Proving Diesel Engine Viability for Utility Snowmobile Applications

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ABSTRACT

For the 2017 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 Mercedes-Benz/Smart OM660 0.8L turbo diesel engine into a 2015 Polaris Indy 550 Adventure 144 utility chassis. This engine is commercially available in the Smart ForTwo CDI diesel vehicles distributed in Europe. The engine was chosen for its lightweight design, reliability, and efficiency. The engine can achieve a brake specific fuel consumption as low as 216 g/kW-hr. The UB CSC Team broke new ground by implanting this engine into a snowmobile chassis, a feat that had previously never been accomplished. Significant improvements were made in the exhaust and intake system to reduce emissions and increase performance.

An intercooled intake system was paired with a Borg-Warner KP39 turbocharger for decreased oxides of nitrogen (NOx) formation, lowered exhaust gas temperatures, and increased power output. Emissions control was addressed by employing an Emitec/Continental diesel oxidation catalyst (DOC) and diesel particulate filter (DPF), utilized in series. The front suspension system was modified to yield an increase in handling characteristics and to support the increased weight of the diesel engine. Through these improvements, the 2017 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, paired with 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 the 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 re-engineer a current production snowmobile with the goal of reducing emissions and environmental impact. The stated purpose of the CSC 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.

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

Equation 1: E-Score Equation for Emissions Testing

For the 2017 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 demonstrate diesel engine viability in utility snowmobile applications. Remaining consistent with the stated goal of the CSC to reduce environmental impact, the utility snowmobile must pass multiple emission testing events while also being able to 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 re-engineered snowmobiles should maintain their current 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 re-engineering of the snowmobile. It directly relates to the main objectives of the CSC, 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 the following 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 considerations were 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.

ENGINE SELECTION

For the 2017 Challenge, the UB CSC Team chose a common-rail direct injected Mercedes-Benz OM660 turbocharged diesel engine. This engine was chosen for its adaptive electronic engine management system, exceptional brake specific fuel consumption, low emissions, and high torque output. Table 1 shows the specifications of the OM660.

Table 1. Mercedes-Benz Smart OM660 Engine Specifications

Model	OM660
Engine Type	3 Cylinder
Displacement	799cc
Bore x Stroke	65.5mm x 79mm
Compression Ratio	18.0:1
Number of Cylinders	3 in-line
Dry Weight	190 lb.
Combustion Chamber	Direct Injected
Valve Mechanism	Chain-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. The brake specific fuel economy can be calculated using the following formula:

$$BSFC = \frac{r}{\tau\omega}$$

Where r is the fuel consumption in grams per second, τ is the engine torque in Newton-meters, and ω is the engine speed in radians per second, yielding the BSFC units of g/Kw-hr.

The OM660 can achieve a brake specific fuel consumption (BSFC) as low as 216 g/kW-hr [11], when many small gasoline engines struggle to achieve less than 400 g/kW-hr.

Figure 1: Mercedes Smart CDI OM660

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.

Testing our snowmobile using a Dyno-Mite Dynamometer yielded results shown in Table 2 and Figure 2. This engine was able to reach the same horsepower and torque levels that were achieved in the 2015 UB CSC snowmobile using a heavily modified Briggs & Stratton/Daihatsu DM-954DT engine. This engine selection was indicative of a long term strategy to continue to prove diesel engine viability in the snowmobile market in years to come due to the high power output the engine can achieve in stock form coupled with the engineering durability of the stock engine internal components and engine block.

Table 2. Mercedes Smart OM660 Engine Output

Horsepower	54.5 @ 3942 rpm
Torque	84.7 @ 2460 rpm

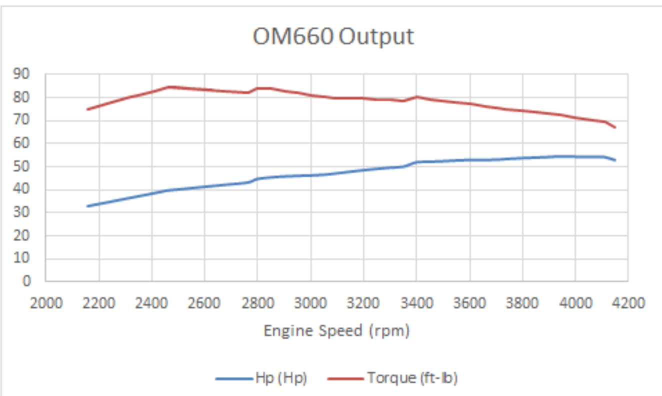

Figure 2:Mercedes Smart OM660 Engine Output Graph

The power output of the OM660 while producing low CO, HC and NOx emissions output was an important reason the UB CSC team chose this engine. Widespread torque output capability is a fundamental design specification to meet when designing a diesel utility snowmobile. The torque output coupled with the high-speed power output achieved technical design specifications as well as our operator design considerations for snowmobile operation. When evaluating the three major design considerations of the snowmobile- the operator, manufacturer and the environment- it was decided that the OM660 was the optimal choice.

ENGINE CONTROL UNIT

In order to successfully implant the Mercedes-Benz OM660 engine into the 2015 Polaris chassis, the UB CSC design team utilized a standalone engine control unit (ECU). The stock engine control management system would not provide the UB CSC team with an adequate means to successfully calibrate the engine to optimal emissions levels. A Specialist Components (SC) stand-alone Smart OM660 ECU and injector driver was implemented to provide complete control over fuel injection timing, fuel quantity, and other key functions. The SC ECU unit was completely (re)programmable and utilized to optimize power gains and efficiency. This allowed the UB CSC team the ability to further increase the power of the OM660 engine while a low E-Score was maintained. The SC ECU allows the UB CSC design team to communicate with the engine during operation which allows for critical engine response testing and detailed control. This level of communication and control is a marked improvement over the previously used DM-954DT engine, which was a mechanical indirect injection design.

EXHAUST SYSTEM

The Mercedes-Benz OM660 engine has inherently low measured exhaust emissions. The UB CSC design team took steps to further lower the measured combustion emissions and thereby lower the calculated E-score. The 2017 UB CSC design team has implemented a system to control a system to control oxides of nitrogen, hydrocarbons, and particulate matter (PM) output. 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 tailpipe as harmless compounds, while the particulate filter uses the nitrogen dioxide downstream. Figure 3demonstrates the effect the Emitec/Continental DOC had on emissions. During emissions testing, the DOC reduced NOx by a 47% reduction on average, as shown in Figure 4.

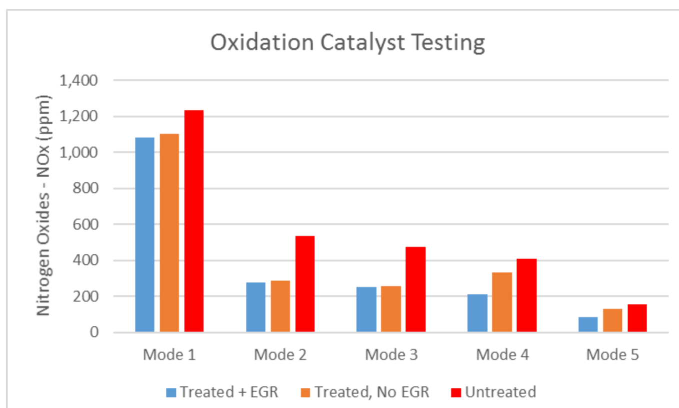

Figure 3: Oxidation Catalyst Testing

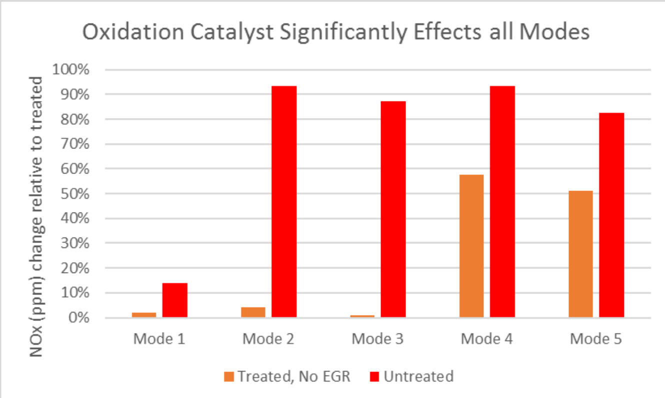

Figure 4: Treatment Significantly Decrease NOx Pollutant

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/Continental 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. Catalyst inlet temperatures peaked at 895°F during Mode 1 testing, thereby confirming that the catalyst was positioned correctly to maintain inlet temperatures in the target operation region. 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 requires 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 programming capabilities, 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. Catalyst inlet temperatures peaked at 480°C during Mode 1 testing, thereby confirming that the catalyst was positioned correctly to maintain inlet temperatures in the target operation region. The DPF was placed immediately after the oxidation catalyst to ensure these temperature levels were met. To ensure correct system functionality, the DPF was also sourced from Emitec/Continental. This pair was used to reduce the particulate matter by up to 77%, and hydrocarbon and carbon monoxide by up 90% [4].

Included in the 2017 UB CSC testing program was to calibrate a record the effectiveness of the Exhaust Gas Recirculation valve. This valve operates by returning a portion of the post-combustion exhaust into the engine intake, post-turbocharger, as a function of throttle position and engine speed. The operating principle is to decrease combusted emissions by recycling the unburnt portion of the exhaust back into the intake. Figure 4 shows the change in effectiveness of reducing NOx emissions as a function of the EGR. The results of the testing showed that high engine speed/high torque testing modes (modes 1, 2, and 3) that required more throttle engagement were not significantly impacted by the removal of the EGR. When the EGR was engaged in Modes 4 and 5, NOx emissions were effected by as much as 50%. This is in line with expectations as the EGR valve was programmed to open only under conditions of less than 25% throttle engagement and 3500 rpm.

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.

Figure 5: Catalyst and Diesel Particulate Filter

CHASSIS SELECTION

The creation of the diesel utility class in 2015 changed many design considerations for the UB CSC design team. For the 2017 competition, the UB CSC design team choose to utilize a 2015 Polaris Indy 550 Adventure 144 chassis for the advantages that it provided to the operator during operation. This marked a 23" increase in track length from the previously used 2011 Polaris Turbo IQ 121. The increase in track length allowed the snowmobile to gain better traction over a larger surface area which ultimately led to an increased towing capacity.

Due to the 30% increase in weight over the factory Adventure 144, the weight bearing capability of the front shocks of the snowmobile was a concern that was addressed. Through testing, it was immediately apparent that the stock front suspension did not have the robustness necessary to support the added load during operation. In order to compensate for the additional front end weight subjected on the sled, the stock shock absorbers were replaced with Fox Float II front shocks previously used on the 2015 UB CSC snowmobile. The weights the OM660 and DM-954DT are shown in Table 3. The 2017 UB CSC design team decided to use the shock absorbers previously used on the 2015 snowmobile due to their demonstrated ability to handle similar loads during operation. The 2014 and 2015 snowmobiles 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 2017 snowmobile.

Table 3. Engine Weight Comparison

	2015	2017
Engine	DM-954DT	OM660
Weight (lb.)	196	190

CHASSIS TO ENGINE ADAPTATION

Design and Implementation

In order to ensure proper fitment and operation angle of the OM660 engine in the 2015 Polaris chassis, the tubular over-structure needed to be modified. The function of the over-structure is to provide support for the steering column and plastics. The frame is connected to the bulkhead with six M8 bolts and to the tunnel with four. Modifications were made in order to achieve proper geometry and to handle loading applied by the operator. All modifications were made using 6061 aluminum alloy, which was chosen for its light weight, good mechanical properties and good weldability. The modified over-structure was designed in Solidworks to ensure the design would not fail due to a force on the steering column imposed by a rider, as well as for compression loading in the event primary and secondary chassis braces simultaneously failed. Utilizing average North American male weight, it was concluded the most force a rider could impose on the over-structure is approximately 175 lbs. After performing a finite element analysis (FEA), the maximum stress in the frame from the 175 lb. force was determined to be 3540 psi and the maximum displacement was 0.00671 inches. Given the yield stress of 6061 aluminum is 35,000 psi, the modified over-structure achieved a factor of safety of 9.88. The modified design utilized welded joints rather than the stock two-piece over-structure design to reduce system complexity and to ensure superior system strength.

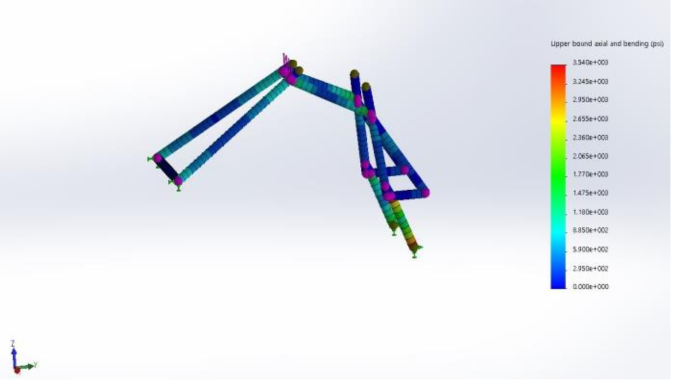

Figure 6: FEA results show no signifigant stress concentrations

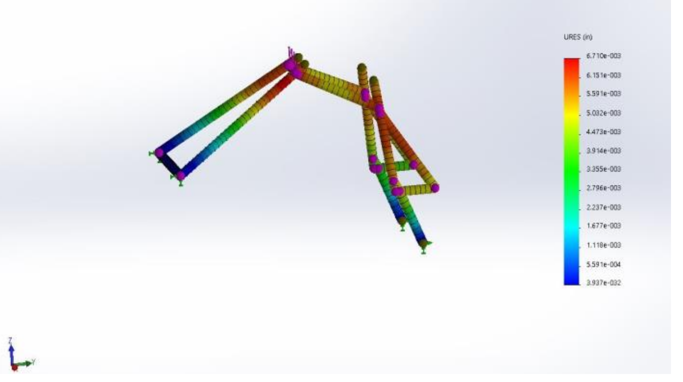

Figure 7: FEA results show negligible deflection

Engine mounts were designed and developed to withstand both the rigid loading as well as the rotational torque from the engine loading. Three engine mounts were developed in total, one front, one rear, and one plate style to take the place of the flywheel housing. The mounts were designed and tested using Solidworks to ensure that they were sufficiently robust to handling the loading present. Utilizing the weight of the engine as well as estimated rotational forces, it was determined that a 150 lbs. force would be a realistic loading force to apply to each mount location. All mount locations were rigidly fixed to the chassis.

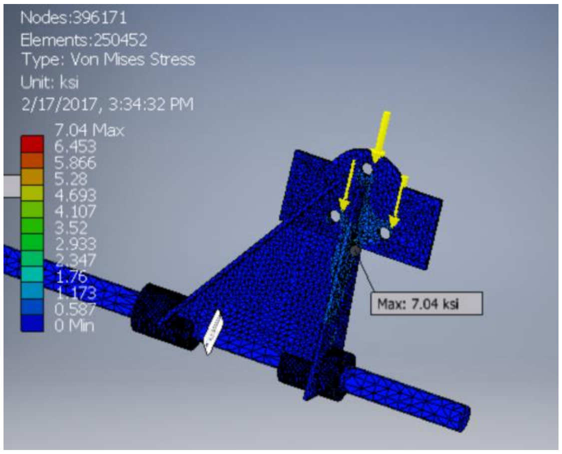

Figure 8: Front Engine Mount Stress

After performing a finite element analysis, the maximum stress in the frame from the 150 lb. force was determined to be 7,040 psi and the maximum displacement was 0.0012203 inches. Given the yield stress of 6061 aluminum is 35,000 psi, the side plate engine mount achieved a factor of safety of 4.97. Due to the location of local stress concentration near a weld, it was determined that this mount should be fabricated from mild steel in order to increase the factor of safety of this part.

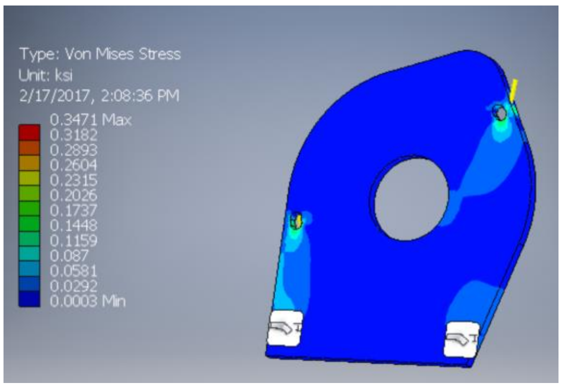

Figure 9: Side Plate Engine Mount Stress

After performing a finite element analysis, the maximum stress in the frame from the 150 lb. force was determined to be 347.1 psi and the maximum displacement was 0.0000414 inches. Given the yield stress of 6061 aluminum is 35,000 psi, the side plate engine mount achieved a factor of safety of over 100.

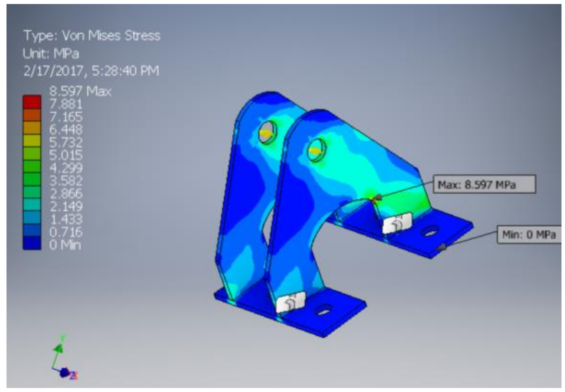

Figure 10: Rear Engine Mount

After performing a finite element analysis, the maximum stress in the frame from the 150 lb. force was determined to be 1,247 psi and the maximum displacement was 0.00006261 inches. Given the yield stress of mild steel is 35,000 psi, the side plate engine mount achieved a factor of safety of over 100.

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 a rear chassis tunnel heat exchanger was chosen to provide sufficient cooling capacity. This system was chosen over a radiator because of both space concerns and better cooling system performance relative to a snowmobile application. Utilizing the heat exchanger provided adequate cooling of the engine's coolant while also occupying unused space on the snowmobile chassis. Currently, industry standards for snowmobile design for liquid cooled engines is a tunnel heat exchanger, which allowed the UB CSC team to hold system costs relatively low compared to implementing a radiator system.

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. Extensive analysis was conducted in 2015 to rectify engine cooling problems due to flow restrictions. This work provided a basis for the 2017 UB CSC cooling system tests.

The 2017 UB CSC team developed a dynamic testing procedure to validate in service cooling functionality. A test track was established to consistently allow the snowmobile at the indicated engine loading levels in figure 8. Using engine logging techniques that captured the average throttle position during a spirited riding session, it was determined that average throttle position was about 60% of full load. The test was designed to determine that, at 60% throttle during operation exerted on the engine, our system would be able to maintain the proper operating temperature of 82°C. The average coolant temperature during five-minute trial runs was captured via the SC ECU and shown in Figure 11.

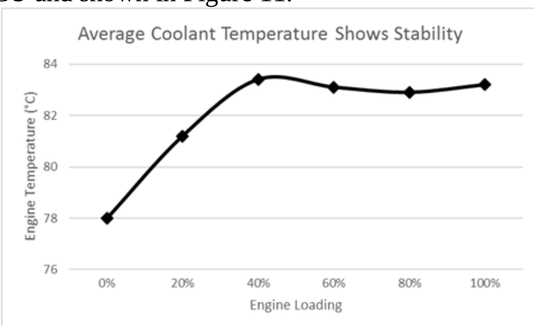

Figure 11: Heat Exchanger Cooling is Adequate during Operation

The cooling system operated as expected and our testing was deemed a success. The idling engine is characterized by 0% of maximum engine loading, at which point an average temperature of about 78 ℃ was maintained. Engine temperatures peaked at 40% of maximum engine loading, which is indicative of projections that on average the snowmobile would be moving at a speed that would less efficiently cool the tunnel heat exchanger via conduction. However, the peak temperature of 83.5 ℃ falls at 74% of the maximum allowable safe operation engine temperature of 113 ℃. The tests performed validated the operational efficiency of the stock water pump coupled with an in-tunnel heat exchanger.

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 because it is an efficient and cost effective, direct injected, turbocharged diesel engine.
- Calibration of the engine was performed to optimize emissions and power output through extensive theoretical and experimental research, producing 54.5 horsepower and 84.7 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.
- Tailpipe emissions were reduced by the use of an Emitec/Continental Diesel Particulate Filter and Diesel Oxidation Catalyst, maintaining high catalyst efficiencies with a specially designed exhaust system and calibration.
- Towing capacity was increased by utilizing a 144-inch track and adjusting shock absorber preload to accommodate increased loads.
- Specialist Components ECM unit was implemented into the design which allows for on-the-fly tuning capabilities and real time engine performance monitoring.

Based on the above points, the 2017 UB CSC snowmobile design definitively proves the viability of diesel powered snowmobiles for utility applications. The combination of performance, low emissions, high reliability, and high fuel economy makes the 2017 UB CSC snowmobile an ideal utility snowmobile.

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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
FEA	finite element analysis
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