for flow obstructions due to large engine components. The steady-state cowl air temperature at this airflow is approximately 13ºC (286K).

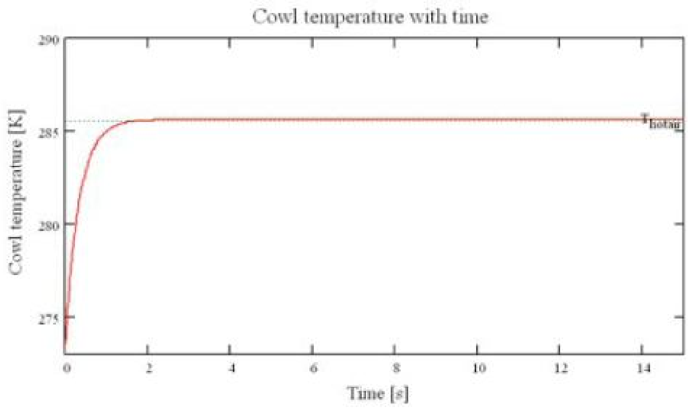

Figure 19: Cowl temperature with time (at constant airflow)

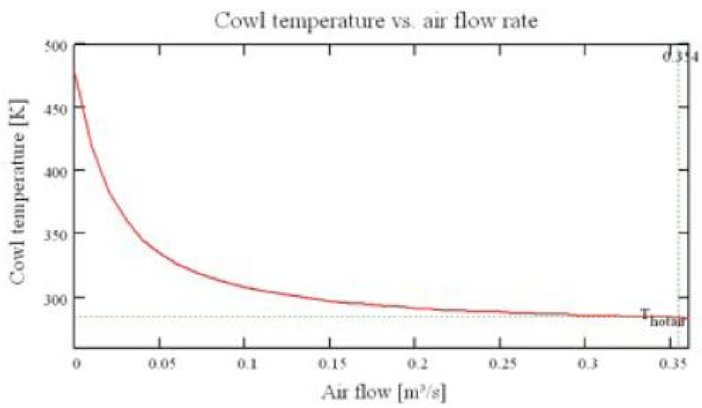

Figure 20: Cowl temperature vs. airflow rate

EXTERNAL COOLING SYSTEM – The purpose of the external cooling system is to provide auxiliary cooling of the engine via an added water-to-air cooler when snow conditions are such that the stock cooling system is no longer effective at providing the required level of cooling capacity. Without the auxiliary cooler, engine cooling is provided by two coolers located within the tunnel of the snowmobile; one of which is located at the front of the track, and the other which runs the length of the tunnel above the snowmobile track. These coolers function as water-to-water coolers, as the track rotates snow is thrown up from the track onto these coolers. The melting action of this snow transfers heat from the coolers to the snow/melt water and cools the engine. As these coolers are dependent on snow as a cooling medium, there are circumstances when the cooling system in its stock configuration may become insufficient due to a lack of snow cover:

- When travelling across a lake
- After a period of freezing rain, when a crust of ice has formed over the snow
- After a melt, which also causes a crust of ice to form over the snow.

By adding an additional water-to-air cooler, which is not dependant on the availability of snow, cooling capacity can be maintained even when snow conditions are unfavorable.

Placement and Configuration – It was determined that the auxiliary cooler would be placed at the front of the engine compartment. This position was chosen because of available space and available air flow through the opening in the nose of the snowmobile. The auxiliary cooler is connected in series with the stock coolers in the cooling loop as shown in the system schematic. A shroud is used to direct air through the cooler and a cooling fan is used to assist in providing the necessary air volume.

Sizing – The selected water-to-air cooler is a double tube bank type radiator with core dimensions 240mm x 195 mm x 30 mm (Length x Height x Thickness). This radiator was chosen because it was the largest cooler readily available which would fit in the available space and should therefore provide the greatest cooling capacity.

Cooling Fan – A Spal VA07-AP12/CWP-58A 12V 9” low profile, puller type fan is used to provide air flow through the water-to-air cooler. This fan also provides some air cooling to the engine.

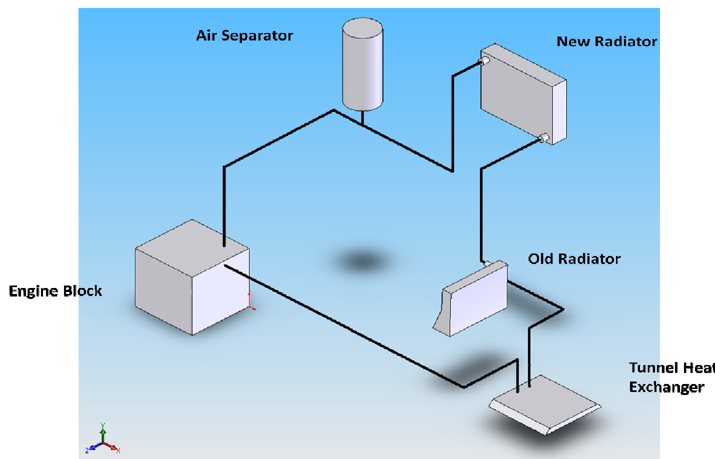

Figure 21: Engine Cooling Diagram

PYRAMID SUPPORT STRUCTURE RE-DESIGN – The use of the 2006 Yamaha Genesis 120 973 cc 4-stroke engine and fuel injection system, coupled with the 2005 Bombardier Ski-Doo MXZ chassis (built for carbureted 2-stroke engine) resulted in a loss of space under the hood. This necessitated the redesign of the pyramid frame support. The support was designed to prevent the rising of the pyramid structure during riding. It was designed to prevent the pyramid structure from moving upward upon application of forces at the skis and the track.

Due to the fact that the new engine displaces a larger volume than the stock engine in the chassis, the redesign was to incorporate these new dimensions while avoiding the plumbing for the turbo system on one side of the engine and mounting to the existing engine mounts on either side.

The stock pyramidal support was bench-marked in terms of strength in order to ensure that the new design would meet and/or exceed said strength. In doing so, the existing support was modeled in Solid Edge. Figure 22 depicts the actual support and the modeled.

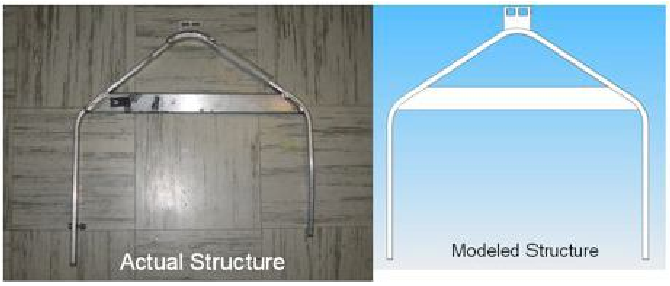

Figure 22: Actual and modeled structures – pyramidal

Measurements of the actual structure were taken to ensure that the modeled structure represented the actual. It was assumed that the welds on the actual structure were of sufficient quality such that they were equal in strength to the base material. The base material was assumed to be 6061-T6 aluminum. It is known that the material was in fact aluminum; however, the exact composition was not known. The assumption made was valid as the model was only to serve as a baseline qualification of the strength of the geometry. In performing the redesign of the pyramidal support, the material used was again 6061-T6 aluminum. In doing so, the strength of the material is affectively negated and the relative strength of the geometry of the structures was compared. The final structure will be formed for 6061-T6 and as such, the assumption will be valid as long as the composition of the existing structure is not an aluminum alloy with a greater strength than that of 6061-T6 aluminum.

The stock pyramidal support was analyzed using Finite Element Analysis (FEA). The material chosen was the aforementioned 6061-T6 aluminum. This grade of aluminum has a tensile strength of 37 ksi. The support was loaded in tension due to the fact that this is the loading experienced by the support when in service. The support was equally loaded on each of the legs and the upper mounting through hole was used as the constraint.

Since the actual load force was not known; successive loads were applied to the modeled structure until yielding was observed. The yielding load was determined as the load which caused the stress experienced by a portion of the structure to increase until the said stress was close to the yielding stress. A safety factor of two was utilized in the investigation. The total yielding load was determined to be 1000 lbf as evidenced by Figure 23 below.

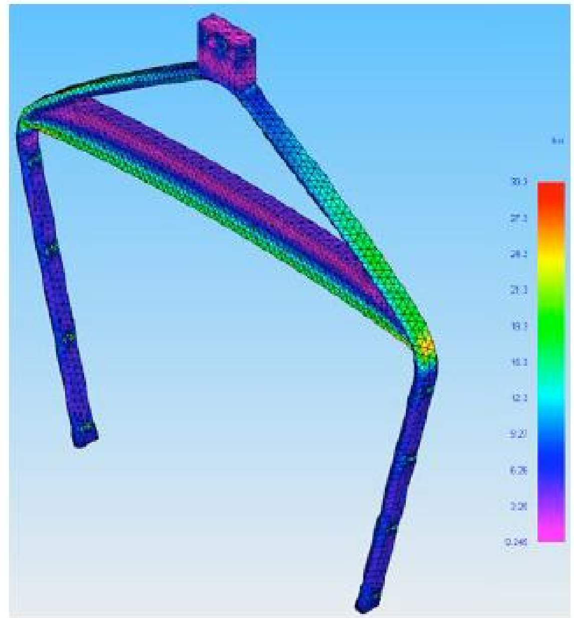

Figure 23: Modeled existing pyramidal support – isometric view

The mesh used to analyze the part was reduced in size upon each subsequent running of the analysis. The maximum stress determined at each mesh size was recorded and the yielding force was obtained when a change in mesh size no longer meant an increase in observed maximum stress. Thus, it was concluded that the stock pyramidal support could be subjected to a maximum tensile load of 1000 lbf equally distributed between the two legs.

With the baseline established, a new pyramid support which maintained the required strength and had the required geometry was designed. This may be observed in Figure 24 below.

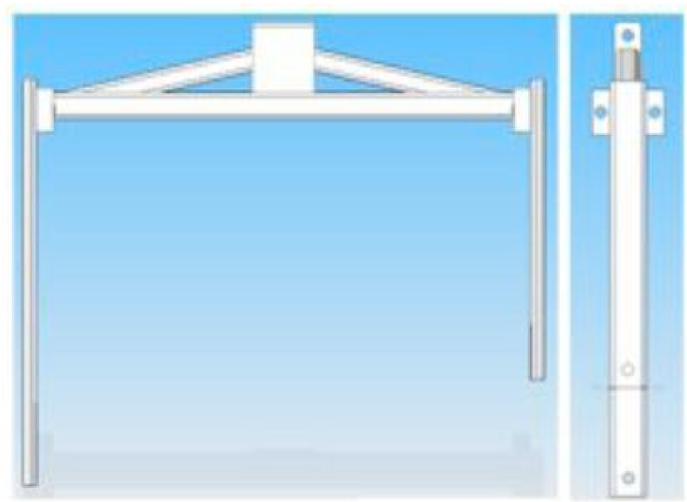

Figure 24: Pyramidal support new design – front and side views

FEA was conducted on the new design using the aforementioned tensile load of 1000 lbf (distributed evenly at 500 lbf per leg). This support was analyzed using FEA and the results are viewed below in Figure 25.

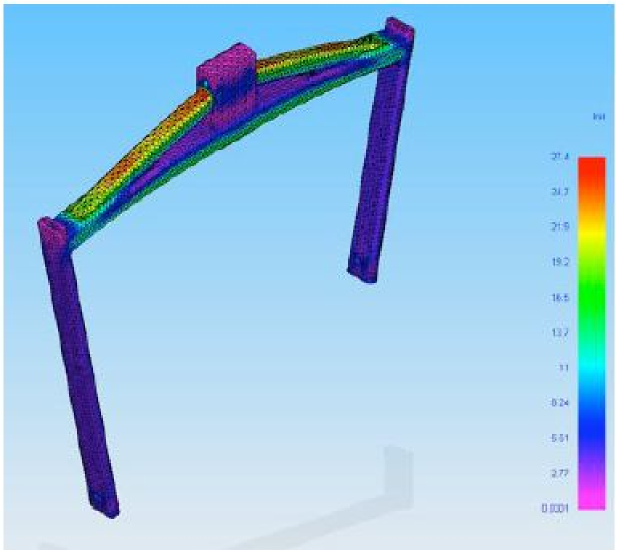

Figure 25: Modeled new pyramidal support – isometric

As may be seen from the above figures, the new design exceeded the existing in terms of strength, as the maximum stress encountered was 27.4 ksi (versus 30.3 ksi for the existing) with an applied total force of 1000 lbf.

CVT DRIVE DESIGN – When matching a four stroke Yamaha engine with a two stroke Ski-Doo chassis, the Continuously Variable Transmission (CVT) needed to be evaluated for performance and for reliability.

Background – A CVT drive system is essentially a transmission with an infinite amount of gears. It allows for the drive shaft to maintain constant RPMs while having a range of outputs. This allows for the engine to be operating the majority of the time in its peak efficiency range and to be smooth operating. However, one of the major disadvantages to the CVT is that they are complicated systems that require expertise to tune. The primary clutch which is attached to the engine operates on centripetal force and a series of weights to change the belts operating diameter. The secondary clutch is attached to a shaft that is connected to the final drive before the track. This clutch operates using torque feed back from the track and from belt tension due to the changing diameter of the primary clutch.

The Yamaha Genesis 120 engine has a stock 120HP band from 8000 to 10000 RPM and thus the primary clutch is designed to operate using those parameters [12]. However, the secondary clutch that was design for a two stroke 600CC Ski-Doo engine is setup to operate with its 110HP peak at 7750 RPM [13]. These clutches are tuned for different style engines and different power and torque curves, thus they will not operate very efficiently if paired together.

Through analysis of different clutch pairs and tuning the existing clutches to work together, it was decided that the best system to use was to have a pair of stock clutches from the Yamaha Vector snowmobile in which the engine came from. However, in mating a Yamaha secondary clutch to a Ski-Doo chassis it was determined that a new secondary shaft would need to be designed to transmit the power from the CVT to the final drive because the splines used to transmit power from the secondary clutch are different for each manufacturer. A model of the newly designed secondary shaft can be seen below in Figure 26.

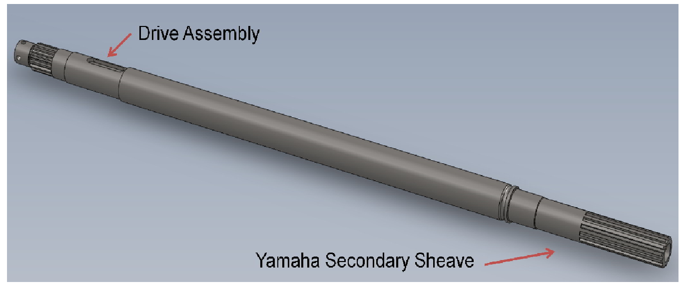

Figure 26: Yamaha/Ski-Doo Secondary Shaft

The implemented CVT system can be seen below in Figure 27.

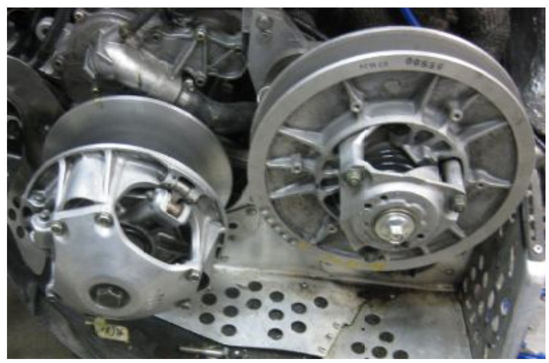

Figure 27: Pair of Yamaha Clutches

NOISE REDUCTION

EXHAUST SILENCER - The 2010 University of Waterloo competition sled features a custom exhaust silencer designed using the theoretical work of Blair [14]. The Yamaha Genesis 120 Engine yields a critical frequency range of 125-200 Hz, resulting in a focus of attenuation in this frequency range by the design.

The main silencing unit of the exhaust system is the three-in-one combined element- consisting of two diffuser type silencers combined with an integrated side resonant silencer. The combination of elements and their respective geometries of chambers and tube sizes are optimized to attenuate high levels of sound in the critical frequency range as well as over the spectrum of audible frequencies. An automotive absorption silencer has also been implemented into the design for attenuation of higher frequencies. These components are both fabricated of stainless steel to avoid corrosion and are mounted under the running board of the sled using rubber vibration damping mounts. Images of main silencing unit can be seen below in**Error! Reference source not found.**.


Figure 28: Silencing Units

The flow of exhaust gases through the combined system is shown in the below in Figure 29. Gas enters through the left into the first chamber, being redirected by the inner wall and out the three smaller pipes into the second chamber. In coming into the second chamber, the small pipes act as side resonators, forcing gases along the outer walls of the second chamber as well as against the end of the chamber at the right. Gas collects within the second chamber and comes out of the large pipe at the right. A cross sectional area equivalent to a 2" diameter pipe is maintained through the system in an attempt to minimize performance loses of the engine.

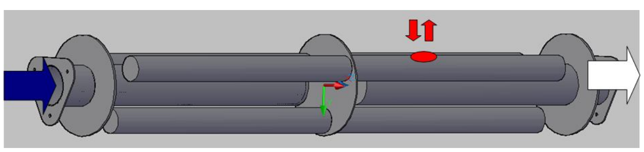
Figure 29 - Exhaust gas flow

The optimized result gives at most a theoretical passed noise of about 65 dBA in the critical range (125-200HZ) based on an approximation of 100 dBA output from the engine (this approximation has proven reasonable with prior testing). This result puts the team in a favorable position with respect to noise attenuation of the engine- the loudest component of the sled. Figure 31 below shows the passed sound through the exhaust system where Figure 32 below shows the sound cancelled out with in the system.

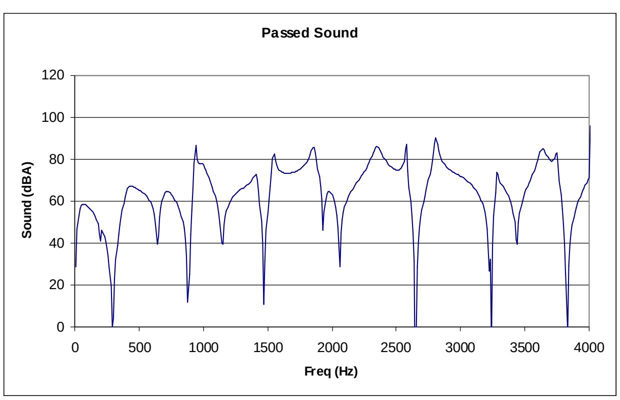

Figure 31: Passed Sound

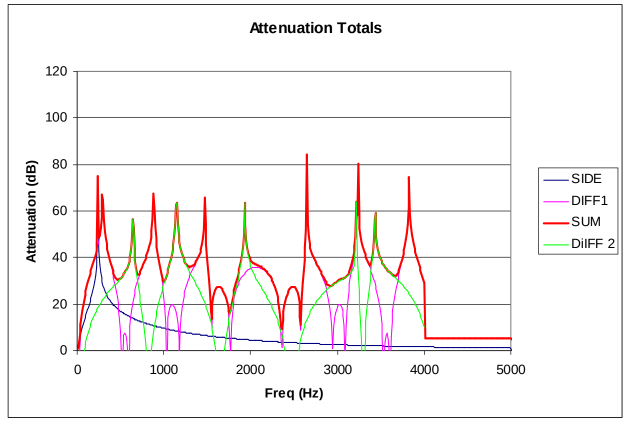

Figure 32: Attenuation Totals

AIR INTAKE SILENCER DESIGN - Various methods for attenuating the engine through the intake air box were considered when building the sled; these methods included custom high-pass and low-pass sound filters, expansion chambers and baffles to produce destructive interference, and sound absorptive materials. One of the main things to consider when designing a silencer is the hearing range of the human ear; it is most sensitive in the range of 1000 Hz to 5000 Hz and therefore the A-weighted curve, which is shown below in Figure 30, is used when assessing sound levels (both at the competition and in industrial settings)

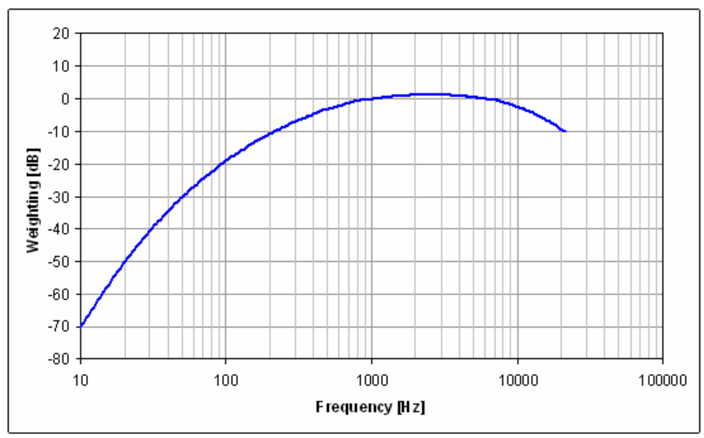

Figure 30: A-Weighted Curve

With the A-weighted curve in mind, the frequencies that the snowmobile generally operates at need to be determined. This is calculated using the following equation:

$$f = (\text{rpm}/60\text{ sec}) \times (1\text{ ignition}/2\text{ revolutions}) \times 3\text{ cylinders} = [\text{Ignitions/second}] = [\text{Hz}]$$

Using this formula, the following values were obtained for the frequency emitted by the engine at idle and full throttle:

RPM	Frequency	Wavelength
1000	25 Hz	3314 mm
8500	213 Hz	390 mm

Based on these values, it is deemed that a slightly modified stock air intake with acoustic insulation is suitable for its required task since the emitted sound is far from the sensitive region on the A-weighting curve.

ENGINE COMPARTMENT SILENCING – Sound deadening materials were researched, analyzed, and tested to determine the best candidate for use to line the hood and side panels. The results of testing are shown in Figure 33 below.

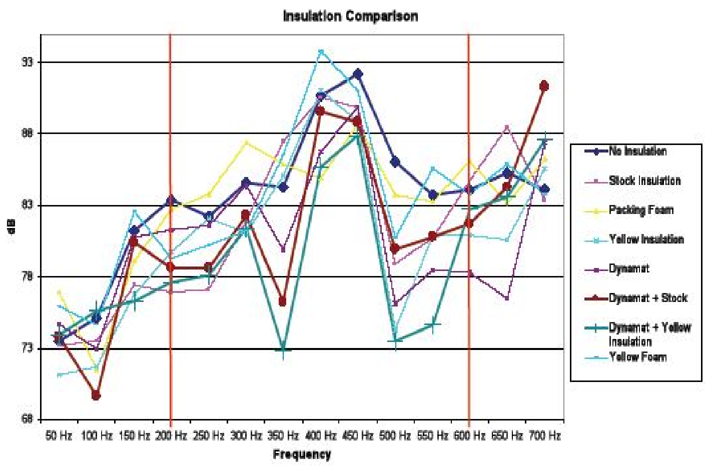

Figure 33: Comparison of sound insulating material based on shop testing

A combination of Dynamat X-Treme and the Ski-Doo stock insulation was found to be the best choice for expected frequency ranges. A rubber gasket will be used for seam covering between panels and the hood, and fiber glass will be used to cover any unnecessary vents to minimize noise leaks from the engine compartment.

TESTING

OFF-SEASON TESTING COMPONENTS - The offseason testing components do not have a direct impact on the performance characteristics of the sled, but instead, give the team the ability to perform test runs even in warmer conditions when there is no snow on the ground. This way, the team can test new modifications and fine tune any critical engine, drive-train, and chassis components without being dependent on weather conditions.

The completed design includes: a slick track that can be equipped for use on asphalt as to prevent damage to the studs on the primary track; an external radiator assembly that can be used as a stand-alone system to keep the engine cool while idling, or can be mounted to the chassis to act as a complete cooling system; and finally, a set of aluminum skis complete with wheels to provide a smooth and stable ride on asphalt. All components are mechanically joined and therefore, can be disassembled and reassembled quickly to make the change-over for testing on asphalt, quick and simple.

NOISE AND EMISSIONS TESTING – The final noise and emission testing was not completed at the time of composing this report. However, with proof of concept shown in most of the preliminary designs, the University of Waterloo clean snowmobile team is confident that the snowmobile will provide the required reductions in both pollutant and noise emissions while improving on snowmobile performance.

Engine and tuning is expected to occur in the following week, followed by detailed testing using the five-gas analyzer and noise meter.

CONCLUSION

Having the industry implement an ethanol based flex fuel system and a multistage exhaust system in their snowmobiles is the answer to environmental concerns regarding the use of traditional snowmobiles in national parks. The innovative ideas included in the University of Waterloo clean snowmobile are effective solutions for producing a high performance snowmobile with lower pollutants and noise emissions. These solutions are easily implementable by leaders in the snowmobile industry and are easily marketable as they provide a reduction in noise and pollutants allowing them to be rode anywhere.

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- Snowline Sports
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- Woodys
- ABM OMNI
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