Optimizing the Diesel Utility Snowmobile

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INTRODUCTION

The Society of Automotive Engineers (SAE) Clean Snowmobile Challenge (CSC) was created to not only bring together like minded college students to share and build their knowledge, but also to use that knowledge to solve a persisting problem. The problem that this competition was created to solve is designing a environmentally friendly, quiet, and efficient snowmobile that is still marketable to consumers. This ongoing problem exists because of increased awareness of the negative effective of internal combustion engines and the effects on the environment. With years of research, trial, error, success, and innovation we are closer than ever to reaching our goals. Here at the University at Buffalo (UB) our CSC team has dedicated the past several years to research toward improving our diesel utility snowmobile. So much so that we became focussed on innovation and finding the next greatest solution to ensure a cleaner solution.

This year we decided to focus on our systems. Instead of trying to tackle all new unproven systems, we re-designed and perfected the systems that we know yield the best results. This has focused our efforts on improving our performance and reliability. Everyone loves a new style and innovation, however in industry it is the reliable and test proven products that will sell best.

ABSTRACT

For the 2019 SAE CSC, the UB diesel snowmobile team will be using a 2015 Polaris Indy 550 Adventure 144 utility chassis fitted with our turbocharged 0.8 liter Mercedes OM660 diesel engine. With this combination, accompanied by custom interface systems we are able to retain performance, cost and reliability while decreasing emissions, noise and fuel consumption.

With the implementation of a stand alone programmable Engine Control Unit (ECU) and a boost controller we are able to increase power and torque. We have implemented a new and improved exhaust system along with an emission elimination system to reduce soot and emissions. Also our sled contains a redesigned coolant system, wiring harness and throttle control system to increase efficiency and reliability. Lastly our introduction of sound-detining Lizard Skin applied throughout the chassis and additional insulating foam-materials applied throughout the engine cavity, we were able to further reduce our noise output to make our sled design quieter in hopes of improving public appeal.

INNOVATION

ENGINE OPTIMIZATION

For the 2019 competition the UB diesel utility team began with installing a new OM660 Mercedes 0.8L diesel engine out of a Canadian Smart ForTwo CDI as well as a new Borg-Warner KP31 turbocharger. In doing so we were able to maximize cylinder compression and turbo boost. Then after rewiring the entire engine wiring harness, fuse and relay control, and all other snowmobile electronics, we were able to increase reliability as well as decrease power draw on the battery. We also decided to eliminate the engine vacuum pump and replace the original alternator with a smaller, lightweight 35 Amp Denso Street Rod Racing alternator in order to reduce unneeded mechanical strain on the engine. Lastly we began using our Specialist Components stand alone programmable Typhoon 2 ECU to tune our engine to obtain optimal efficiency. Adjusting fuel pulse width, injection timing and target fuel pressure allowed for a combination for various scenarios tha optimized our air fuel ratio. We put an emphasis on tuning that increases power on the high end, increases efficiency at the low end and decrease emissions throughout.

EMISSION REDUCTION

In order to decrease emissions as much as possible while retaining fuel economy and power we decided to incorporate a completely redesigned exhaust system. Using a Diesel Oxidation Catalyst (DOC) along with a Diesel

Particulate Filter (DPF) from a Ford F-250 Powerstroke, we were be able to greatly reduce our HC, CO, NOX and soot levels emitted from our snowmobile. To optimize our DOC and DPF performance we also redesigned our coolant system to eliminate the heater core bypass from the original engine in order to increase engine and Exhaust Gas Temperature (EGT) to get a higher catalyst activation. With the reduction of our heater core, we noticed that the catalyst produced better results.

PERFORMANCE

In order to increase our snowmobiles performance and improve rider control we decided to upgrade our boost, throttle and resized our fuel tank. We first installed an inline turbo charger boost controller to make engine tuning more simple, also increasing user control. Then we replaced our original throttle control with a Arctic Cat throttle body mounted throttle position sensor to convert our analog throttle input to a digital signal to electronically control our stand alone ECU. Lastly we decided to reduce unneeded weight in order to improve maneuverability by removing the stock fuel tank and replacing it with a much smaller one. This decrease in fuel tank size allowed for an increase in available space to reroute our exhaust. Having originally been fitted with a 11.5 gallon fuel tank, we were able to travel well over 200 miles without refueling, which roughly added an additional 80 lbs in fuel, restricting performance significantly. Upon replacing the fuel tank with a smaller 4 gallon tank, we were able to reduce weight, increase space for our exhaust system and still maintain a traveling range of over 100 miles.

GEARING RATIO

One major problem in the CSC is maintaining maximum snowmobile speed after swapping to a diesel engine or when tuning for emissions and efficiency. The main reason for such a speed loss when converting to a diesel engine are the restrictions in the engines revolution per minute (rpm). Traditional snowmobile gearboxes have high gear ratios to accommodate for high rpm gasoline engines. However, when you install a low rpm diesel engine with a high ratio gearbox, the result is low maximum speed. To correct this issue we decided to exchange gears to transform a 2.2 ratio gearbox into a 1.7 ratio. We only made a 0.5 ratio reduction so that we could increase the maximum speed to one more desirable to consumers while still retaining high engine torque to ensure the snowmobiles ability to assist in a variety of tasks.

NOISE SUPPRESSION

To reduce noise on our snowmobile, we introduced the application of Lizard Skin Sound Control Insulation and insulating foam. With these additives, we were able to sound dampen the entire engine cavity as well as the track tunnel and overall throughout the entire chassis. These applications were implemented in hopes of combatting both the engine and track noise and vibrations throughout the entire snowmobile.

TEAM ORGANIZATION AND TIME MANAGEMENT

Table 1. UB SAE CSC Diesel Work Schedule Gantt Chart

UB_Diese Team Management																										
Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Research Innovation	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
Base tuning and Testing																							■	■		
Snowmobile Tear Down																									■	■
Week	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
Engine and Turbo Swap	■	■	■																							
Rewire Engine Harness				■	■	■																				
Wire in Fuse Box							■																			
Install and Plumb Fuel Tank								■	■																	
Replumb Coolant Lines										■	■															
Christmas Vacation												■	■													
Fabricate Exhaust														■	■	■										
Swap Drive Gears																	■									
Install New Alternator																		■								
Tune Snowmobile																			■	■	■	■	■	■	■	
Design Report and MSRP																				■	■	■	■	■		
Lizard Skin																					■					
Sound and heat Insulation																						■	■			
UB Engineering Week																								■		
Install Snowmobile Wraps																								■		
Competition Prep.																									■	
Compete																										■

This year the UB SAE Diesel Snowmobile team consists of five student members with the same goal in mind, building a clean, quiet, and efficient competition and production ready diesel snowmobile.

Table 2. UB SAE CSC Diesel Team

Team Member	Role
Noah White	Captain
Ethan Schonhaut	Research Lead
Nicholas Larson	Systems Expert
George Malero	Electrical Expert
Austin Ocwieja	Noise Expert

We were able to maintain organization and progress throughout the year by planning ahead. We were able to host weekly meetings where we were able to track and plan our progress as well as to keep up with local and club events. Such as shop tours, general club meeting, UB engineering week and homecoming bonfire.

BUILD

Table 3. UB SAE CSC Diesel Build

Chassis	2015 Polaris Indy 550 Adventure 144
Engine	Mercedes-Benz/Smart OM660 0.8L CDI
Track	Shockwave 15 x 121 x .91
Diesel Oxidation Catalyst	2008-2010 Ford F-250 PowerStroke
Diesel Particulate Filter	2008-2010 Ford F-250 PowerStroke
Skis	Curve XS
Electronic Control Unit (ECU)	Specialist Components Typhoon 2
Turbo Charger	Borg-Warner KP31
Suspension	Fox Float II

DISCUSSION

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 order 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 2019 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 5. 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], whereas 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 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 6. Mercedes Smart OM660 Engine Output

Horsepower	54.5 @ 3942 rpm
Torque	84.7 @ 2460 rpm

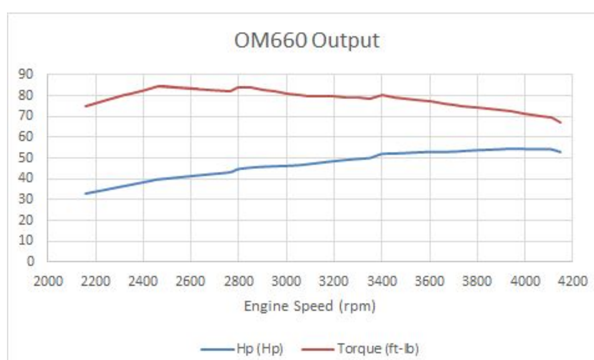

Figure 2:Mercedes Smart OM660 Engine Output Graph

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.

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 lightweight, 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.

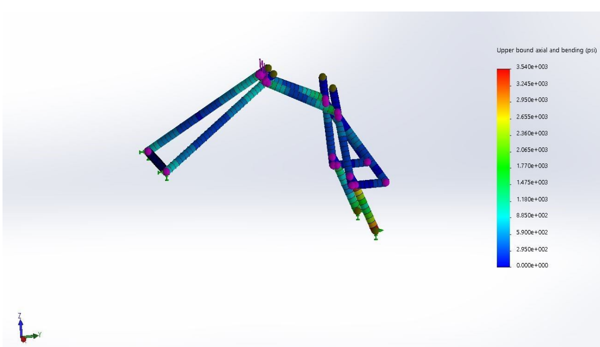

Figure 3: FEA results show no significant stress concentrations

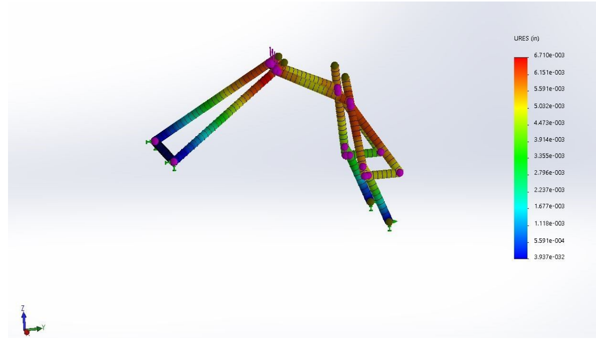

Figure 4: FEA results show negligible deflection

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.

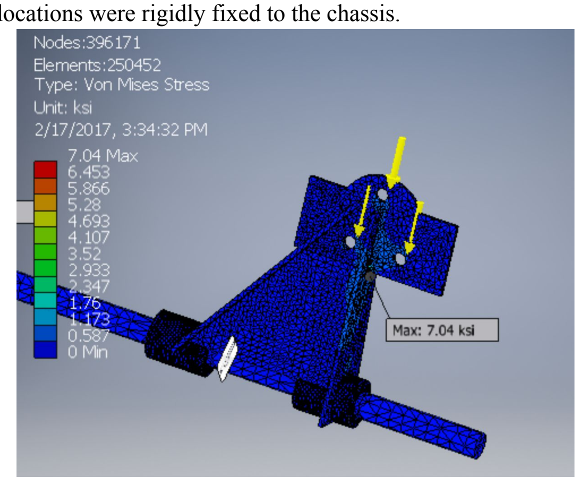

Figure 5: Front Engine Mount Stress

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.

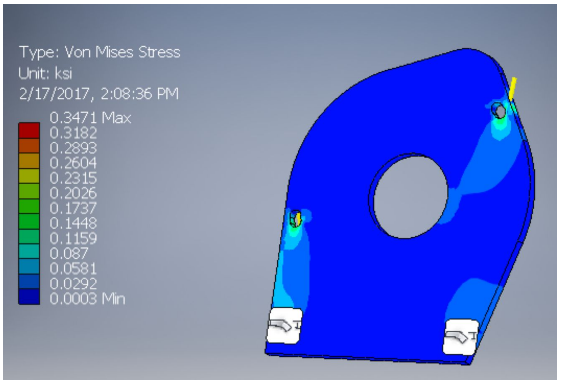

Figure 6: Side Plate Engine Mount Stress

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.

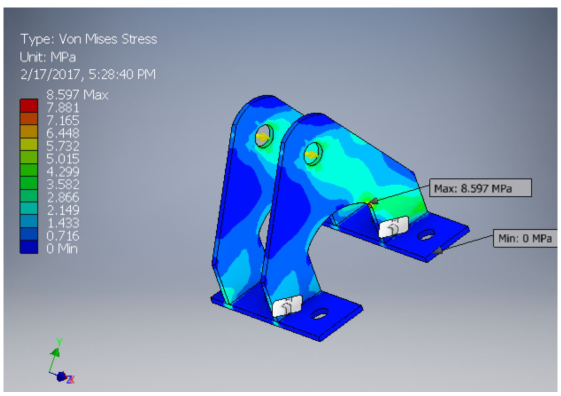

Figure 7: Rear Engine Mount

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.

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

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 2019 UB CSC design team has implemented a system to control a system to control oxides of nitrogen, hydrocarbons, and particulate matter (PM) output. A Ford F-250 diesel oxidation catalyst and a diesel particulate filter were used collectively to decrease these emissions .

To correctly monitor our exhaust gas temperatures as well as Air Fuel Ratio (AFR), a pyrometer and a Bosch LSU 4.9 Wideband O2 Sensor were incorporated into the 2019 UB CSC exhaust system. Each gauge allows for direct monitoring of AFR and EGTs in order to ensure the most effective use of our catalyst and DPF, as well as to monitor and tune the engine to desired EGTs, NOx emissions, and soot emissions.

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. 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 particulate 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.

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 8: Catalyst and Diesel Particulate Filter

COOLING SYSTEM

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. 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. Testing during 2016 and 2017, showed signs that the thermometer was inaccurately reading engine coolant temperature, increasing risk for mechanical failure. This was corrected soon after competition, ensuring correct thermometer readings. This work provided a basis for the 2019 UB CSC cooling system tests.

The 2018 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 9.

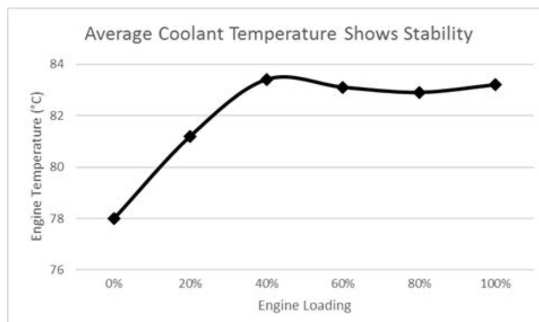

Figure 9: Heat Exchanger Cooling is Adequate during Operation

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.

However, after modifying our exhaust system for our 2019 Competition we decided to modify the coolant system once again. We started with the elimination of the heater core bypass lines. In doing this we believe that we will achieve more stable engine temperatures while increasing the EGTs enough to activate the DOC and DPF.

SOUND TESTING

The Mercedes-Smart OM660 is inherently quiet compared to modern diesel engines. The 2019 UB CSC decided this year to evaluate different combinations of exhaust tailpipes and snow flaps, as well as sound dampening linings in order to reduce the sound of the snowmobile. Two days of testing were conducted following SAEJ1161 testing standards: the first occurring in late summer, testing the UB CSC 2017 design against a 2-stroke IC reference snowmobile; the second occurring in mid-February testing the 2019 modified snowmobile against the same 2-stroke IC reference snowmobile.

The stock snowflap was tested against a fabricated snow flap made of aluminum, lined with rubber and noise dampening material. A straight exhaust tailpipe was fabricated and tested straight and with a non-restrictive flow baffle. In Table 3, results of the tests were shown, showing our sled to meet the SAEJ1161 requirements when compared to the reference snowmobile. Results showed that the baffled exhaust with our fabricated snow flap produced a differential of .5 dB from our initial test, as well as a 2.4 dB difference from the reference snowmobile in our second trial.

Table 7: Sound Test Comparisons

Snowmobile/ Average dB	First Trial	Second Trial
Reference	78	77.3
Diesel (straight)	75.4 (2017 CSC snowmobile)	75.2
Diesel (baffled)	N/A	74.9

However this year the 2019 CSC team decided to go even further by applying a new lizard skin paint-on sound dampening material to the underside of the tunnel as well as the inside of the exhaust compartment. Accompanied with foam insulating materials as well as fiberglass sheeting, we will be able to reduce our noise levels even further.

ACKNOWLEDGEMENTS

The University at Buffalo thanks the following sponsors for helping us pioneer the development of a clean and efficient diesel powered snowmobile.

UB Engineering Machine Shop	Polaris Industries
UB Student Association	Honeywell
UB SEAS Department	Custom Laser
SolidWorks	NYSSA
Klispie Motorsports	Autometer
DEI	Camoplast Solideal
Pfeifer Industries	Ballistic Battery
Peter Dietrich	Specialist Components
Woody’s	McGard
PCB Piezotronics	Curve Industries

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- UB SAE Mini Baja Team
- UB Engineering Machine Shop Personnel

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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
AFR	Air Fuel Ratio