SAE Clean Snowmobile Challenge 2014

Proving Diesel Engine Viability in the Snowmobile Industry

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ABSTRACT

For the 2014 Society of Automotive Engineers (SAE) Clean Snowmobile Challenge (CSC), the University at Buffalo (UB) Clean Snowmobile Team has made significant strides to reduce the environmental impact of the snowmobile while retaining the performance, cost, and reliability that riders and manufacturers require. This year the UB CSC Team implemented the three-cylinder Daihatsu/Briggs and Stratton, DM-954DT turbo diesel engine in a 2011 Polaris 600 IQ Shift chassis. The engine chosen was an indirectly injected diesel engine for its mechanical simplicity, reliability, and efficiency. Significant engine improvements were made in order to increase power output to a level suitable for snowmobile use while maintaining satisfactory emissions.

An intercooled intake system was paired with a Garrett GT1541-V turbocharger for decreased oxides of nitrogen (NOx) formation, lowered exhaust gas temperatures, and increased power output. A UB CSC Team developed engine control system, referred to as the "Eco-System," allows the user to select a performance or economy mode, varying multiple engine parameters to give increased engine output or decreased fuel consumption. Emissions control was addressed by employing an Emitec diesel oxidation catalyst (DOC) and diesel particulate filter (DPF) combination, and reducing fuel injection quantity via the Eco-System. Overall, the Eco-System with exhaust treatment reduced wide-open throttle (WOT) NOx emissions from 24.48 g/kW-hr to 2.67 g/kW-hr. Front and rear suspension systems were modified from the 2013 sled to yield an increase of 0.14g in maximum lateral acceleration to 0.38 g. With these improved design solutions, the UB CSC team has proven the effective implementation of the diesel engine into the snowmobile to improve emissions, reduce fuel consumption and retain the excitement of the snowmobile.

INTRODUCTION

Over the past decade, the awareness of the negative effects internal combustion engines can have on the environment have driven regulations on exhaust emissions. These regulations and societal demands for increased fuel efficiency and decreased emissions have affected the recreational vehicle market, specifically the snowmobile industry. This has caused an ever-growing need for further development of new technologies to make snowmobiles cleaner, quieter, and more efficient as regulations become increasingly strict. The Clean Snowmobile Challenge is a collegiate design competition for student members of SAE to reengineer a current production snowmobile with the intent to reduce emissions and environmental impact. The purpose of the Challenge is to "Develop a snowmobile that is acceptable for use in environmentally sensitive areas. The modified snowmobiles are expected to be quiet, emit significantly less unburned hydrocarbons, carbon monoxide and particulate matter than conventional snowmobiles, without significantly increasing oxides of nitrogen emissions." [1] The emissions of the snowmobiles entered in the Challenge are evaluated by an E-Score. This E-Score is shown by Equation 1, uses HC, CO and NOx measurements to quantify and rank the emissions outputs of the snowmobiles.

$$E - Score = \left[1 - \frac{HC + NO_x - 15}{150}\right] * 100 + \left[1 - \frac{CO}{400}\right] * 100$$

Equation 1: E-Score Equation for Emissions Testing

While the intention of the Challenge is to improve the environmental impact, the snowmobile must meet certain performance expectations that most snowmobile enthusiasts desire. Specifically, this requires the snowmobiles to travel at least 45 miles per hour (mph), travel 500 feet within 12 seconds, and be able to travel 100 miles without refueling. [1] The reengineered snowmobiles should maintain the current snowmobile's reliability while also focusing on cost effective solutions to the problems of emissions, economy and noise reduction. With all of these constraints considered, the UB CSC Team has chosen to continue to pioneer the diesel engine with supporting systems in order to engineer an efficient, low emission, reliable and cost effective snowmobile.

DESIGN CONSIDERATIONS

To effectively redesign a snowmobile, the main design factors or parties influenced by the design must be considered and their requirements must be adequately met. The UB CSC Team has identified the three most important factors to the redesign of the snowmobile and their expectations, which are listed below.

The Environment

It was decided that the environment was the most important factor in which the UB CSC Team sought to improve through the reengineering of the snowmobile. It directly relates to the main goal of the Challenge, which is to design innovative ways to make a snowmobile clean, quiet, and efficient. The customer requirements which relate to the environment include decreased HC, CO and NOx emissions, noise reduction, and improved fuel economy. To achieve these objectives, various emissions control devices were implemented, design for efficiency was stressed upon all components, and decreased weight was emphasized.

The Operator

The operator is an important customer that the UB CSC team considered for the redesign because the excitement and recreation of the operator is the main purpose of a snowmobile. An operator expects adequate power output and good handling characteristics to make the machine enjoyable, while also maintaining acceptable fuel economy. If these requirements are not met, the snowmobile will not be successful in today's market. To address this design factor, the team focused on engine power output, improved handling and decreased fuel consumption. Operator design consideration was mainly reflected in the suspension configuration and tuning as well as the engine turbocharger and intake systems.

The Manufacturer

The manufacturer also needed to be taken into consideration when design choices were made. The most important requirement is that the cost of the snowmobile be minimized whenever possible, while still producing a high quality and desirable snowmobile. The manufacturer also requires the snowmobile to be durable in order to minimize lifecycle cost and warranty claims. To reduce the cost of the snowmobile the UB CSC Team emphasized cost effective solutions such as minimizing part counts, fabrication amount, and overall system complexity. By focusing on simplicity the snowmobile was improved by not only decreasing cost and weight, but also increasing sled reliability. This influenced all system designs of the snowmobile, but most notably the intake, exhaust belt drive, and emissions systems.

ENGINE SELECTION

For the 2014 Challenge, the UB CSC Team chose an indirect-injected Daihatsu DM-954DT turbocharged diesel marketed by Briggs & Stratton. This engine was chosen for its simple, fully mechanical design, exceptional brake specific fuel consumption, low emissions, and high torque output.

Model	DM-954DT
Engine Type	3 Cylinder 4-Cycle Diesel
Displacement	952cc
Bore x Stroke	72 x 78 mm
Compression Ratio	24.8:1
Number of Cylinders	3 in-line
Dry Weight	196 lb
Combustion Chamber Type	Swirl Chamber
Valve Mechanism	Gear-driven OHV

Table 1. Daihatsu DM-954DT Engine Specifications

The UB CSC Team chose a diesel platform over a bio-isobutanol 2 or 4 stroke for multiple reasons. The most important reason was the naturally low HC and CO emissions of the compression ignition combustion process compared to a spark ignition engine. [2] Another significant reason for choosing a diesel- fueled engine is the immense decrease in fuel consumption. Shown by Figure 1, the DM-954DT can achieve a brake specific fuel consumption (BSFC) as low as 260 g/kW-hr [3], when many small gasoline engines struggle to achieve less than 400 g/kW-hr.

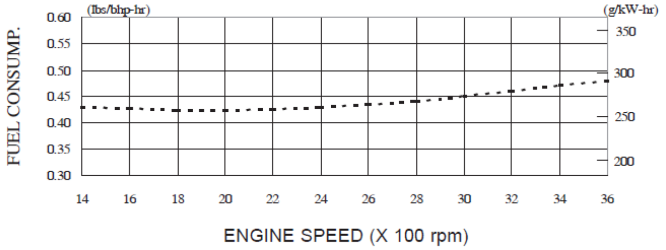

Figure 1: DM-954DT Brake Specific Fuel Consumption
(Courtesy of Briggs and Stratton)

Unlike a gasoline-fueled engine, a diesel engine does not need to stay at the fuel's stoichiometric ratio. Therefore even if the energy content of the fuel changed, it would only hinder the full power operation and have no effect at partial throttle operation. This reduces overall engine system complexity and increases reliability.

Although many new diesel engines are utilizing homogeneous charge compression ignition (HCCI) direct injection systems, there are certain benefits to an indirectly injected, stratified charge compression ignition (SCCI) implemented by the DM-954 DT. With SCCI, combustion is initiated at the fuel rich spot in the pre-combustion chamber, propagating into the main combustion chamber into the cavities of the piston. The fuel rich point is important in achieving a full combustion, but also causes unburned fuel to puddle on cylinder walls before the rich point is ignited, leading to exhaust soot. However, due to the fuel rich ignition point, NOx formation is minimized. Conversely with HCCI, there is no fuel rich ignition point because it has a homogenous fuel concentration in the combustion chamber, resulting in minimal soot formation. While soot output is low due to a lean cylinder composition and raised cylinder temperature, NOx formation is very high. [4] When considering the emissions of an engine for our application, the required catalyst technologies were taken into account. While particulate filters can easily trap soot formed from combustion, reducing the NOx formed in HCCI engines to acceptable levels requires expensive catalysts, external exhaust injection systems, and exhaust gas recirculation technologies.

The ability of the DM954-DT to produce excellent horsepower while producing low CO, HC and NOx emissions output was the main factor for choosing the engine. The good low-speed torque of the engine, coupled with adequate overall power to achieve needed snowmobile speed, improves operator enjoyment. Great engine-out emissions are achieved by engine design, calibration and added low-cost catalysts. Prices remain low due to the simplicity of the design, along with easily manufactured components. When evaluating the three major design considerations of the snowmobile- the operator, manufacturer and the environment- we have concluded that the DM-954DT is the optimal choice.

INTERCOOLER SYSTEM

Design and Implementation

In forced induction engines charge cooling is often necessary to decrease inlet air temperature (IAT) for many reasons, the most important being decreased combustion temperatures, increased charge air density and increased combustion efficiency. [5] In-cylinder combustion temperatures are known to directly correlate with NOx formation in diesel engines; therefore decreasing combustion temperatures is fundamental in lowering NOx emissions. Brake specific fuel consumption is extremely reliant upon combustion efficiency, thus improving BSFC can yield large gains in fuel economy. These are all very important factors which can greatly affect fuel economy, power output and emissions from the engine. Given the potential improvements in these customer requirements it was decided that an intercooler would be used again on the snowmobile.

A liquid to air intercooler system was again chosen this year, eliminating the need for large air charge pipes throughout the engine bay and allowing for a high capacity of charge cooling, dissipating heat through the snowmobile's unused rear mounted heat exchanger for simplicity and low weight.

With unsatisfactory performance from the intercooler used on the 2013 sled, a new intercooler was designed. The new intercooler was designed to fit directly above the engine to completely eliminate the need for air charge pipes, reducing overall system size, weight and cost. In order to improve turbocharger transient response, intake volume was to be reduced dramatically. From the 2013 intake system, volume was reduced from 255 cubic inches to 76 cubic inches, a 70% reduction in volume. Excess intake track volume caused transient turbocharger behavior to become poor (turbocharger lag), as well as transient soot output to increase. Both of these factors affect the operator and environmental design requirements, thus causing a reduction in intake volume to become crucial.

Another goal was to significantly improve IAT's by the use of a higher quality intercooler core. To achieve this a Bell Intercooler liquid-air core was used. With a core density of 3 plates per inch it can transfer heat much more efficiently than the 2013 intercooler of 1.5 plates per inch. The increased core density increases heat transfer area, which provided more efficient cooling from the intercooler.

Using the Bell Intercooler core, the designed end tanks were manufactured from aluminum sheet and welded to the intercooler core. Total weld time was decreased from 6 hours to 3 hours due to the elimination of many aluminum components of the intake track, also significantly decreasing weight. The assembled intercooler was then bolted onto the turbocharger and factory intake manifold using silicone couplers for noise, vibration and harshness (NVH) isolation. The finished intercooler was then polished and beads were rolled onto the piping sections.

Testing and Validation

Once the intercooler was finished, testing began to quantify performance gains from the new intercooler. Initial testing was to measure the efficiency of both the 2014 and 2013 intercooler systems, Equation 2 shows the intercooler efficiency equation used.

$$Intercooler\ Efficiency = 1 - \frac{\substack{Post-Intercooler \\ Air\ Temperature}}{\substack{Pre-Intercooler \\ Air\ Temperature}}$$

Equation 2: Intercooler Efficiency Calculation

Testing was then completed using the UB CSC Team's Land and Sea Dynomite water-brake dynamometer, using thermocouples in the intake track to measure both pre and post intercooler air temperatures. Full load, full torque dynamometer runs were then completed for each intercooler system and multiple power levels, with steady state air temperatures being recorded. Using Equation 2 the intercooler efficiencies at each power level were then calculated and are shown by Figure 2.

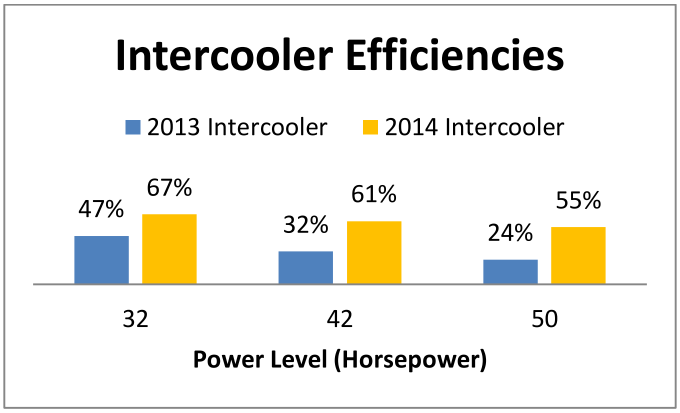

Figure 2: Intercooler Efficiencies by Power Level

As demonstrated by Figure 2, the 2014 intercooler was 55% efficient at 50 hp, while the preceding intercooler was less than half that. At this power level pre-intercooler air temperatures were over 200 degrees Fahrenheit, and if this temperature air were to enter the engine combustion temperatures would rise and NOx formation would be very high. [5] Therefore the 2014 intercooler is a very effective tool in lowering NOx emissions, maximizing power output, retaining fair transient operation and maintaining a simple, cost effective design.

TURBOCHARGER SELECTION

This year the turbocharger was an important design decision for the engine's operational emissions and power output. The turbocharger is a very critical component of the engine because it affects both intake air and the exhaust gas properties. Utilizing a correctly sized and implemented turbocharger can decrease emissions outputs, increase power output and improve transient engine operation characteristics. All of these factors are important to the operator, environment and manufacturer.

From the manufacturer the engine is equipped with an IHI RHF3 turbocharger. The RHF3 has a 22mm compressor inducer, can flow up to 9 lbs/min of air, and has the ability to maintain a maximum pressure ratio of 2.7. While 9 lbs/min (245 kg/hr) is an acceptable amount of air needed for the increased power output, the efficiency of the RHF3 is very low at this airflow. The peak compressor efficiency of the RHF3 is 72% at 7 lbs/min (190 kg/hr) and 2.0 pressure ratio (14.7 PSIG). Utilizing a higher efficiency compressor is important to reducing intake air temperatures, as a lower efficiency compressor increases air temperatures during the compression of the air. [11] Looking into dynamic test data from the engine, it was found that the RHF3, which was run on the snowmobile at the 2013 Challenge, was operating at approximately 59% efficiency. Therefore it was decided that the RHF3 was past the optimum efficiency point and the Garrett GT1541V turbocharger was then considered. The GT1541V has a 32mm compressor, which could flow approximately 13 lb/min of air and maintain a pressure ratio of 2.7. Comparatively the Garrett is much larger, designed for a much larger engine than the IHI, and is commonly used on engines 1200 cc or larger. Sizing a turbocharger for a diesel engine is especially difficult because airflow is often dependent upon the entire engine setup, and not solely based upon power output as with a gasoline engine. However because the RHF3 was proven to be out of the peak efficiency range, testing with the GT1541V was initiated.

With the GT1541V turbocharger installed on the engine, emissions and power output testing began. A UEI AGA5000 5-Gas Analyzer was used to measure HC, CO and NOx emissions with the GT1541V at different pressure ratios. At a constant fuel flow rate the new turbocharger increased power output from 47 hp to 55 hp and increased torque output from 70 to 90 ft-lbs. Engine emissions were also affected by the turbocharger. Figure 3 shows the results of the NOx emissions testing.

During calibration of various turbocharger pressure ratios, it was found that the brake specific NOx (BSNOx) emissions were minimized at a pressure ratio of 2.36 or 20 PSIG with the GT1541V turbocharger. Looking at data from the 2013 Challenge, the RHF3 produced greater BSNOx for all air fuel ratios when compared to the 20PSIG pressure setting of the GT1541V. At WOT the RHF3 produced 5.833 g/kW-hr of NOx while the GT1541V produced only 2.679 g/kW-hr of NOx. Therefore the GT1541V was proven to be the superior choice when considering BSNOx.

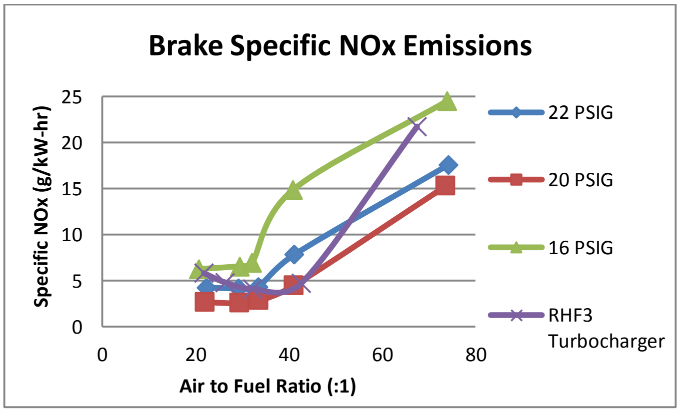

Figure 3: GT1541V vs. RHF3 Turbocharger BSNOx

While the GT1541V did produce lowered NOx emissions, it is important to verify that the turbocharger is still within a high efficiency performance range. Figure 4 shows the compressor map for the GT1541, giving the efficiency of the compressor at various pressure ratios and mass flow rates.

Operating the engine at a power level of 55 hp, it was found to flow 265 kg/hr, or 10 lb/min. Using the minimized BSNOx pressure ratio of 2.36 and a 10lb/min mass flow, compressor efficiency is approximately 78% shown by the red X on Figure 4. Comparatively the GT1541 is 19% more efficient on the engine, thus contributing to decreased emissions as shown by Figure 3 and increased power output.

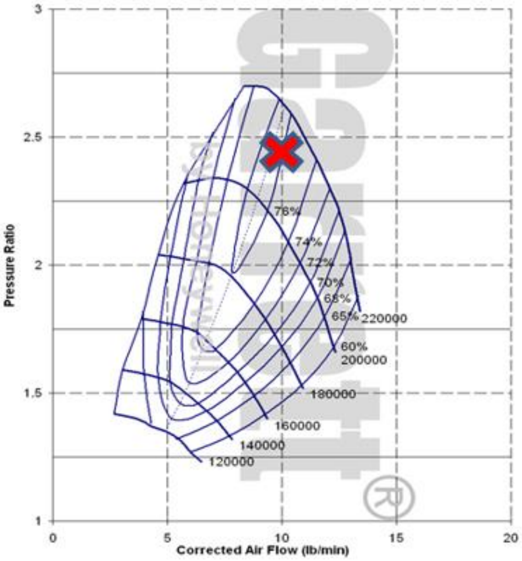

Figure 4: GT1541 Compressor Map (Courtesy of Garrett)

When considering the benefits in terms of emissions, power and efficiency, the GT1541 satisfies all design considerations. While the price of the turbocharger is significant, the GT1541 is on par with the cost of the RHF3, but clearly outperforms it. Therefore it was decided that the GT1541 would be used on the snowmobile for the customer and environmental design consideration benefits.

ENGINE MOUNTS

Design and Implementation

With durability being a major priority this year, the engine mounts were redesigned in order to achieve increased reliability, riding enjoyment, and decreased vibration. Due to the inherent imbalance of a 3-cylinder engine, past teams have been plagued with engine mount issues. [6] These issues have consisted of excessive fatigue, unwanted vibrations, and ultimately failure.

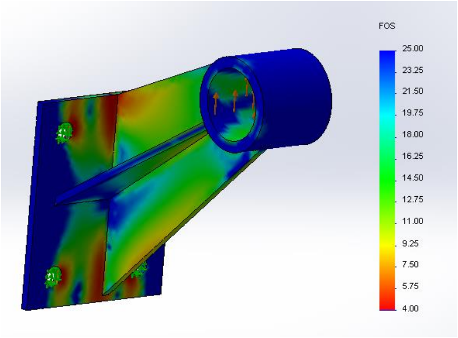

Figure 5. Right Side Engine Mount FOS Plot

This year the mounts were designed to isolate vibration, while still providing excellent support to the engine as simple and cost effective as possible.

This was accomplished using 4130 steel. This steel provided a high strength to weight ratio, allowing an increase in strength and decrease in weight of the engine mounts. High density polyurethane bushings were utilized to allow a reduction in mechanical vibrations transmitted to the chassis from the engine. Shown in Figures 5 and 6 is the factor of safety plots for both left and right side engine mounts, having a minimum factor of safety of 3.5 with 300 lbf applied to each mount. This force corresponds with a 1 foot vertical drop of the front suspension, representing a slight bump or drop located on a trail during slightly aggressive riding.

The axis of rotation for both mounts (the axis of the through bolts for the mounts) is offset between the different side mounts. Offset axes of rotation provide different primary functions for both mounts; the right mount provides acceleration torque resistance, while the left mount provides the braking torque resistance of the engine. Varying major tasks of the mounts decreases the range of stress realized by each mount, thus decreasing any fatigue effects the steel might see.

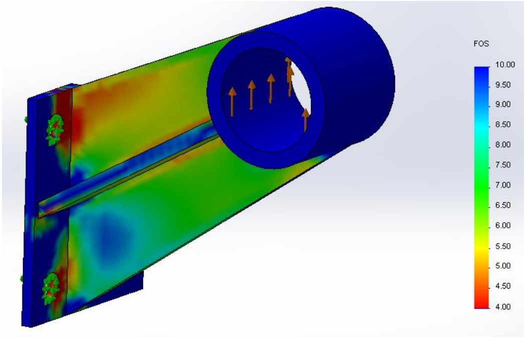

Figure 6. Left Side Engine Mount FOS Plot

Manufacturablility remains simple and inexpensive by designing the mounts from plate steel, which can then be cut using any number of processes, and welded together for final assembly. This illustrates the positive manufacturer considerations of the engine mount assembly by limiting costs, but still maintaining product life through durability.

Testing and Validation

The engine mounts were installed and tested for a total of 200 total test miles, then removed for inspection. All welds were inspected for cracking and surfaces measured for warping or bending. No weld cracks were found and all faces measured within .010" of their original geometry, thus confirming their successful use. They were then powder coated for aesthetic purposes. The engine mounts have proven to be very effective both in terms of their simplistic design, low weight and cost thus fulfilling their environmental, operator and manufacturer design requirements.

FUEL SYSTEM

In previous years power output was increased dramatically due to the changes in the fuel injection pump of the engine. Previously, a modified Bosch VE-9A4 was run with modified plunger depth, for increased fuel delivery capabilities. The current engine's injection pump, a Bosch VE-9UH, was feared incapable of delivering the needed fuel mass for the desired power level. Further investigation into the fuel pump found that while the plunger volume was decreased, it was equipped with a varying injection pulse width timing device. This allows the increase in duration of the fuel injection, providing an equal amount of fuel to be delivered as the previous modified injection pump. This variable pulse width is also a key contributor to the exceptional fuel economy of the engine. Due to the fact that the engine utilizes a mechanical indirect injection fuel system, it operates without any computer control. Therefore fuel quantity injected is conventionally calculated off of a simple linear relationship from engine speed and load, varying injection advance to achieve the correct quantity of fuel. However when injection pulse width is able to vary, the fuel advance does not need to be so large, being able to also retard the injection deeper into the combustion stage. As shown in Figure 3 this allows for a more controlled fuel quantity, lowering soot emissions and maintaining power output.

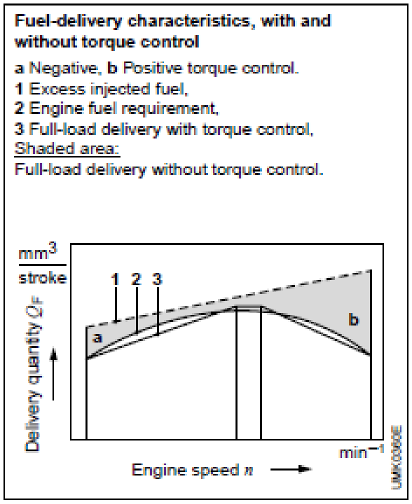

Figure 7. Bosch VE-9UH Torque Control Diagram

Varying injection pulse width, also called torque control, allows for a longer injection period, which corresponds to increased ignition lag. The ignition lag, or time from the injection event to the time of the ignition, allows for the proper in cylinder air fuel mixture distribution to achieve efficient combustion. The more homogeneous fuel mixture reduces the unburned fuel content of the exhaust gases, improving HC and soot emissions of the engine. This choice of injection pump demonstrates the snowmobiles attentiveness to user function in terms of both power output and fuel economy, while also decreasing tailpipe emissions to improve the snowmobile impact on the operational environment.

COOLING SYSTEM

Design and Implementation

A persistent obstacle which must be addressed when implementing a diesel engine into a snowmobile is generating the cooling capacity needed to cool the engine. An engine has a very specific operating temperature range in which; too low and combustion efficiency is negatively affected, or too high and mechanical failure likelihood is increased. [6] In order to achieve optimal operating temperatures in the engine, changes were made to optimize the cooling rate of the engine and facilitate the removal of heat from temperature sensitive areas of the engine.

The use of a 1.5" core Mishimoto radiator, constructed from 5052 aluminum, was chosen to provide sufficient cooling capacity for the engine. This radiator has a thicker core than those used in previous years, allowing for a smaller footprint in the chassis of the snowmobile while still having ample heat dissipation capabilities. The radiator is a standard tube and fin radiator with a tube thickness of 0.125" and a fin height of 0.25".

Utilizing a radiator with a thicker core than previous years provides adequate cooling of the engine's water while also having smaller overall dimensions to fit better in the space provided by the snowmobile chassis. The chosen radiator was selected with price in mind, and is fabricated with sheet end tanks, and was produced for a relatively low price.

Various methods were used to achieve maximum cooling efficiency in the setup of the radiator. The radiator was placed at a 60° angle to the horizontal to maximize the velocity of the incoming air. In previous designs the radiator was placed at a higher angle with respect to the horizontal, which created zones of high-pressure air directly behind the radiator. These high-pressure zones formed due to the location of chassis sheet metal directly behind the radiator. By setting the radiator in the chassis at an angle, the flow of air has a much more direct route to follow, creating a zone of lower pressure behind the radiator, facilitating high velocity airflow, and aiding in the dissipation of heat.

Testing and Validation

During the 2013 competition a continuous problem with engine cooling prevented the snowmobile from operating reliably during high load. During testing for the 2014 Challenge, the CPC quick disconnects used in the cooling system were suspected to be inhibiting the cooling system's ability.

In order to characterize the losses in flow accompanied by the use of the CPC quick disconnect Bernoulli's equation was used, shown by Equation 3. Couplings, fittings, valves and pipe bends are known as minor losses in a pipe flow system. The quick disconnect was simplified as a sudden contraction, followed by a sudden expansion in the diameter of the flow path. This simplification shows the impact on the flow as a best case scenario, as changes in flow direction will further negatively impact the flow of the fluid through the system.

$$\left(\frac{p_1}{2} + \alpha_1 * \frac{V_1^2}{2} + gz_1\right) - \left(\frac{p_2}{2} + \alpha_2 * \frac{V_2^2}{2} + gz_2\right) = h_{lT} = \Delta p_T$$

Equation 3: Bernoulli's Equation

In this best-case scenario analysis a pressure rise of 4.1 psi is directly attributable to the inclusion of the quick disconnects in the system using the Darcy-Weisbach equation shown by Equation 4. This pressure rise causes energy losses which cascade through the system, as the water pump must do additional work to force the fluid through the quick disconnect. [7]

$$\Delta p = h_l = f\ (L\ /\ D)\ (\rho\ V^2\ /\ 2)$$

Equation 4: Darcy-Weisbach Equation

The coolant flowing through the system is accelerated to at least 270% faster than the fluid traveling through our coolant lines. Removing the quick disconnects eliminates both the 4.1 psi pressure rise and increased coolant velocity, resulted in a more efficient cooling system, and increased heat dissipation rates. The impact from these connectors is shown by Table 2, in which coolant temperatures were allowed to settle to their steady state value during various engine loads.

Steady State Coolant Temperatures (*F)

Engine Load	With CPC Quick Disconnects	Without CPC Quick Disconnects
0%	180	168
20%	181	172
40%	185	176
60%	193	180
80%	210	180
100%	225	180

Table 2: Steady-State Engine Coolant Temperatures

Engine coolant temperatures at 100% load are decreased by 45 *F, much below the overheating threshold. The design of the cooling system illustrates all of the intended considerations of the snowmobile in general. The overall high efficiency of the cooling system improves the operator interaction by preventing any overheating and subsequent poor operation of the engine. With the engine staying within the desired operating temperature, engine life is prolonged enormously and reliability is improved, positively affecting both the manufacturer and the operator.

ECO SYSTEM

Mechanically fuel injection and governor greatly reduces the electrical components needed to operate the DM-954DT, improving the engine's simplicity, cost effectiveness and reliability. However it creates serious constraints in the control of the outputs, namely power, fuel consumption and emissions. This causes a problem because all of these factors are interdependent, and without adequate control over all operating engine parameters these three factors cannot be simultaneously optimized. For the 2014 Challenge a user selectable switch may be used to switch between a performance and economy mode. [1] When decreased power is required, fuel injection quantities are decreased across the engine speed spectrum; however airflow can then diverge from the optimum point in terms of emissions outputs. Therefore an "Eco-Mode" can be used when required power output is reduced and a "Power mode" can be activated when needed. Transient engine characteristics are difficult to regulate because of the open loop dynamics of a mechanical injection system. Giving the engine any type of closed loop operating condition dramatically increases control of necessary operating parameters. [8] Therefore an "Eco-System" was developed using an Arduino micro-controller to increase the dynamic control of the engine to improve the low power operating conditions, transient characteristics, and to add closed loop engine control.

Design and Implementation

To improve emissions outputs during decreased power situations both fuel injection quantity and turbocharger pressure ratio must be altered. Through testing demonstrated in Figure 3, it was determined that at the engine power level of 55 hp optimum BSNOx pressure ratio was 2.36. However during normal trail riding when power is not needed for acceleration, decreasing power output can decrease engine BSFC by causing the engine to operate at peak torque. This trend can be seen in Figure 1, where BSFC is minimized at peak engine torque speed of 2200 rpm. On the Bosch VE injection pump there are three main controls: throttle lever, idle speed set screw and fuel quantity gain screw. Decreasing the gain of the fuel injection pump decreases fuel injection quantity and power output, thus improving fuel economy and emissions outputs. [4] Therefore it was decided that the gain screw of the injection pump would be dependent upon user power demands.

Transient operation of turbocharged engines is often subpar because of the principles on which turbochargers function: using spent exhaust gases to spin a compressor which feeds the intake track of the engine. [5] Therefore in the positive transient operation of accelerating, with little previous exhaust gases present the turbocharger cannot provide adequate air to the engine. This causes the engine's air fuel ratio to be lower than ideal causing soot formation to be high. [6] Therefore in order to correct this period of high soot formation, fuel flow should be restricted until adequate air is being supplied by the turbocharger. From these concepts it was decided that the UB CSC Team would reduce fuel injection quantity by use of the injection pump's fuel gain screw. The fuel injection quantity would be reduced when the manifold air pressure (MAP) sensor detected atmospheric pressure inside of the manifold. Once the MAP sensor detected air pressure, the gain screw would slowly increase fuel injection quantity until the standard level was reached.

An Arduino micro-controller was decided to be the main computer controlling the system because of the low cost, high reliability and flexibility in controlling the system. To precisely control fuel injection quantity by actuating the fuel quantity gain screw, a small stepper motor was implemented which is easily controlled by the Arduino. A Bosch temperature-manifold air pressure (TMAP) measures both air temperature and pressure for determining fuel injection quantity. Another very important parameter to monitor is exhaust gas temperature (EGT). At extended periods of high speed, full load operation EGTs can become dangerously high causing an increased risk of mechanical failures, as well as raised NOx formation. An EGT thermocouple probe was inserted into the exhaust and connected to the Arduino for reference during WOT operation. When the EGTs exceed a pre-determined threshold the Arduino then commands a reduced quantity of fuel to be injected. Using a specially designed transfer function the Arduino works to decrease EGTs until they are within acceptable limits. To successfully design a transfer function for the Arduino's EGT control Simulink was employed to develop a functional model. The required transient response characteristics such as rise time, percent overshoot and settling time were then used to design the controller [8] shown by Figure 8.

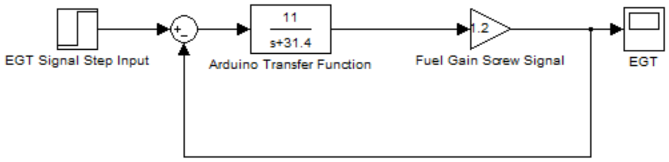

Figure 8: Arduino EGT Control System

To better illustrate the Eco-System's connections and various control functions Figure 9 was created. This diagram displays the different sub-systems and their integration into the overall system, as well as the hardware to software interfaces, which were made in order to operate the control function effectively. As shown by the diagram, inputs to the Arduino micro-controller are the user selected calibration switch position, throttle position, exhaust gas temperature, intake air temperature and pressure, while the outputs are fuel gain screw stepper motor position and turbocharger boost control duty cycle.

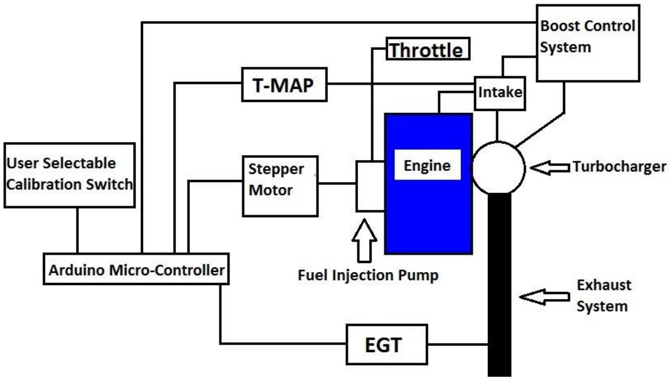

Figure 9: Eco-System Block Diagram

Testing and Validation

Emissions testing of the engine were completed with the Eco-System installed and calibrated to the specified parameters using the Arduino IDE. Similar to the intercooler testing, the UEI AGA5000 was used to measure HC, NOx and CO outputs of the engine while load was applied via a Land and Sea water brake dynamometer. The 5-mode lab emissions test completed at the CSC was replicated and the results recorded and analyzed.

The AGA 5000 displays results in PPM, which needs to be converted to a mass flow for E-score calculation. Using a Bosch hot-wire mass airflow sensor, and Land and Sea fuel flow transducers, exhaust mass flow can be calculated. Once exhaust mass flow is known HC, NOx and CO mass flow rates can then be calculated from measured data during emissions testing. These emissions mass flow rates are then weighted and normalized by power output for each mode. The results are shown in Figure 10, as well as the 2013 Challenge emissions results.

An E-Score of 206.6 was achieved at the 2013 Challenge, and during testing of the 2014 snowmobile "Power Mode" achieved an E-Score of 206.9. While this is still very respectable, the "Eco-Mode" of the 2014 snowmobile attained an E-Score of 207.8 out of a total 210.

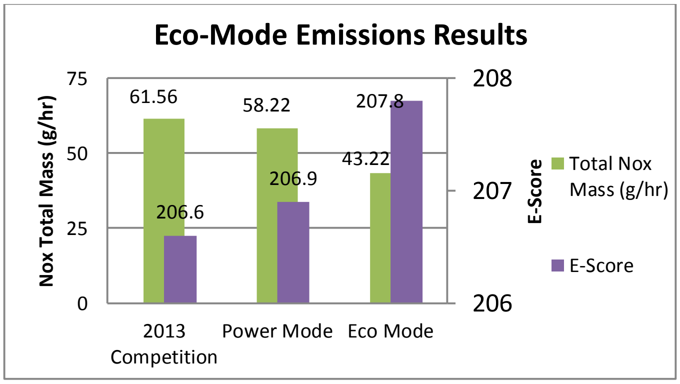

Figure 10: Emissions Measurements and Calculated E-Scores

The Eco-System in Power-mode achieved 55 hp and 90 ft-lbs of torque, and in Eco-mode achieved 49 hp and 79 ft-lbs as shown in Figure 11. Operator interaction with the snowmobile is improved with the Eco-System by giving increased power when needed resulting in a more enjoyable experience. Fuel economy is also improved reducing the operator's cost of riding and increasing distance to travel before refilling the tank. Giving the operator a choice also increases the interactions between the rider and snowmobile, which gives added confidence and likability in the snowmobile.

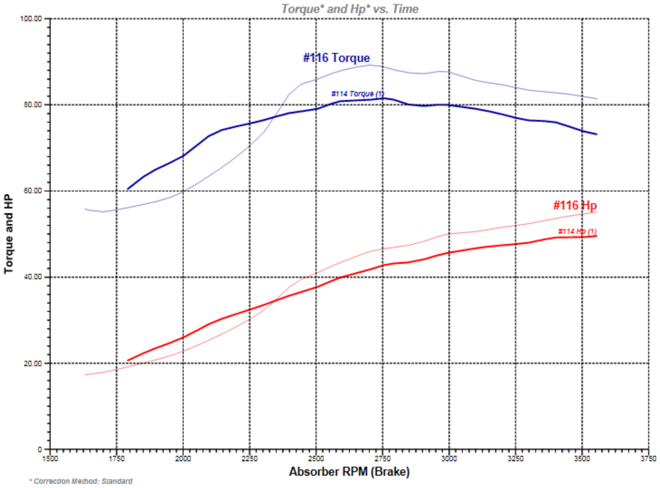

Figure 11: Dynamometer Power vs. Eco Mode Data

The manufacturer benefits from the Eco-System by the low cost parts utilized and the system's simplicity, reducing part counts. EGT sensing and control also gives improved engine reliability by decreasing high combustion temperatures causing mechanical failures. Transient soot reduction demonstrates the environmental design considerations, as does the decreased NOx formation during both modes. The Eco-mode's fuel injection quantity reduction also improves the snowmobile's fuel consumption further benefiting the environment.

EXHAUST SYSTEM

Exhaust Treatment

The engine is used in off-road applications that currently do not have strict emissions regulations. Since it is not necessary, the stock motor is not equipped with a system to control oxides of nitrogen (NOx), hydrocarbons (HC), or particulate matter (PM) output. In addition, more fuel is being used by the motor in order in increase power to a useable level. This will bring the emissions, specifically the NO_x and particulate matter, to an unacceptable point. To control this, a diesel oxidation catalyst and a diesel particulate filter are being used collectively to achieve this goal. [9]

The oxidation catalyst is used to reduce the hydrocarbon, carbon monoxide, and NO_x levels by converting each one to H_2O, CO_2, and NO_2, respectively. The water and carbon dioxide will exit the tail pipe as harmless compounds, while the particulate filter will use the nitrogen dioxide downstream. Figure 12 demonstrates the effect the Emitec DOC had on emissions testing. In mode 1 testing the DOC reduced NOx by 117 g/hr, a 42% reduction.

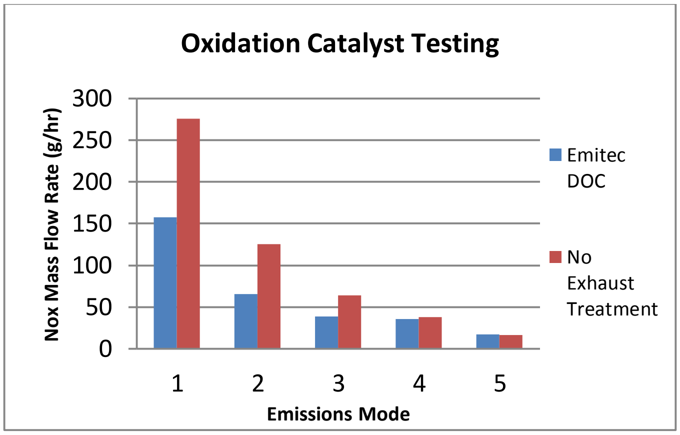

Figure 12: Oxidation Catalyst Testing

The oxidation catalyst used is optimized for NO_2 production and is coated with Platinum to interact with the harmful HC's and CO to create safer emissions. This unit is produced by Emitec and is placed post turbine in the exhaust system. It requires high EGTs to function properly, therefore it has been placed as close to the turbine as the engine bay geometry allows. The catalyst has been encased in exhaust wrap to retain as much heat as possible.

The diesel particulate filter (DPF) will reduce the amount of particulate matter, or soot, exiting the tail pipe. There are two main types of filters, active and passive. Both collect particulate matter to be burned off with the use of relatively high EGTs. Automobile manufacturers commonly employ the active system, as packaging does not allow the DPF to be located in an area with high temperatures. This necessitates a regenerative cycle of abnormally high EGTs to burn off the collected particulate matter. An engine control unit and specific engine calibration are required to periodically raise the EGTs to the desired level. A sensor determines when the DPF is full and the regenerative cycle must initiate. It was decided that without the correct sensors and ECU, this would be an expensive and complicated system to implement; therefore a passive system was employed. This style requires constantly high EGTs and a particular oxidation catalyst. The soot will interact with oxygen at a temperature of 600°C, but with the NO_2 produced by the catalyst at 250°C. The DPF is located immediately after the oxidation catalyst to ensure this temperature level is met. To ensure correct functionality, the DPF was also sourced from Emitec. This pair is used to reduce the particulate matter by up to 77%, and hydrocarbon and carbon monoxide by up 90%. [9]

The environment was the leading design factor driving the decision to employ the Emitec DOC/DPF combination for the decreased HC, CO, NOx and particulate emissions. The reduction of particulate matter also improves operator enjoyment by appearing to have much cleaner tailpipe emissions.

Exhaust Manifold

Design and Implementation

When installing an upgraded turbocharger on an engine it is typically necessary to replace the exhaust manifold. This is a result of differences in both turbocharger positioning and turbine housing mounting flanges. Because of the choice of the upgraded turbocharger it was decided that the most effective way of implementing said turbocharger would be with the fabrication of a new, custom exhaust manifold. The exhaust manifold is needed to meet many different criterions to be a positive modification of the snowmobile; the most important being that the turbocharger needed to be positioned in a better orientation than where the factory manifold would have positioned it. Other important considerations were flow characteristics and simplicity of fabrication. The factory exhaust manifold was considered as a possible option by utilizing an adapter plate to fit the new turbocharger's exhaust flange. The main drawback of the factory manifold was that the turbocharger's center rotational housing was at an angle that was outside of the manufacturer's suggested limit. In light of these considerations, it was decided that rather than implementing an intricate tubular manifold design, the best option was a simple log style manifold.

The fabrication process for the exhaust manifold was very short and simple. The tubing used was ¾" 304 stainless steel schedule 10 tubing and the flanges were laser cut from ¼" 304 stainless steel plate. All of the tubing was then cut to the appropriate lengths and TIG welded together. The manifold's main body consisted of one large flange, two ninety-degree tubes, and one tee piece. These parts of the manifold were welded together first. After the correct angle for the turbocharger flange was determined, the flange was welded to a reducer and then to the main body. The total time required to fabricate and weld the exhaust manifold was 3 hours and the material cost was approximately $30 dollars. This low cost and fabrication time would allow the manufacturer to easily and cost effectively implement this design into the production snowmobile. After the exhaust manifold was built, it was tested to determine if it truly met the design criteria.

Testing and Validation

The first test performed on the new exhaust manifold was a fitment test. This test would determine whether the turbocharger was positioned at the correct angle per manufacturer specifications and whether the turbocharger interfered with any of the surrounding components. It was immediately clear that the turbocharger was not contacting any other components and the angle of the center rotational housing was 2.3 degrees, well within the manufacturer's specified range. The second test conducted on the new exhaust manifold was used to determine possible performance benefits of the manifold's design. To quantify possible performance advantages, a flow analysis was performed on a model of the factory exhaust manifold, as well as on the new manifold design using SolidWorks. The resultant flow trajectories are shown in Figures 13 and 14 below.

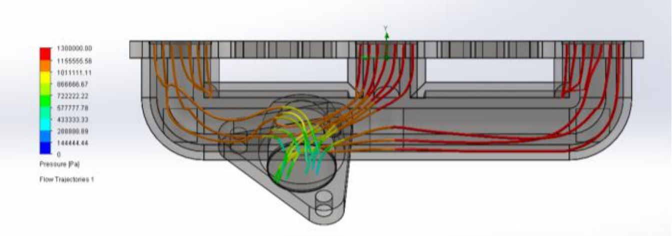

Figure 13: Factory Exhaust Manifold CFD

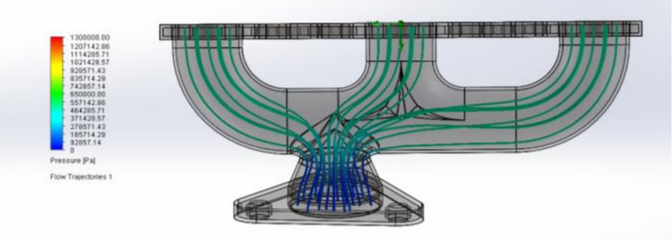

Figure 14: New Exhaust Manifold CFD

When analyzing these results the difference in flow characteristics between the two manifolds was immediately noticeable. The analysis showed that the factory manifold created 1200 kPa of backpressure and created a large vortex directly before the outlet. The backpressure was also very uneven in the factory manifold, which can highly impact performance and efficiency. [10] The new design created only 500 kPa of backpressure along with no vortices. Based on the results of these tests it was evident that the new log manifold allowed for correct turbocharger placement, possessed far superior flow characteristics than the factory unit, and was very simple to fabricate, making it the easy choice as the best exhaust manifold option. Other positive aspects of the new manifold design were a reduction in weight of almost two pounds, easier serviceability of the turbocharger and surrounding components, and the ability to implement a very short intake tract.

BELT DRIVE SYSTEM

Design and Implementation

The operating engine speed range of this diesel engine is less than half that of the gasoline motor typically found in the chassis. Due to this, the stock final drive ratio is incompatible. This left the option of either modifying the existing chain drive with an optimized sprocket ratio or finding a completely different solution.

Belt driven power transmission systems are one of the most durable and efficient power transmission systems on the market today. They can achieve efficiency ratings of 96 to 98% and are becoming more and more prominent in the snowmobile industry. Due to the nylon-coated teeth on the belt, noise is reduced drastically compared to that of the steel on steel contact on a chain driven system. The rider will notice the smoother and quieter operation of the belt drive. The lifespan of the belts are statistically 3 times longer than steel chains [11], reducing the maintenance costs. Belt drive systems also do not need to be contained in a sealed case subjected to a constant oil bath. This decreases the weight of system, produces less drag force, and totally eliminates the use of toxic petroleum products. Because no sealed case is needed, the ease of maintenance and part interchangeability increases drastically. Draining the oil and disassembling the case is no longer needed when replacing or upgrading parts, which is appealing to the end user. The parts count will remain the same, but less material will need to be purchased and machined since full enclosure is not required. Because of all of these benefits, our team decided to pursue the concept of the belt drive system.

Research revealed that there were aftermarket options available to retrofit belt drive systems to snowmobiles. Unfortunately, there were none available for the Polaris 600 IQ Shift. This would have led to modifying the mount for the system and the center-to-center distance between the two pulleys. After that, the final drive ratios would still have to be corrected to match the diesel operating range. It was quickly decided that designing a custom belt drive system would be a more cost effective solution. The initial design was modeled in Solidworks seen in Figure 15 below.

Figure 15. Belt Drive Assembly Designed in SolidWorks

Following the trend of the stock chain case and aftermarket options, the assembly's back plate was machined from a single billet of 6061 aluminum. This would retain the same weight as the part it was replacing. An adjustable belt tensioner was added to this year's model, which allowed for quick belt adjustability as well as the ability to swap out different pulley sizes and belt lengths to optimize snowmobile performance. The industry leading Gate's Poly Chain GT Carbon Belt was chosen because of its durability, low noise characteristics, high efficiency, and availability.

In order to keep cost down, steel was chosen, rather than aluminum, as the production material of the drive pulleys. Steel has a high enough strength and durability without the treatment that aluminum would require. The pulleys were designed based off the belt choice, therefore the tooth pattern is well known. Pfeifer Industries, a manufacturer of timing belt pulleys, was able to fabricate both the drive and driven pulleys to the ratio required. After calculation and testing, a 34-tooth drive pulley and 49-tooth driven pulley were ordered resulting in a final drive ratio of 1.44. Considering the engine's maximum speed and the overdrive provided by the CVT's, the maximum vehicle speed is 70 miles per hour. The design allows for this to be easily altered since the pulleys are mounted on a studded hub, rather than a splined bore.

Final Drive Calculations

	Stock Chain Drive	2013 Belt Drive	2014 Belt Drive
Drive (teeth)	23	32	34
Driven (teeth)	39	53	49
Drive Ratio (unitless)	1.69	1.65	1.44
Top Speed (mph)	59.3	60.7	69.8

Table 3: Theoretical Final Drive Top Speeds

Testing and Validation

Once solid modeled, an FEA was done on both the drive and driven pulleys using AISI 1020 steel as the material. The results are shown in Figures 16 and 17.

The results from dynamometer testing determined the max torque produced by the engine is 86 lb-ft. Using this maximum value, the following calculation was conducted:

Input Torque (M_i): 86 lb-ft = 1032 lb-in

Max CVT Ratio (r): 3.5:1

$$M_o = M_i * r$$

Equation 5: Gear Reduction Formula

Using Equation 5, the torque that is applied to the driver pulley from the CVT was calculated to be 3360 lb-in. Through angle of wrap calculations and solid model simulation, it was determined that 22 teeth will be in contact with the belt at once. Therefore, the torque was then divided on to each of the 22 teeth. The FEA of the pulley's stress distribution is shown in

Figure 16. The figure shows that the highest concentration of stress occurs only around the boltholes and results in a factor of safety of 2.2, which is an acceptable safety rating for trail riding purposes.

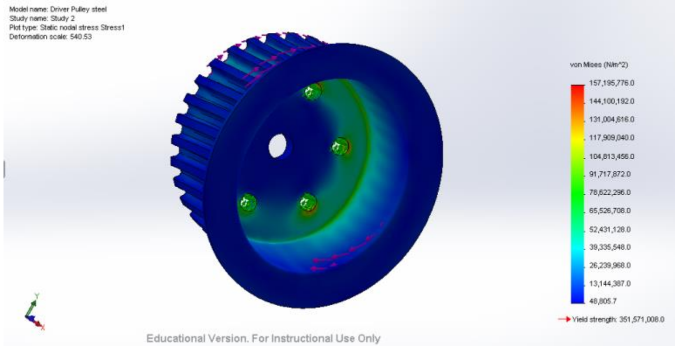

Figure 16: Von Mises Stresses and Exaggerated Deformation of Driver Pulley

The same process was executed for the driven pulley as well. A torque of 7715.4 lb-in was calculated and applied to the pulley and distributed to 31 teeth. The FEA simulation, shown in Figure 17, shows a concentration of forces around the mounting holes as expected. The factor of safety for the driven pulley is 3.6.

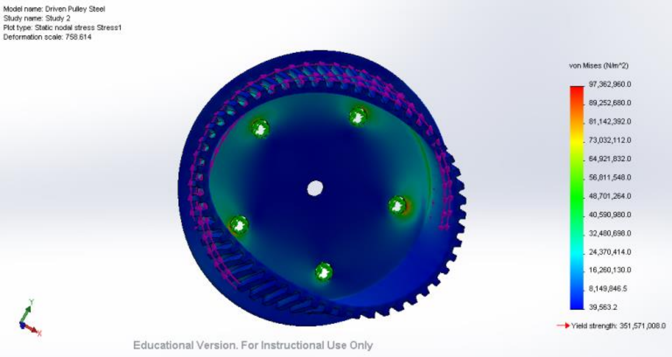

Figure 17: Von Mises Stresses and Exaggerated Deformation of Driven Pulley

SUSPENSION

Design and Implementation

A properly tuned suspension can make or break how a rider judges the quality of a snowmobile. The suspension system is what determines the capabilities of a sled and dictates how fast or how slow you can go when trying to traverse various terrains. The UB CSC Team recognized the importance of meeting the needs of the operator, and how a well-tuned suspension is instrumental to an exciting riding experience.

At the beginning of this year the overall handling of the snowmobile was a major concern. Due to a 30% increase in weight over the stock 600 Shift IQ, the first generation Team Fast Air M10 suspension did not have the range of travel or robustness necessary to provide a strong, responsive suspension. However, there are benefits to this suspension's sub frame, in that it was lightweight and could be easily implemented on the IQ Shift chassis, along with the ability to mount different shocks to account for the increased weight. The center shock in the M10 air suspension had a limited travel of only 1.25" and a maximum air pressure of 120 psi. Through preliminary testing this shock failed to withstand the added weight during a towing situation. This shock has been replaced with a Team Fast M10 Gas Shock. By switching to this type of shock a number of benefits were realized. One such benefit was preloading the shock after installation; this increased the static ride height of the snowmobile up to 6". This was made possible due to the fact that the gas shock's rebound was controlled by a mechanical spring rather than air pressure, allowing for a more even weight distribution between the track and skis. While the air shock was a more forgiving shock absorber, the gas shock improved reliability, which was paramount to the suspension system.

Another important suspension component considered for improvement was the skis. C&A Pro XTX skis were chosen due to their designed handling characteristics of extremely acute cutting during turning. This wider ski allowed for a wider stance, ski edge to ski edge, improved from 47" to 48.5". Having a wider ski stance, even by a small distance, was crucial to improving the stability during turning with the added weight. Equation 6 demonstrates the calculation for front lateral load transfer.

$$\Delta W_{YF} = \frac{W A_Y H}{t}\left(\frac{K_{\phi\mathrm{Front}}}{K_{\phi\mathrm{Total}}}\right) + W A_Y\left(\frac{b}{l}\right)\left(\frac{Z_{RF}}{t}\right)$$

Equation 6: Lateral Load Transfer Equation

The engine was mounted considerably higher than the stock position for packaging reasons. This increased weight at a higher vertical position caused the center of gravity height (H) to increase. Shown by Equation 6, an increased H increases lateral load transfer during lateral acceleration, reducing the overall lateral force capability of the skis. [12] This reduced lateral force capability not only contributed to poor handling characteristics, but also increased risk of rollover. By widening the stance of the snowmobile, increasing track with (t) in Equation 6, the CG height (H) remained high however the lateral load transfer (ΔW_{YF}) decreased. Therefore this ski choice effectively improved the overall lateral acceleration of the snowmobile by decreasing lateral load transfer.

Testing and Validation

In order to test the improvements in the suspension and handling of the snowmobile a series of controlled tests were established with the intent of quantifying both the steady state and transient handling characteristics of the snowmobile. These tests were conducted using the same snow conditions for each run and the variables that were tested include shock pressures and skis. By testing a variety of pressures the goal was to optimize the suspension setup to accommodate for the 30%

increase in weight. The first test used a 60ft. radius circular track to determine the maximum lateral acceleration under steady state conditions given the specific suspension settings. The faster the sled was able to go the more stable it would be during normal riding. To make sure the snowmobile was equally stable turning both directions this test was performed both clockwise and counterclockwise. The second test was a slalom course where 6 cones were set up 35ft apart to test the agility of the snowmobile's handling during transient conditions. In that test the rider started 50ft before the first cone to get up to speed before entering the course. The results of the testing are shown in Figure 18.

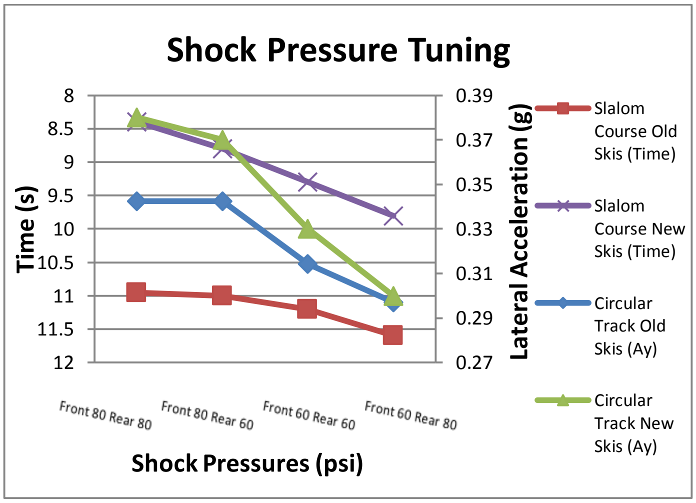

Figure 18: Suspension Shock Pressure Tuning

The above figure relays several important tuning specifications for the snowmobile. First of all, when the front shocks are set to a higher pressure the effect of varying the rear air shock has little effect on the average lateral acceleration (Ay) and had only a small increase in the time through the slalom course. Alternatively when the front shocks are set to a lower pressure the effects can be noted by the sharp decline of lateral acceleration. Overall it has been determined that with higher pressures in the front and rear shocks the snowmobile handling improved. By upgrading the skis it can be seen that significant improvements were made particularly in the slalom course test. The wider skis along with larger carbides accounted for 22% faster runs through the course.

Overall handling characteristics of the 2014 UB CSC snowmobile were studied in order to achieve a more exciting and enjoyable riding experience for the operator. This has been accomplished through the use of upgraded front skis and the meticulous testing and tuning of the suspension setup. Improved handling also benefits the manufacturer by producing a more rounded sled, able to be sold to a wider market of snowmobilers. Because the basis of the snowmobile is for the recreation of the operator, it was deemed very important to perfect this system.

CONCLUSION

Implementing a diesel fueled engine into a snowmobile application has its apparent difficulties, but when properly executed can provide excellent fuel economy, very low HC, CO, NOx and soot emissions, good reliability and maintain performance levels of an average snowmobile. The UB CSC Team accomplished this through the design considerations of the operator, environment, and the manufacturer applied to various systems of the snowmobile as follows.

- The engine was selected for being efficient and cost effective by utilizing indirect injection, turbocharged diesel.
- Calibration of the engine was performed to optimize emissions and power output through extensive theoretical and experimental research, producing 53 horsepower and 89 ft-lbs of torque.
- To give the operator increased control, improved fuel economy and lowered emissions an Eco-System was developed, allowing an E-Score of 208 to be reached.
- Engine mounts were fabricated having a high strength to weight ratio for increased reliability with a minimum factor of safety of 3.5.
- The cooling system was developed to efficiently maintain desired engine temperatures in all situations, and eliminate potential restrictions in coolant flow.
- An intercooler was refined to properly cool the charge air, reducing brake specific NOx, and deliver the cooled air charge to effectively increasing power output.
- A belt drive was engineered to implement a more effective drive ratio, increase driveline efficiency, improve fuel economy and reduce maintenance required.
- Tailpipe emissions were reduced by the use of an Emitec Diesel Particulate Filter and Diesel Oxidation Catalyst, maintaining high catalyst efficiencies with a specially designed exhaust system and calibration.
- Handling was enhanced by theoretical evaluation leading to suspension modifications and shock pressure tuning to improve transient handling characteristics as well as maximum lateral acceleration to 0.38g.

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