University of Waterloo Clean Snowmobile Design Paper

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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 while the forced induction system ensures no reduction in snowmobile performance and increased fuel efficiency through variable compression ratios.

INTRODUCTION

BACKGROUND – The strive 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 new flex fuel (E10-E85) requirement outlined by the rules of the 2009 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. Including catalytic converters to reduce gaseous emissions and exhaust silencers to reduce noise cause restrictions in 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. 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 a forced-induction system to negate any power loss due to flow restrictions that may result from the addition of a catalytic converter and exhaust silencer and increase fuel efficiency through varying compression ratios.

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 fuel sensor, and a cold start system capable of starting the engine with any blend of ethanol.

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 fuel ranging from an E10 to an E85.
- All components must be E85 compatible.
- Snowmobile noise must not exceed 78 dBa.
- The engine must start within 20 seconds and move 100 feet within 120 seconds without stalling.

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; the maximum allowable engine size being 973cc based on the CSC 2009 rules.

The three-cylinder Yamaha Genesis 120 engine 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.

FORCED INDUCTION SYSTEM – The purpose of the forced induction system is threefold; negate any power losses due to flow restrictions imposed by the catalytic converter and silencers, increase the power to weight ratio of a four-stroke engine, and increase ethanol fuel efficiency by varying the compression ratio based on the fuel's ethanol composition.

Sizing – A good design should have a power curve that travels through the maximum efficiency islands in the operating range of the powerband, and have the maximum output power as far right of the efficiency islands as possible. This will allow the engine to minimize turbo lag and maximize the engine's output and efficiency. Plotting multiple charts and operating ranges are necessary to optimize the design. [5]

After mapping multiple turbocharger compressor maps two different housing types were chosen, and the selected one plotted in Figure 3. The chosen housings are the Garrett GT2554R and the GT2056. The last two digits indicate the exducer diameter of the compressor turbine wheel, while the R designates the use of a ball bearing type turbocharger, and the absence of an R indicates a journal type bearing.

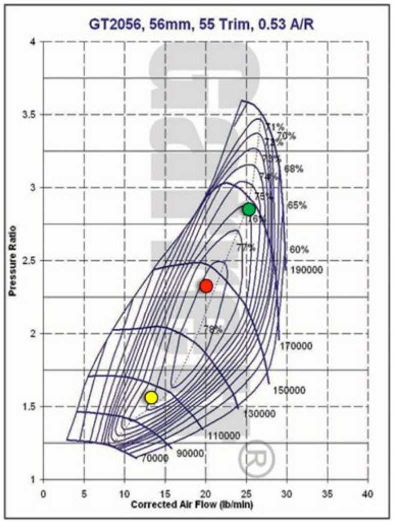

Figure 3: GT2056 turbocharger map (red dot denotes 180 HP)

Both turbochargers are a good choice for the 180 HP range. However, the journal type would allow for a greater turbine speed, allowing for future modification of the engine, allowing the boost to be increased, resulting in an output of 225 HP. While the bearing type turbocharger would allow for faster spooling, it actually has a lower efficiency in the mid to peak operating range. Since the engine operates from 3600 RPM, primary clutch engagement speed, to 8600 RPM, maximum engine speed, the need for a bearing type turbocharger is not necessary.

The superior choice for this particular application using a Yamaha Genesis 120 engine would be the GT2056 turbocharger for its compact package, increased efficiency and future modification abilities. This turbocharger is a simpler installation, and features the same T25 exhaust flange as its larger counterpart. This allows for direct bolt on application to the custom exhaust header if a future upgrade to a GT2554R is desired. The installed turbocharger is shown in Figure 4 below.

Figure 4: Turbocharger installation and custom exhaust manifold

Performance – The switch from a two-stroke to four-stroke engine and addition of an exhaust system comprised of a catalytic converter and four-stage silencer results in an overall loss of snowmobile horsepower. This is unwelcomed as a key goal in designing the clean snowmobile is to ensure the performance of the snowmobile is not reduced. Therefore, the first motive for including a turbocharger is to increase the horsepower produced by the engine.

A naturally aspirated and uses the downward stroke to create a volume of low pressure within the combustion chamber to draw in air at no more than atmospheric pressure (14.7 psi). The turbocharger increases the engine horsepower by increasing the amount of air forced into the cylinders (volumetric efficiency) by increasing the inlet manifold pressure, which allows more fuel to be injected, and increases the power output of the engine. The turbocharger increases the amount of air forced through the engine by capturing waste heat from the high temperature exhaust gas through the use of a turbine that powers a compressor [5]. This use of waste heat from the exhaust gas makes the turbocharger more efficient than a supercharger, and was the primary reason in selecting a turbocharged instead of supercharged forced-induction system.

An unwanted side effect of the turbocharger compressing air is a rise in combustion air temperature [5]. This is a problem when using a lower octane fuel as it can result in pre-detonation. Therefore, to reduce combustion air temperatures, an air-cooled intercooler and fan were installed between the turbocharger and air plenum. The intercooler also provides the advantage of cooling the air, which results in a denser intake charge allowing for more fuel to be injected to further increase performance [5]. Additionally, the head volume at top dead centre (TDC) was increased by raising the height of the head gasket by 2mm (shown in Figure 5 below).

Figure 5: Installation of 2mm engine head gasket

Fuel Efficiency – The most innovative use of the turbocharger is to take advantage of the higher octane rating of an ethanol based fuel to increase the compression ratio, which in turn can make up for the lower energy density of ethanol compared to gasoline.

The octane rating for pure ethanol is 117 compared to a rating of 87 for straight gasoline [6]. This higher octane rating increases the fuel's resistance to detonation, allowing for higher combustion temperatures and pressure. On the other hand, the energy density of pure ethanol is approximately 30% less than that of gasoline, resulting in lower fuel economy per gallon of fuel [ref]. This variation in octane rating and energy density is important when running an ethanol blend between 10% and 85%. If one were to run an E85 blend at the same compression ratio as an E10, fuel economy would be approximately 30% less because of the difference in energy density of both fuels.

The truly innovative idea comes from using the fuel management system to detect the ethanol content of the fuel and vary the turbocharger boost and fuel injection volume accordingly using the programmable ECU. This increase in boost allows for an increase in compression ratio for higher ethanol content fuels, which have a higher resistance to detonation, increasing the power obtained from a smaller volume of injected fuel. Where non-forced induction engines have to increase the amount of high ethanol content fuel injected to make up for lower energy densities, a forced induction system can reduce the amount of fuel required by varying the compression ratio instead, greatly increasing fuel economy. This variation in compression ratio is accomplished by using 8 pounds of boost for fuels ranging from E10 to E65 and 15 pounds of boost for fuels ranging from E65 to E85.

FUEL INJECTION SYSTEM – The Yamaha Genesis 120 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, that 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 [7].

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 2009 CSC.

<u>Intake Air System</u> - 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 91' 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 modelled using SolidWorks and is illustrated in Figure 6 below.

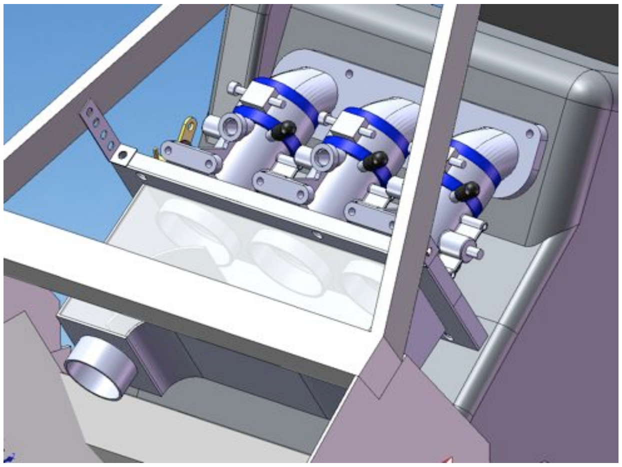

Figure 6: Original intake air system design

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 7 below.

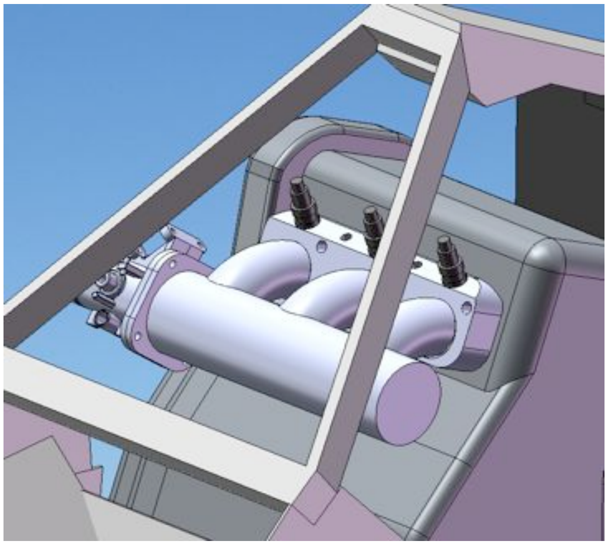

Figure 7: New intake air system design

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 turbocharged engine, which is slightly above the minimum recommended for this application. The flow of the air through the plenum was modelled using ANSYS. The analysis incorporated the same internal and external conditions as applied for sizing the turbo charger. The results of the CFD analysis are illustrated in the following images labeled Figure 8 and 9.

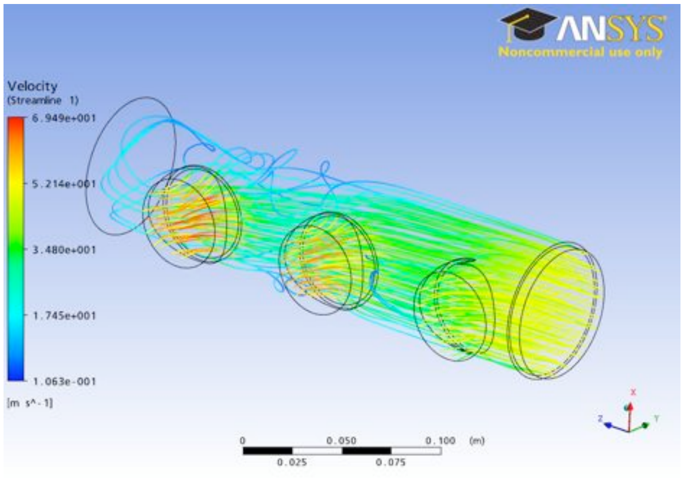

Figure 8: Isometric view of velocity stream profiles in custom plenum

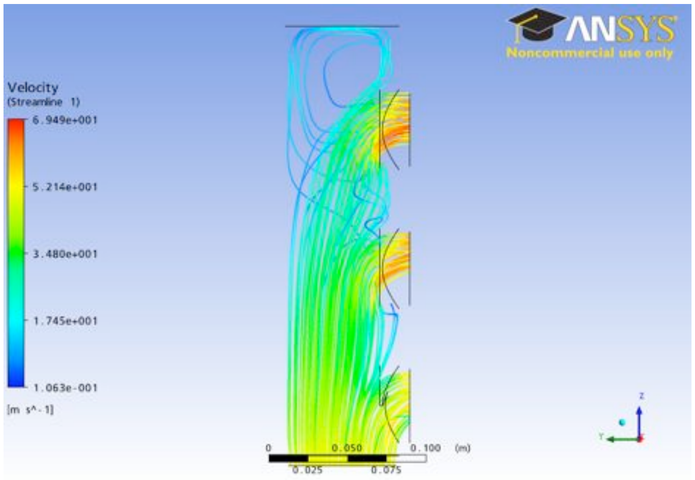

Figure 9: Velocity stream profile at plenum entrance and exits

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 Figures 8 and 9 above demonstrates a large improvement in flow distribution and thus the fabricated intake system has included this modification. Figure 10 below shows the as machined plenum, the as fabricated engine intake flange and the complete as welded assembly.

Figure 10: As-welded final air intake assembly with fuel rail mounted.

The increase in manifold pressure due to boost generated by the turbocharger required the installation of a 3 bar manifold absolute pressure (MAP) sensor. 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 [7]. 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 aluminium and coated for protection against ethanol-induced corrosion. The fuel injection system is shown in Figure 11 below.

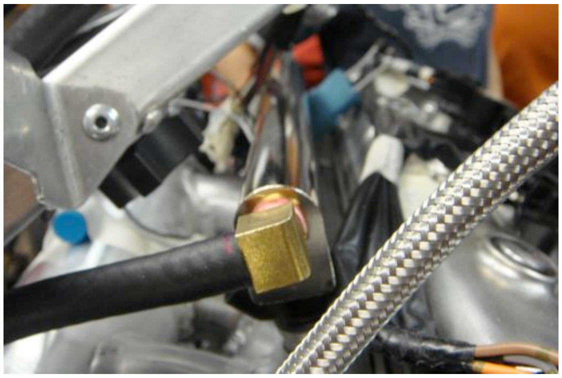

Figure 11: Fuel injection system (looking down fuel rail)

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.

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.

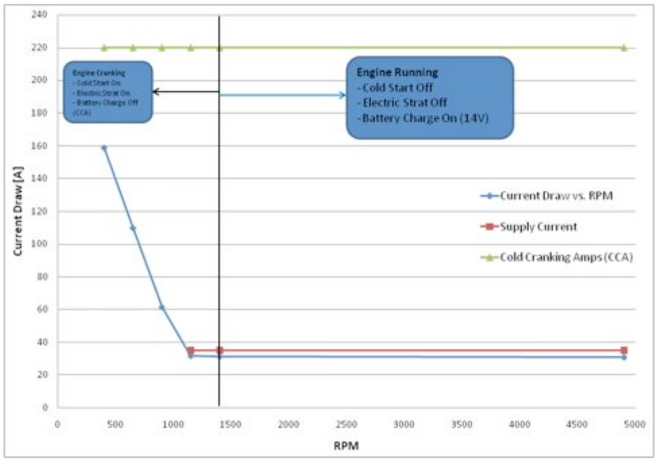

Figure 12: Current draw of electrical system

Based on the electrical analysis, an Odyssey PC680MJ 12 Volt battery was selected as the best for the clean snowmobile application. Other comparable batteries were better in some respects but they failed to meet constrain criteria, and failed to match the Odyssey 650 cold cranking amp (CCA) 5 second rating.

In terms of mechanical design, the mounting of the battery on the sled chassis, a combination of preliminary design, along with finite element Analysis (FEA) was utilized in order to develop a final detailed design. The design materials selected were steel for the mounts due to high strength, low cost, and no fatigue limit, while Polycarbonate was chosen as the box material due to its high impact strength, operating temperature range, and machinability.

The FEA analysis revealed that the preliminary design was sufficient in terms of maximum stress and deflection. Two cases were run: normal operating conditions (Figure 13), and extreme load conditions (modal analysis as shown in Figure 14). The normal operating conditions revealed maximum stresses of 0.4MPa, while the maximum load conditions had stresses as high as 119MPa (lower than the allowable of 180MPa).

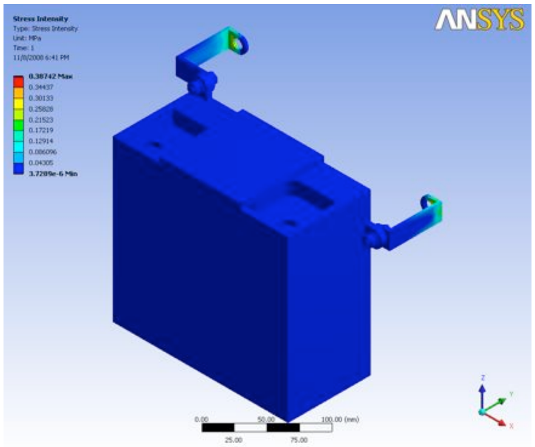

Figure 13: Stress intensity at normal operating conditions

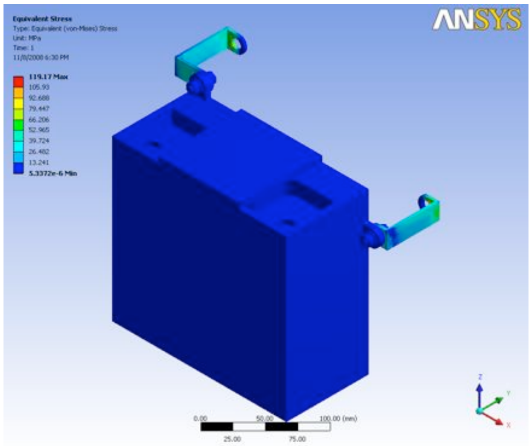

Figure 14: Stress intensity at extreme operating conditions

Since the maximum stresses are lower than both the allowable limit and the fatigue limit, the design is deemed safe from mechanical failure.

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 an E70 ethanol blend within 20 seconds, and enable the snowmobile to move 100 feet within 120 seconds without stalling as per the SAE CSC 2009 rules.

The previous University of Waterloo cold start system utilized an on-board distillation system to separate the ethanol and gasoline from the E85 blend and use the gasoline to start the engine. The new rules for the 2009 CSC specify a flex fuel, which provides an additional design challenge. This modification requires a re-evaluation of the cold start problem and a new innovative design.

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 aluminium 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 [8]. The record low for Houghton, Michigan, in the month of March is -23°F [9]. 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 2009 CSC rules.

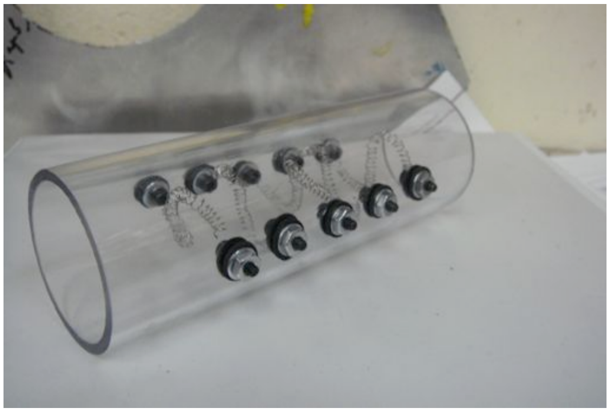

Figure 15: Flex fuel cold start system

The final cold start system design, shown in Figure 15 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 snowmobile's fuel distribution system and the variability in the fuel type requires the use of an after-market 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 both 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 16 below.

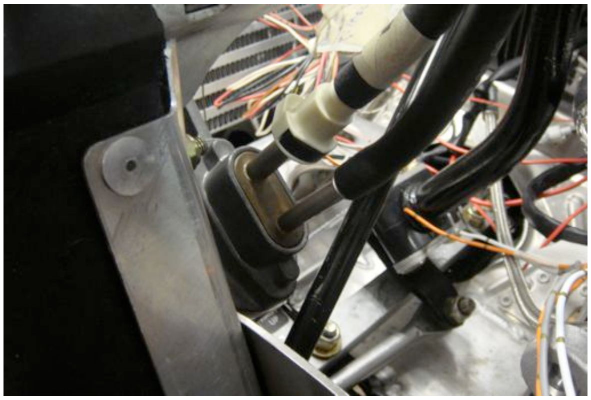

Figure 16: Flex fuel sensor mounted in location.

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 17 below.

Figure 17: Fuel pump and regulator installation locations (high pressure fuel pump, low pressure fuel pump and regulator)

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 an automobile 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 MagnaFlow 46004 as it is compact (6.00" h x 6.00" w x 14.00" l), rated for use in California (stricter emission regulations compared to 49 state catalytic converters) and is used on automobiles with similar exhaust flow rates.

UNDER-COWL THERMAL PROTECTION SYSTEM - Due to the installation of a turbocharger and catalytic converter within the engine compartment, 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 turbo and exhaust pipes alone is roughly 4 kW. This value is based on an expected surface-to-air temperature difference of 280°C. 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 and turbocharger, 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. Since the turbo is oil-cooled, it will be left uncovered to prevent oil burn-up due to overheating. A large intake fan, rated at 1500 CFM (0.708 m³/s), is already located at the front of the cowl for forcing air through the intercooler. A 7” exhaust fans is to be mounted near the top-rear portion of the cowl and will be controlled by an air thermostat.

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 0°C, this thermal protection system is expected to maintain the fuel tank surface at a very safe temperature of about 3°C. The temperatures of other sensitive surfaces such as hoses and wires will also be kept at similarly safe levels. Figures 18 and 19 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 13°C (286 K).

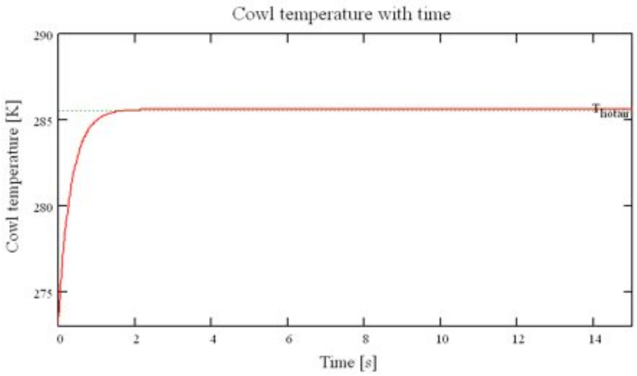

Figure 18: Cowl temperature with time (at constant airflow)

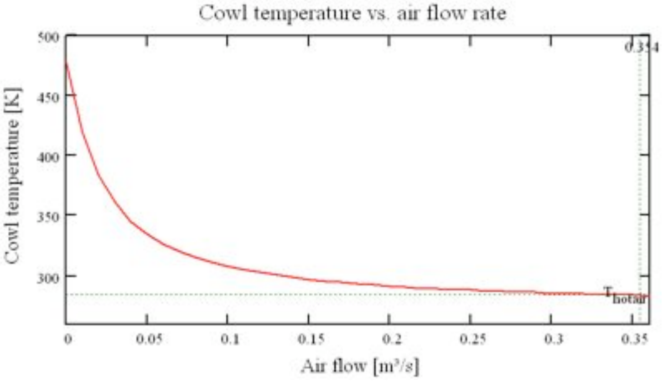

Figure 19: Cowl temperature vs. airflow rate.

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. Figure 20 below depicts the pyramid structure without the support.

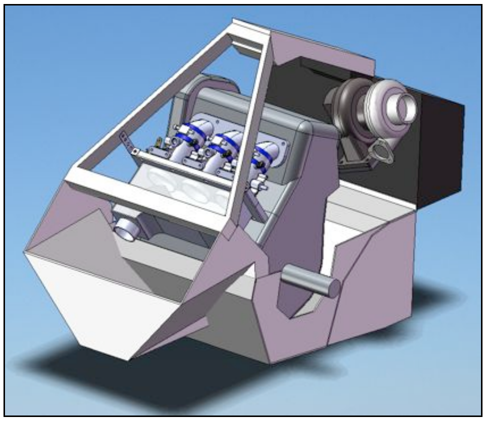

Figure 20: Pyramid structural support

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 SolidEdge. Figure 21 depicts the actual support and the modeled.

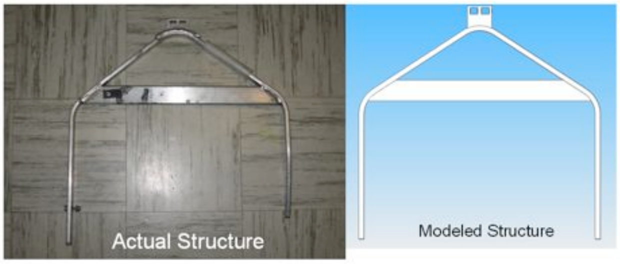

Figure 21: Actual and modeled structures – pyramidal support

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 22 below.

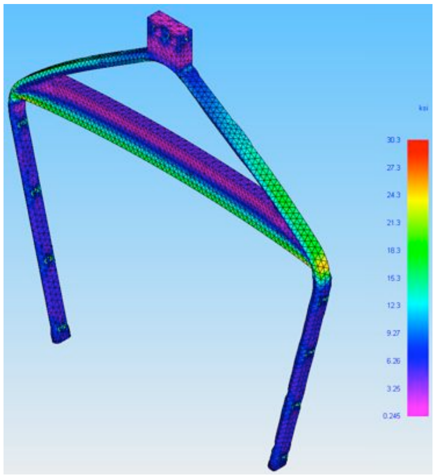

Figure 22: Modeled existing pyramidal support – isometric view

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 23 below.

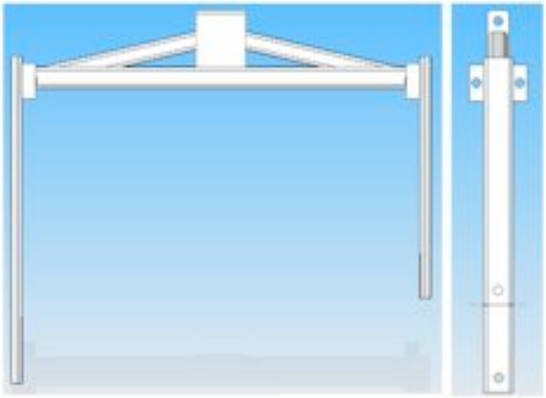

Figure 23: Pyramidal support new design – front and side views

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 24.

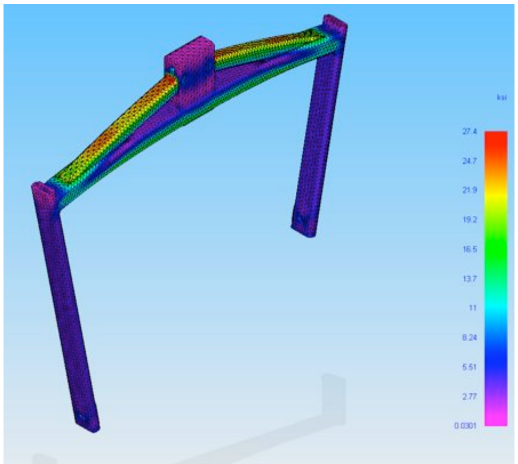

Figure 24: Modeled new pyramidal support – isometric view

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.

NOISE REDUCTION

EXHAUST SILENCER – The exhaust silencer designed for the Bombardier MXZ is based on sound attenuation of a two-stroke engine, which differs from that of a four-stroke engine. At the same time, the exhaust system used for the Yamaha Genesis 120 is not compatible with the MXZ chassis. Therefore, the chosen solution is to custom design the exhaust system of the UW clean snowmobile.

The exhaust system is composed of three different silencing elements that possess unique sound attenuation properties and rely on their geometries (and sound insulation properties) to passively reduce noise by generating the maximum destructive interference achievable.

<u>Diffuser</u> - Diffuser elements consist of a central hollow circular chamber through which inlet and outlet pipes of smaller circular diameters pass through. This type of element provides significant attenuation over a wide range of frequencies. However, gaps (pass-band frequencies) exist where no attenuation is provided. This can be accounted for by placing two diffuser elements in series and have each cover the other's pass bands. The designed diffuser is shown in Figure 25 below.

Figure 25: Exhaust silencer diffuser

<u>Side-resonant</u> - Side-resonant elements consist of a small circular pipe running through a larger hollow cylinder. The smaller central pipe is perforated with holes of uniform diameter to allow exhaust gas to reflect within the central cavity before exiting the element. This type of element provides very high attenuation for a narrow range of frequencies and minimal attenuation at frequencies beyond the targeted range. The designed side-resonant element is shown in Figure 26 below.

Figure 26: Exhaust silencer side-resonant element

<u>Absorption Silencers</u> - Absorption silencers are constructed in a similar fashion to side-resonant elements except that the central cylindrical chamber is packed with a sound absorbent insulation (i.e. fiberglass) and the ratio of central pipe holes area to central pipe area must be greater than 5. Absorption elements are

usually located after all other elements to account for pass-bands and dampen the noise generated by sharp changes in geometry (turbulence) of the preceding elements. The designed absorption silencer is shown in Figure 27 below.

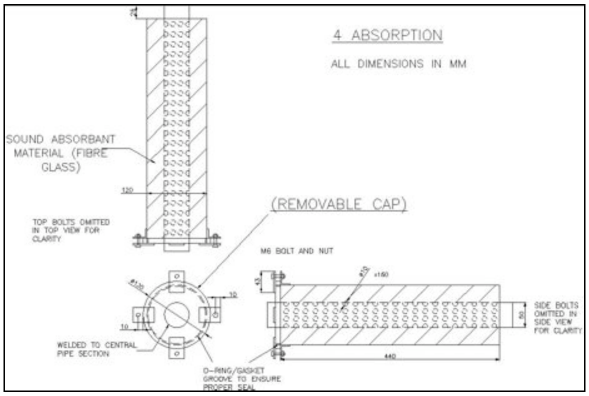

Figure 27: Exhaust silencer absorption silencer

Sound Attenuation - The exhaust noise target is a maximum of 73 dBA to keep the total snowmobile noise emission below 78 dBA as required in the competition guidelines. The exhaust silencing system achieves the target by using four passive elements and three different element design types. The element ordering and types are: Diffuser-1, Side-Resonant-2, Diffuser-3 and Absorption-4. The predicted noise passed by the first 3 elements in series (assuming constant 100dB noise input across all frequencies) is shown in Figure 28.

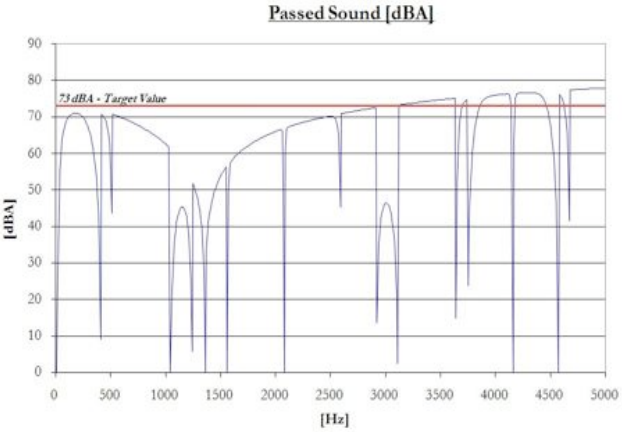

Figure 28: Predicted snowmobile noise with exhaust silencing system

Although the passed noise exceeds the target value of 73 dBA for some frequencies, most of noise values are considerably below 73 dBA. When the total noise is integrated and averaged to give the final dBA reading on which performance is based, the expected value will be below 73 dBA. It is also important to note that the preceding figure is very conservative as it does not include the absorption element's effects since they cannot be precisely modelled, and 100 dB across all frequencies is an overestimation of noise generated by the snowmobile engine.

FORCED INDUCTION SILENCING – The turbocharger was implemented into the design of the snowmobile to negate any power loss from flow restrictions. However, the cost of additional power comes at the expense of increased noise. Therefore, the challenge is to design an innovative forced induction silencing system to attenuate the additional noise created by the turbocharger.

The purpose of the intake air system is thus to provide fresh air to the turbocharger/engine in conjunction with an air-box to attenuate the passage of compression waves from the turbocharger and engine. The two systems must work in tandem to minimize the associated noise propagation while increasing the performance of the snowmobile.

Background - In order to understand the reasons why the design was developed, it must be understood how the noise is originated. A turbocharger is added to a snowmobile to increase the performance of the engine by increasing the amount of intake pressure. The compressor wheel within the turbocharged system is a component that is driven at high speed, in the range of 100,000 to 150,000 rpm [10]. The high rotation speed of the turbine and compressor wheels causes the blades to generate a high level of noise, which is known as Blade Pass Frequency, or Turbo Whine.

Turbocharged engines that operate at high rpm (ie. full throttle) require a large volume of air to flow between the turbo and the inlet of the engine [5]. As the compressed air flows through the plenum, the open throttle valves allow the air to enter the engine chambers. When the throttle is closed, the compressed air still flows into the plenum, but is stopped by the closed throttle valves. The excess air causes a surge, which causes the air to decompress back across the turbocharger [5]. The sudden flow of air will often cause turbulence within the pipes, which cause a subsequent whistling noise as the air moves pass the compressor wheel. The flow against the compressor wheel causes the turbine shaft to exhibit a rapid reduction in speed. When the throttle is open again, the turbo will produce "turbo lag" – that is, the turbo has to make up for the decreased momentum and, as a result, requires longer times to achieve the desired speed.

Blow-Off Valve - To prevent the occurrence of turbo lag, a blow-off valve can be fitted between the intercooler and air plenum to vent the excess air pressure. Different configurations can be utilized when determining how to vent the excess air – including releasing it into the atmosphere or re-routing it. By utilizing the blow-off valve it releases the turbocharged air that is not utilized by the engine. If the air is released to the atmosphere, it causes a loud noise to be released. Instead, the excess air can be re-routed back prior to the turbocharger. This configuration (shown in Figure 29 below) reduces the associated noise with the air release, and still provides compressed air to the turbocharger, thus increasing efficiency [5].

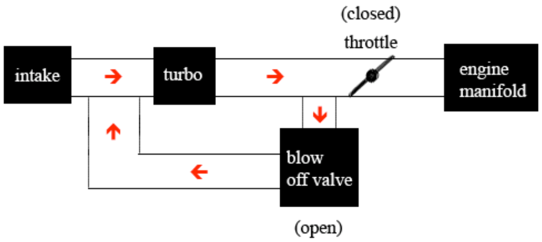

Figure 29: Blow-off valve schematic

The final installation of the blow-off valve is shown in Figure 30 below. It is located after the intercooler and prior to the air plenum and fuel injection system.

Figure 30: Blow-off valve location

Air Intake Silencer Design - Since sound propagates as a pressure wave, the intake system was treated as a duct to simplify the analysis. It was determined that the main tools to control noise transmission in ducts are acoustic filters – which are grouped as high-pass and low-pass filters. As the name suggests, the high-pass filter is a device that allows high frequencies to pass, while attenuating the lower frequencies. A low pass filter does the opposite. The high pass filter is created by the use of side branches along the main duct, where the short side branches apply acoustic impedance to the system [11].

As the incident pressure wave escapes through the side branch, a portion is reflected and transmitted. Subsequently, the coefficient of transmission can be plotted by determining the intensity of the transmitted sound and relating it to the incident intensity. A low pass tube on the other hand is created by the use of an expansion chamber where the sound enters the chamber through a small opening [11]. The sound wave then expands as it travels through the chamber, until the point where it encounters another reduction in diameter. This reduction causes the wave to be reflected back towards the source, while a portion is transmitted. Again the coefficient of transmission can be determined and plotted.

By combining the use of high-pass filters, low-pass filters, filter membranes and sound absorption material, a preliminary model is developed. As can be seen in Figure 31, the ambient air enters the air box via an inlet tube that is adjoined via a boot and coupler. The inlet air then pass through the air filter, which is used to filter any foreign matter (dirt, particulates, debris) from entering the turbocharger. The air then passes through both the high and low pass tubes, and into the turbocharger inlet.

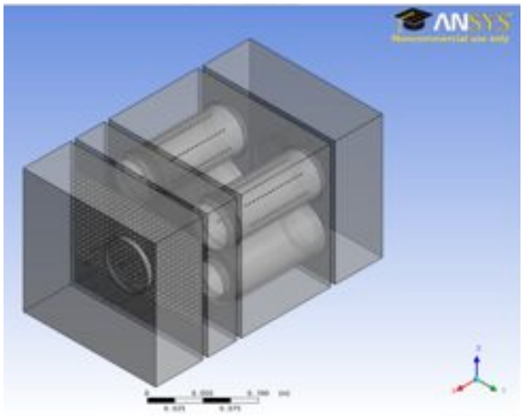

Figure 31: Air intake silencer

The model shown in Figure 32 above was modeled using computational fluid dynamics (CFD) to determine velocity stream profiles of air passing through the air box. This was used to modify the box to ensure optimal airflow through the high and low pass tubes. The optimized CFD is shown in an isometric and planar view in Figures 32 and 33 below.

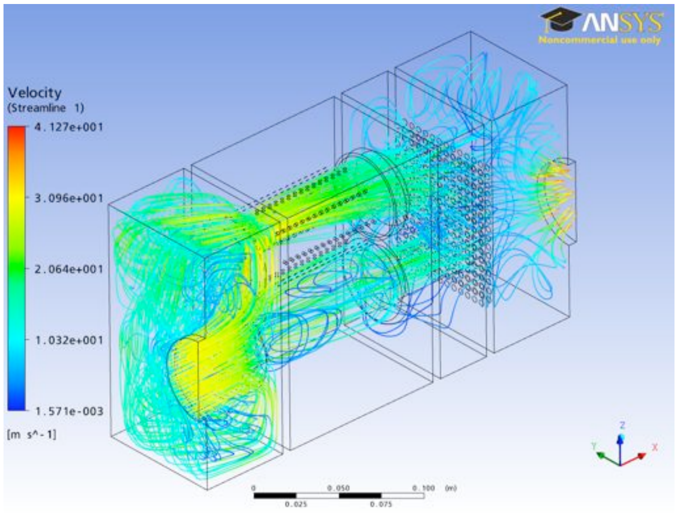

Figure 32: Optimized CFD of air box (isometric view)

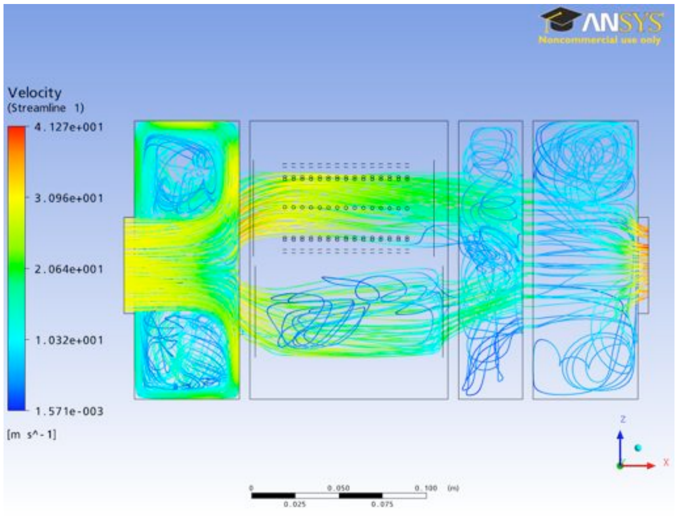

Figure 33: Optimized CFD of air box (planar view)

In order to design the intake silencer, the targeted frequency range of the turbocharger was obtained by utilizing the compression curves. It was determined that the operating frequency of the turbocharger was 2500Hz, which was confirmed using a frequency generator that suggested 2400-3000Hz.

After performing an analysis on the high-pass and low-pass tubes, an optimal design solution was obtained. By overlaying the chosen designs, it becomes evident where complete sound absorption is present. It can be seen from the below figure that there is complete sound attenuation above 1250 Hz. The plotted values are the coefficients of transmission – that is, the amount of transmitted sound intensity relative to the incident sound intensity. As a result, the area under the curve in Figure 34 represents the transmitted sound intensity, and the areas above represent the attenuated sound intensity.

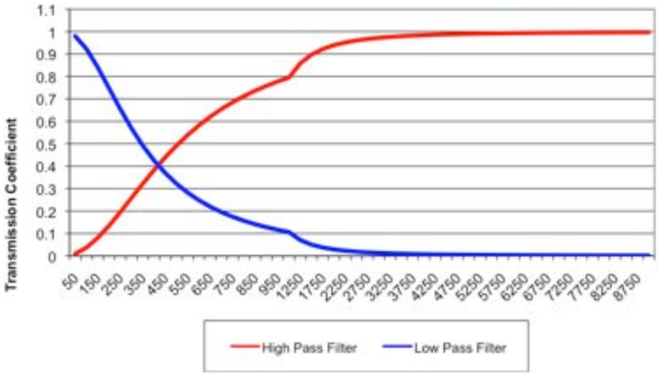

Figure 34: Overall sound attenuation by pass-tubes

Based on the analysis, the noise of the turbocharger should be completely attenuated at the frequency range that is targeted – 2500 Hz. In addition, there is sound absorption below this range but not completely attenuated. With the efforts being undertaken by the pass-filters and under-hood silencing, there should be sufficient noise reduction to completely eliminate any noise associated with the turbocharger. To assist in noise attenuation, sound-absorbing material is lined along the inner walls of the air box.

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 35 below.

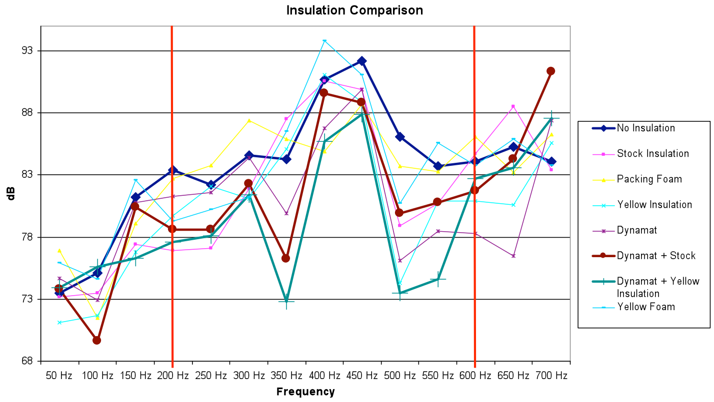

Figure 35: Comparison of sound insulating material based on shop testing

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 fibreglass will be used to cover any unnecessary vents to minimize noise leaks from the engine compartment.

TESTING

OFF-SEASON TESTING COMPONENTS - The off-season 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 turbocharger tuning is expected to occur in the following week, followed by detailed testing using the five-gas analyzer and noise meter.

CONCLUSION

The combination of an ECU controlled turbocharged forced-induction system and an ethanol based flex fuel 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 high performance snowmobiles with lower pollutant and noise emissions. These solutions are easily implementable by leaders in the snowmobile industry and are easily marketable as they provide both an increase in power and a reduction in noise allowing them to be used anywhere.

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.

- Husky Injection Molding Systems Ltd.
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- Team Vincent MotorSports
- Snowline Sports
- Waterloo Engineering Endowment Foundation
- DL Motorsports
- KW Fuel Injection
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- Regional Hose and Hydraulics
- ACCEL
- Petro-Canada
- Carriere Foods (Ontario) Inc.
- Starting Line Products
- Royal Distributing
- Dynamat

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