Proving Diesel Engine Viability for Utility Snowmobile Applications

Nicholas Lanzano, Anthony Marchesiello, Zachery Willis
State University of New York at Buffalo

ABSTRACT

For the 2015 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 a utility snowmobile while retaining the performance, cost, and reliability that riders and manufacturers require. This year the UB CSC Team implemented a three-cylinder Daihatsu/Briggs and Stratton, DM-954DT turbo diesel engine into a 2011 Polaris IQ 600 LXT utility 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 use in utility snowmobiles while also improving emissions.

An intercooled intake system was paired with a Garrett GT1541V turbocharger for decreased oxides of nitrogen (NOx) formation, lowered exhaust gas temperatures, and increased power output. Emissions control was addressed by employing an Emitec diesel oxidation catalyst (DOC) and diesel particulate filter (DPF) combination. Overall, the 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 to yield an increase in both handling characteristics and towing capacity. Through these improvements, the UB CSC team has proven that a diesel engine is a viable solution for a low emission, efficient and capable utility snowmobile.

INTRODUCTION

Over the past decade, the awareness of the negative effects internal combustion engines can have on the environment has 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. It has caused an ever-growing need for development of new technologies to make snowmobiles cleaner, quieter, and more efficient. The Clean Snowmobile Challenge is a collegiate design competition for student members of SAE to reengineer a current production snowmobile with the goal of reducing 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 hydrocarbon (HC), carbon monoxide (CO) and NOx measurements to quantify and rank the emissions outputs of the snowmobiles.

$$E - Score = 100\left(1 - \frac{HC + NOx - 15}{150}\right) + 100\left(1 - \frac{CO}{400}\right)$$

Equation 1: E-Score Equation for Emissions Testing

For the 2015 CSC competition, snowmobiles utilizing diesel engines have been placed in a separate class from spark ignited snowmobiles. The Diesel Utility Class (DUC) was created to exhibit diesel engine viability in utility snowmobile applications. While the intention of the Challenge is to improve the environmental impact, the utility snowmobile must also meet certain performance expectations that most operators desire. These expectations have been slightly altered for the DUC in comparison to the original Internal Combustion Class. Utility snowmobiles are required to be able travel at least 30 miles per hour (mph), tow heavy loads over a distance, and 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 chose to continue to pioneer use of a diesel engine with supporting systems in order to engineer an efficient, low emission, reliable, and cost effective snowmobile.

DESIGN CONSIDERATIONS

The UB CSC Team identified the three most important stakeholders to consider for the redesign of a utility snowmobile, and their expectations. These stakeholders were the environment, the operator, and the manufacturer.

The Environment

The UB CSC team decided that the environmental impact of the snowmobile was the most important factor to address through reengineering of the snowmobile. It directly relates to the main objectives of the Challenge, which are as follows:

- Decrease HC, CO and NOx emissions
- Reduce noise during operation
- Improve snowmobile 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

As a utility snowmobile, the main purpose of this snowmobile was to fulfill the demand of a service vehicle in an off road winter environment. An operator expects the machine to be able to accomplish these tasks:

- Tow heavy loads of cargo
- Easily maintain a riding speed of 30 mph
- Withstand an extended period of time of demanding physical work
- Travel long distances without needing to refuel

If these basic reliability and performance characteristics are not fulfilled, the snowmobile will not be adopted in today's market. To address this design factor, the team focused on reliable engine power output, improved towing capacity and increased range. The operator design consideration was reflected in the forced induction engine calibration and suspension configuration.

The Manufacturer

The manufacturer also needed to be taken into consideration when design choices were made. The most important requirements taken into account were:

- Minimize cost, while maintaining high quality
- Improve durability in to minimize life cycle 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. This resulted in the use of more readily available mass produced parts. By focusing on simplicity, the 2015 snowmobile was improved by redesigning the belt drive tensioner to allow for ease of maintenance and redesigning the cooling system to utilize a more simple solution. Also an air to air intercooler replaced the air to water intercooler used in 2014, greatly simplifying the turbocharger system.

<u>ENGINE SELECTION</u>

For the 2015 Challenge, the UB CSC Team chose an indirect-injected Daihatsu DM-954DT turbocharged diesel engine 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. Table 1 shows the specifications of the DM-954DT.

Table 1. Daihatsu DM-954DT Engine Specifications

Model	DM-954DT
Engine Type	3 Cylinder 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	Swirl Chamber
Valve Mechanism	Gear-driven OHV

The UB CSC Team chose a diesel platform for multiple reasons. The most important reason was the naturally low HC and CO emissions of the compression ignition combustion process [2]. Another significant reason for choosing a diesel-fueled engine was the immense decrease in fuel consumption. Shown by Figure 1, the DM-954DT can achieve abrake 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.

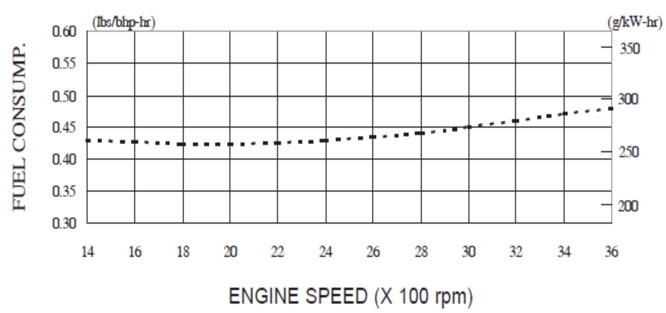

Figure 1: DM-954DT Brake Specific Fuel Consumption
(Courtesy of Briggs and Stratton)

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 is changed, it would only hinder the full power operation and have no effect on partial throttle operation. This reduces overall engine system complexity and increases reliability.

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, while still producing adequate overall power to achieve needed snowmobile speeds, improved towing capacity dramatically. Great emissions were 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- it was decided that the DM-954DT was the optimal choice.

TURBOCHARGER SYSTEM

This year the UB CSC team chose to replace the stock turbocharger system with an upgraded the turbocharger system to improve the engine's operational emissions and power output as well as to optimize system packaging within the bulkhead. An air to air intercooler was implemented to reduce system complexity as well as to reduce the wet weight of the snowmobile when compared to an air to water intercooler. Also, this intercooler design took advantage of the cold ambient temperature of the snowmobile's environment rather than using a water cooling system to cool the intake charge.

Design and Implementation

From the manufacturer, the Daihatsu diesel engine came equipped with an IHI RHF3 turbocharger. This turbocharger was sufficient for use on this engine at factory power levels, but in order to efficiently produce more horsepower and torque required for use in a snowmobile, the turbocharger needed to be upgraded. The most practical replacement turbocharger was found by the team to be the Garrett by Honeywell GT1541V variable nozzle turbocharger. These two turbochargers are compared in Table 2.

Table 2. Turbocharger Specifications Comparison

Turbocharger	RHF3	GT1541V
Compressor Inducer Diameter (mm)	22	32
Maximum Compressor Mass Flow Rate (lb/min)	9	13
Maximum Compressor Efficiency (%)	72	76
Maximum Efficient Pressure Ratio	2.3	2.7

From Table 2, it is clear that the GT1541V outperforms the RHF3 in every category. These findings led the team to conduct comparison dynamometer performance and emissions testing of both turbochargers.

In addition to the upgraded turbocharger, a new intercooler was implemented to further decrease intake temperatures. In previous years, liquid to air intercoolers were used to take advantage of unused chassis heat exchangers. Because the 2015 snowmobile uses these heat exchangers to cool the engine, the factory air to air intercooler from a Polaris Turbo IQ was installed. This intercooler was chosen because the intercooler was designed to fit in the IQ chassis and to be used on an engine creating more horsepower than the team's diesel engine. A photograph of the 2015 snowmobile turbocharger system is provided in Figure 2.

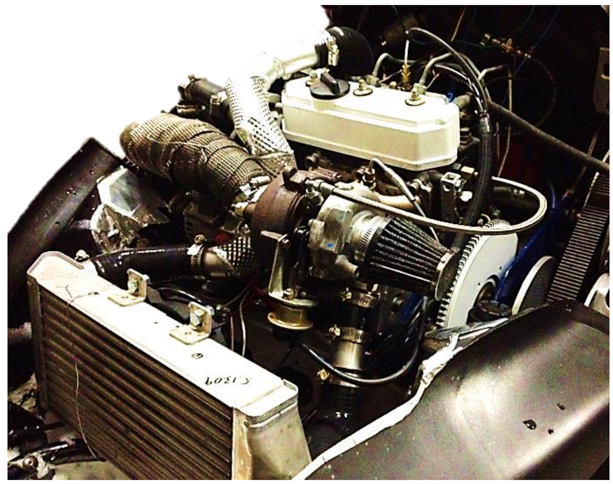

Figure 2: Turbocharger System

Testing and Validation

A UEI AGA5000 5-Gas Analyzer was used to measure HC, CO and NOx emissions with the GT1541V at different pressure ratios running on a DYNO-mite Dynamometer. At a constant fuel flow rate the new turbocharger increased power output from 47 hp to 50 hp and increased torque output from 70 to 82 lb-ft. Engine emissions were also affected by the new turbocharger system. Figure 3 shows the results of the NOx emissions testing.

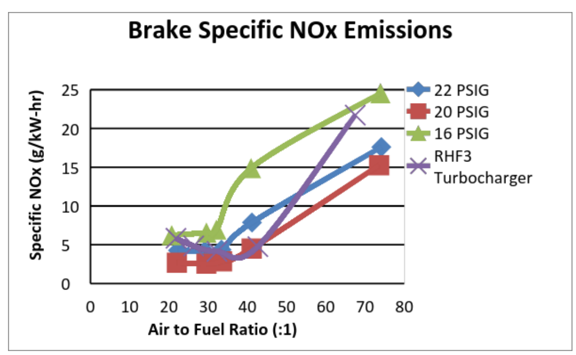

Figure 3: GT1541V vs. RHF3 Turbocharger BSNOx

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 20 PSIG 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.

While the GT1541V and air to air intercooler did produce lowered NOx emissions, it is important to verify that the turbocharger is still within a high efficiency performance range. Using a compressor map provided by Honeywell, the UB CSC team determined that the GT1541V was operating at an efficiency of 74% at 20 PSIG with the engine operating at a power level of 50 hp.

Compared the RHF3, the GT1541V was 19% more efficient on the diesel engine, thus contributing to decreased emissions as shown by Figure 3, and increased power output. Figure 4 shows the horsepower and torque of the diesel engine equipped with the GT1541V.

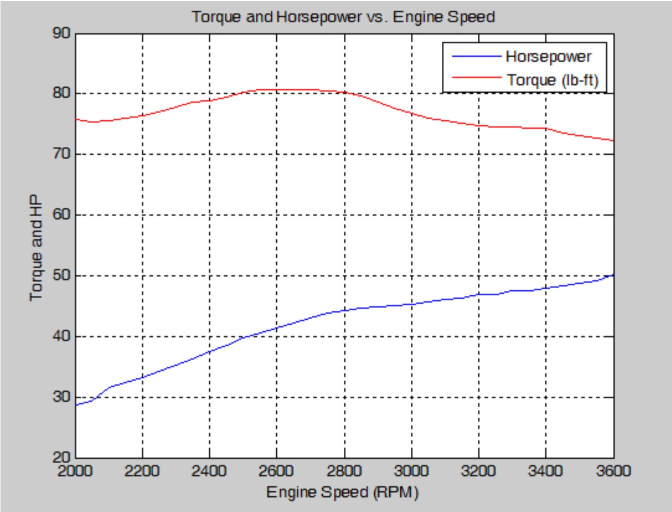

Figure 4: Horsepower and Torque Graph

In terms of emissions, power and efficiency, the 2015 turbocharger system satisfied all design considerations. With the GT1541V, the diesel engine produced 50 horsepower and 82 lb-ft of torque, a substantial increase compared to the original output of the engine. While the price of the turbocharger was significant, the GT1541V was similar in cost when compared to the RHF3, but clearly outperformed it.

EXHAUST SYSTEM

Exhaust Treatment

The Daihatsu engine is used in off-road applications that currently do not have strict emissions regulations. Since it is not necessary, the factory engine was not equipped with a system to control oxides of nitrogen, hydrocarbons, or particulate matter (PM) output. In addition, more fuel was being used by the engine in this application in order to increase power to a useable level. This brought emissions, specifically the NOx and particulate matter, to an unacceptable amount. To control this, a diesel oxidation catalyst and a diesel particulate filter were used collectively to decrease these emissions [4].

The oxidation catalyst was used to reduce the hydrocarbon, carbon monoxide, and NOx levels by converting each one to H_2O, CO_2, and NO_2, respectively. The water and carbon dioxide exit the tail pipe as harmless compounds, while the particulate filter uses the nitrogen dioxide downstream. Figure 5 demonstrates the effect the Emitec DOC had on emissions testing. During Mode 1 condition emissions testing, the DOC reduced NOx by 117 g/hr, a 42% reduction.

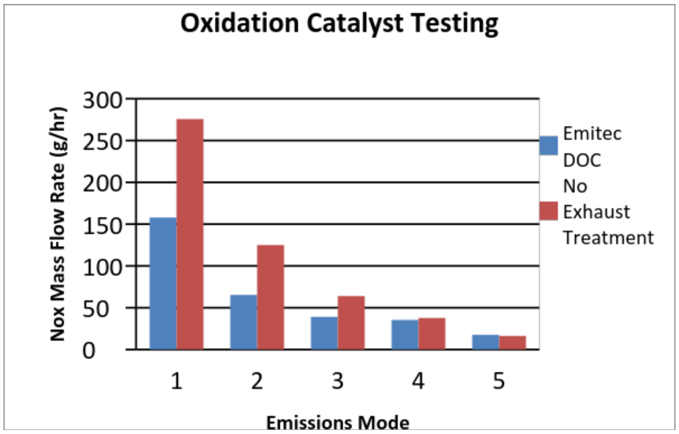

Figure 5: Oxidation Catalyst Testing

The oxidation catalyst used was optimized for NO_2 production and is coated with Platinum to interact with the harmful HCs and CO to create safer emissions. This unit was produced by Emitec and was placed after the turbocharger in the exhaust system. It required high exhaust gas temperatures (EGT) to function properly, therefore was placed as close to the turbine outlet of the turbocharger as the bulkhead geometry would allow. The catalyst was also encased in exhaust wrap to retain as much heat as possible.

Diesel particulate filters reduce the amount of particulate matter, or soot, exiting the exhaust. 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 an 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 (ECU) 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 system 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 was placed immediately after the oxidation catalyst to ensure these temperature levels were met. To ensure correct functionality, the DPF was also sourced from Emitec. This pair was used to reduce the particulate matter by up to 77%, and hydrocarbon and carbon monoxide by up 90% [4].

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 inlet flanges. A new exhaust manifold was fabricated to orient the turbocharger in a better position than where the factory manifold would have positioned it. Flow characteristics and simplicity of fabrication were considered as key factors during the design of the exhaust manifold. 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 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 total time required to fabricate and weld the exhaust manifold was 3 hours and the material cost was approximately $30. This low cost and short fabrication time would allow the manufacturer to easily, and cost effectively implement this design into a production snowmobile.

Testing and Validation

To quantify performance advantages, a flow analysis was performed on a model of the factory exhaust manifold, as well as on the 2015 manifold design using SolidWorks. The resultant flow trajectories are shown in Figures 6 and 7.

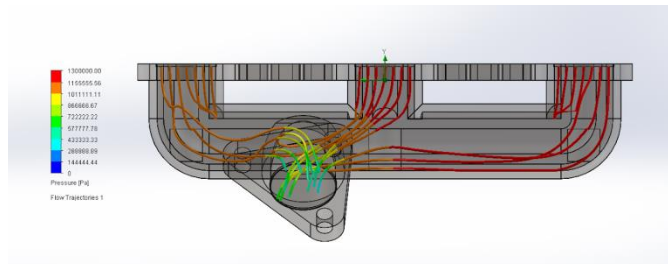

Figure 6: Factory Exhaust Manifold CFD

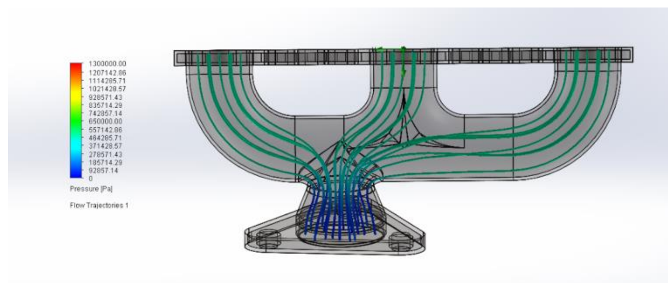

Figure 7: 2015 Exhaust Manifold CFD

When analyzing these results the difference in flow characteristics between the two manifolds was immediately apparent. 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 [5]. The new design created only 500 kPa of backpressure uniformly, along with no vortices. A full assembly test of the manifold and turbo on the engine was performed to ensure that all sides of the turbocharger housing had adequate clearance from the chassis and other engine components. 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 when compared to the factory part, and was very simple to fabricate, making it the easy choice as the best exhaust manifold option. The new manifold design also resulted in 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.

COOLING SYSTEM

Design and Implementation

Internal combustion engines have very specific operating temperature ranges, if engine temperatures are too low, combustion efficiency is negatively affected, and if temperatures are too high, mechanical failure likelihood is greatly increased [6]. In order to achieve optimal engine operating temperatures, 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 both the front and rear chassis tunnel heat exchangers was chosen to provide sufficient cooling capacity. This layout was chosen over last year's radiator because of both space concerns and better cooling system performance. Utilizing these heat exchangers provided adequate cooling of the engine's coolant while also occupying unused space on the snowmobile chassis. Because the factory heat exchangers were implemented, system costs dropped dramatically when compared to the 2014 snowmobile.

Testing and Validation

During the 2013 competition, a continuous problem with engine cooling prevented the snowmobile from operating reliably under 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 to adequately flow engine coolant.

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 2. 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.

$$\left(\frac{p_1}{2} + \alpha_1 \frac{{V_1}^2}{2} + g \cdot z_1\right) - \left(\frac{p_2}{2} + \alpha_2 \frac{{V_2}^2}{2} + g \cdot z_2\right) = h_{lT} = \Delta p_T$$

Equation 2: Bernoulli's Equation

In this best-case scenario analysis a pressure rise of 4.1 psi was directly attributable to the inclusion of the quick disconnects in the system using the Darcy-Weisbach equation shown by Equation 3. This pressure rise caused energy losses which cascaded through the system, as the water pump needed to perform additional work to force the coolant through the quick disconnects [7].

$$\Delta p = h_l = f\left(\frac{L}{D}\right)\left(\frac{\rho V_2}{2}\right)$$

Equation 3: Darcy-Weisbach Equation

The coolant flowing through the system was accelerated to at least 270% faster than the fluid traveling through the coolant hoses. Removing the quick disconnects eliminated 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 3, in which coolant temperatures were allowed to settle to their steady state value during various engine loads at 2000 RPM.

Table 3: Steady-State Engine Coolant Temperatures

	Steady State Coolant Temperatures (°F)		
Engine Load	CPC Quick Disconnects, Radiator	Without CPC Quick Disconnects, Radiator	No CPC Quick Disconnects, Heat Exchangers
0%	180	168	175
20%	181	172	173
40%	185	176	172
60%	193	180	170
80%	210	180	168
100%	225	180	164

Engine coolant temperatures at 100% load were decreased by 16°F from 2014 and 61°F from 2013, much below the overheating threshold. For the 2015 snowmobile, the same steady state testing was performed with the factory heat exchangers rather than a front mounted radiator and the results were very similar, proving the CPC Quick Disconnects as the culprit for the majority of previous cooling system issues. The design of the cooling system illustrated 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 was prolonged enormously and reliability was improved, positively affecting both the manufacturer and the operator.

BELT DRIVE SYSTEM

The operating engine speed range of the Daihatsu diesel engine is less than half that of gasoline engines typically found in snowmobiles. Due to this, the factory final drive ratio was incompatible with the UB CSC Team's engine and Continuously Variable Transmission (CVT) selection. This left the team the options to either modify the factory chain drive with an optimized sprocket ratio or find a completely different solution.

Belt driven power transmission systems are one of the most durable and efficient power transmission systems currently available on the market. They can achieve efficiency ratings of up to 98% and are becoming increasingly prominent in the snowmobile industry because of their many benefits. Due to the nylon-coated teeth on the belt, noise is reduced dramatically when compared to a typical chain driven system. Also, the lifespan of the belts are statistically 3 times longer than steel chains [8], reducing the maintenance costs and increasing the amount of time between services. Because no sealed case is needed, the ease of maintenance and part interchangeability increases drastically. 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, the UB CSC team decided to design and implement a belt drive system.

Design and Implementation

Research revealed that there were aftermarket options available to retrofit belt drive systems to snowmobiles. Unfortunately, there were none available for the Polaris IQ 600 LXT. 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 engine's speed range. It was quickly decided that designing a custom belt drive system would be a more cost effective solution. The belt drive system is shown installed on the 2015 snowmobile in Figure 8.

Figure 8. Belt Drive Assembly

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 and strength as the part it was replacing. An updated adjustable belt tensioner was added to the 2015 model, which allowed for greatly decreased belt adjustment and replacement times. After the belt drive back plate design was finalized, pulleys were designed for use with a Gates Polychain belt.

After calculation and testing, a final drive ratio of 1.65 was determined as being ideal for use in the 2015 snowmobile. This ratio was chosen because it allowed the snowmobile to achieve a high top speed while also providing adequate low speed torque for towing cargo. Considering the engine's maximum speed and the overdrive provided by the CVT's, the maximum theoretical vehicle speed was found to be roughly 60 miles per hour, twice the trail speed required for the Endurance event of the CSC Competition. The drive ratio was increased compared to that of previous years to provide increased torque to the driveshaft, greatly increasing the towing capacity of the snowmobile. Once the team decided on this ratio, Pfeifer Industries, a manufacturer of timing belt pulleys, fabricated a 32-tooth drive pulley and 53-tooth driven pulley to match the 1.65 gear ratio. The 2015 final drive ratio appeared to be the optimal solution for a utility snowmobile due to the increased towing capacity as well as the more than adequate maximum speed. The drive ratio comparisons are shown in Table 4.

Table 4: Theoretical Final Drive Top Speeds

Final Drive Calculations			
Drive System	Chain	2014 Belt Drive	2015 Belt Drive
Drive (teeth)	22	34	32
Driven (teeth)	43	49	53
Drive Ratio	51.4	1.44	1.65
Top Speed (mph)	48.7	69.8	60.7

Testing and Validation

When the belt drive system was completed and installed, extensive testing was performed. First, a simple serviceability test was performed which compared the difference in belt replacement time between the 2014 tensioner bracket design and the new 2015 three piece bracket design. It took a technician over 15 minutes to replace the drive belt with the 2014 tensioner installed, but in comparison it only took 3 minutes for the same technician to change the drive belt with the 2015 tensioner installed. This proved that the new tensioner design greatly increased serviceability of the belt drive system.

In order to test the durability of the belt drive system and to ensure that the gear ratios were correct, the snowmobile was subjected to multiple long distance trail rides, with the belt drive being inspected periodically for abnormal wear and unexpected operation. After 250 total miles it was determined that the belt drive was operating as expected and the drive ratio was optimal for 30 mph trail riding.

SUSPENSION AND TRACTION

Design and Implementation

Due to the 30% increase in weight over the factory IQ 600 LXT, the overall handling of the snowmobile was a major concern. It was immediately apparent that the stock suspension did not have the robustness necessary to support the added loading during operation.

The UB CSC team elected to replace the stock rear suspension with a Team Fast M10 suspension subframe. This suspension's subframe was lightweight and was easily implemented on the IQ chassis. Also, the M10 suspension had the ability to mount different shocks to account for the increased overall weight of the snowmobile. The center shock of 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 towing operation. This shock was replaced with a Team Fast M10 shock absorber. The mechanical nature of this shock absorber allowed for a more reliable overall system, while increasing simplicity.

The 2014 snowmobile underwent a series of tests to gain data on the effect that varying suspension air pressures and preload settings have on the overall handling characteristics. This data was used as a benchmark for the 2015 snowmobile.

Another important suspension component considered for improvement were the front skis. C&A Pro TRX skis were chosen due to their designed handling capability both on and off trail. 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.

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

Equation 4: Lateral Load Transfer Equation

Shown by Equation 4, an increased H value increased lateral load transfer during lateral acceleration, reducing the overall lateral force capability of the skis [9]. This reduced lateral force capability not only contributed to poor handling characteristics, but also increased risk of rollover. By choosing a ski which widened the stance of the snowmobile from 48" to 49", increasing track with (t) in Equation 4, H remained high however the lateral load transfer (ΔWYF) decreased. Therefore this ski choice effectively improved the overall lateral acceleration of the snowmobile by decreasing lateral load transfer. A 9" Stud Boy shaper bar carbide was chosen to aide in on trail lateral acceleration.

In order to create a snowmobile that could maintain adequate towing characteristics both on and off trails, the UB CSC team chose to utilize a Camoplast Intense track. This track has 1.5" lugs which are nearly 0.5" larger than the previously used Camoplast ICE Attak track. The larger lug size allows for a higher longitudinal acceleration specifically in off trail situations, where base snow is typically loosely packed or powdered. The Intense track was also 3 lb. lighter than the previously used track, a significant improvement in un-sprung rotational weight.

Testing and Validation

In order to test the improvements in the suspension and handling of the snowmobile a controlled test was established with the intent of quantifying the transient handling characteristics of the snowmobile in unloaded and loaded towing applications. This test was conducted using the same snow conditions for each run and the independent variable that was tested was track lug size. By testing different lug heights, the goal was to optimize the suspension setup to accommodate for towing and longitudinal acceleration. The test used a 150 ft. long straight track to determine the maximum acceleration. The faster the snowmobile was able to traverse the course from a stop, the better the towing characteristics. The towing test was conducted by adding a 250 lb. load off the tow hitch of the snowmobile. 10 trials were conducted for each configuration and the average results of the testing are shown in Table 5.

Table 5: Acceleration Test

Track Lug Height Comparison		
Lug Height (Inch)	Unloaded Time (sec)	Loaded Time (sec)
1.063	7.017	10.606
1.5	6.076	8.007

The above table relays that the increased track lug size significantly improved the longitudinal acceleration of the snowmobile, particularly during towing. The tests were conducted on un-groomed testing grounds, as to best simulate off trail towing capability.

CONCLUSION

Implementing a diesel fueled engine into a utility snowmobile application has its difficulties, but when properly executed can provide excellent fuel economy, very low HC, CO, NOx and particulate emissions, remain reliable and can maintain performance levels of a typical utility 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 injected, turbocharged diesel engine.
- Calibration of the engine was performed to optimize emissions and power output through extensive theoretical and experimental research, producing 50 horsepower and 82 ft-lb of torque.
- 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 intake charge, 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 required maintenance.
- 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.
- Towing capacity was increased by increasing the lug height of the track and adjusting shock absorber air pressures to accommodate increased loads.

Based on the above points, the 2015 UB CSC snowmobile design definitively proves the viability of diesel powered snowmobiles for utility applications. The combination of simplicity, adequate performance, very low emissions, and high reliability is ideal for utility snowmobiles.

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CONTACT INFORMATION

Team Captain- Nicholas Lanzano nelanzan@buffalo.edu

Team Captain- Anthony Marchesiello ammarche@buffalo.edu

Faculty Advisor- Dr. Edward Kasprzak kasprzak@buffalo.edu

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DEFINITIONS/ABBREVIATIONS

SAE	Society of Automotive Engineers
CSC	Clean Snowmobile Challenge
UB	University at Buffalo
NOx	oxides of nitrogen
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
WOT	wide-open throttle
HC	hydrocarbons
CO	carbon monoxide
DUC	Diesel Utility Class
BSFC	brake specific fuel consumption
BSNOx	brake specific NOx
PM	particulate matter
EGT	exhaust gas temperature
ECU	engine control unit
CVT	Continuously Variable Transmission
H	center of gravity height