Diesel Conversion of a 2018 Polaris Titan SP with a Mercedes-Benz OM660 Engine

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Abstract

The University of Minnesota Duluth Diesel Team designed and created a snowmobile powered by a diesel engine to compete in the Diesel Utility Class of the 2018 Clean Snowmobile Challenge. A Mercedes-Benz OM660 .8L turbo diesel engine was installed into a 2018 Polaris Titan SP. The engine was installed into the chassis using student designed engine mounts that utilized the stock engine mounting locations, and the bell housing. A taper was designed to connect the continuously variable transmissions to the flywheel of the engine, with careful consideration of the increased moment due to the unusual length requirement of the taper. A Delta engine control unit was paired with an injector driver module to allow for customizable fuel supply, better fuel mileage and emissions. Fuel delivery lines were modified to supply the engine with the correct amount of clean fuel. Cooling capabilities of the snowmobile were increased by installing an aftermarket radiator and intercooler that will be able to maintain desired engine temperatures. An air intake was designed and 3-D printed using carbon fiber reinforced nylon 11 to connect the stock snowmobile air intake to the turbo inlet. Emissions were controlled using a catalytic converter and a passive diesel particulate filter. The finished product is a snowmobile capable of pulling heavy loads and achieving improved fuel economy compared to gasoline engines.

Introduction

Snowmobiles are typically spark ignited due to the high-speed capabilities and being lightweight that allows them to be easily maneuvered, and preferred for the common trail sled. The purpose of converting a snowmobile to use a diesel compression ignition engine is to create a utility sled that has the capabilities of pulling heavier loads, and to have a longer ranges between refueling. Diesel engines are known to have higher torque capabilities and improved fuel economy due to the higher compression ratios that are the basis of a compression engine. On the other hand, they are also known to typically be a much dirtier engine in the case of emissions and have larger environmental impacts compared to similar sized gasoline engines.

The SAE Clean Snowmobile Challenge (CSC) has put forth the Diesel Utility Class (DUC) so that collegiate chapters can experiment and engineer a snowmobile powered by diesel engine. Each competing team is challenged to replace a current model snowmobile with a diesel engine, and design it so that it is quiet, emits low amounts of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter, that is often referred to as soot, and is desirable to the market. The environmental impact will be measured by an E-Score that is defined in Equation 1.

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

Equation 1. E-Score Equation for Emission Testing

The diesel snowmobiles will also be put through a series of dynamic tests such as an endurance run while pulling a load, a handling course, and cold-starts, as well as marketability.

Innovations

2018 will be the first year the University of Minnesota Duluth (UMD) will be competing in the Diesel Utility Class. For the snowmobile chassis, a 2018 Polaris Titan SP was obtained to comply with the rules, and other reasons detailed in Chassis Selection. A Mercedes Benz OM660 was the engine of choice for its relatively small size, stock turbocharger, and electronically controlled direct injection. Creating a competition-worthy snowmobile while using an engine designed for a car was a difficult task, and required many innovative ideas.

Engine Selection

The UMD Diesel team chose the Mercedes-Benz OM660 3-cylinder turbocharged diesel engine for competition. The main reasons for selecting this engine is for the CDI high pressure fuel injection system, its high output rating, and turbocharging capabilities. The CDI control unit uses a rail pressure sensor which registers the rail pressure. This regulates by way of the pressure regulator valve and the quantity control valve. The CDI unit also controls the duration of the opening time of the injectors. This unit provides lower combustion noises and lower pollutants, resulting in a more economical engine [2]. It's displacement of 799 cc is higher than most engines of similar size that only have 450-500 cc [3]. This results in a higher torque at 110 N*m at 2000 RPM, and higher output delivery of 33kW at 3800 RPM [4]. More engine specifications can be found in Table 1. The OM660's capability for turbocharging allows the engine to produce a higher output while maintaining the same fuel consumption by forcing more air into the combustion chamber. Turbocharging has also been proven to increase fuel economy, and decrees CO_2 emissions [6] which is vital for this competition.

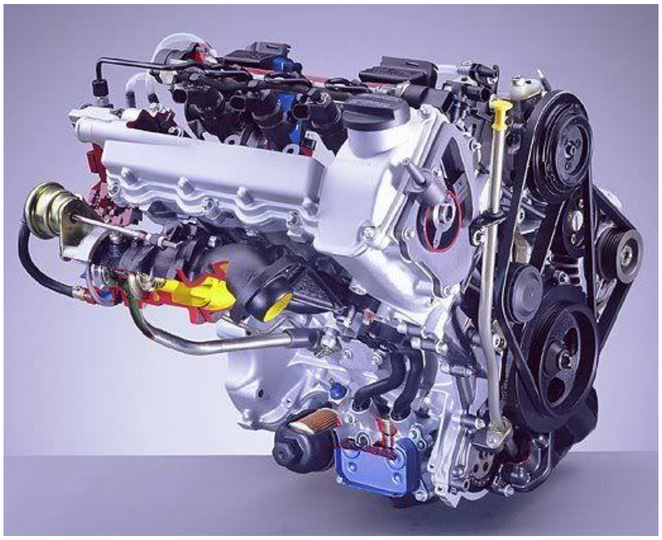

Figure 1. Mercedes- Benz OM660

Table 1. Mercedes-Benz OM660 Engine Specifications

Displaced volume	799 cc
Stroke	79 mm
Bore	65.5 mm
Cylinder Angle	45°
Compression ratio	18:1
Number of Cylinders	3 in-line
Dry Weight	86.18 kg (190 lbs.)
Est. Running Weight	90.71 kg (200 lbs.)
Rated Output	33 kW @ 380 RPM
Rated Torque	110 N*m @ 2000 RPM
Camshaft Configuration	Overhead-single

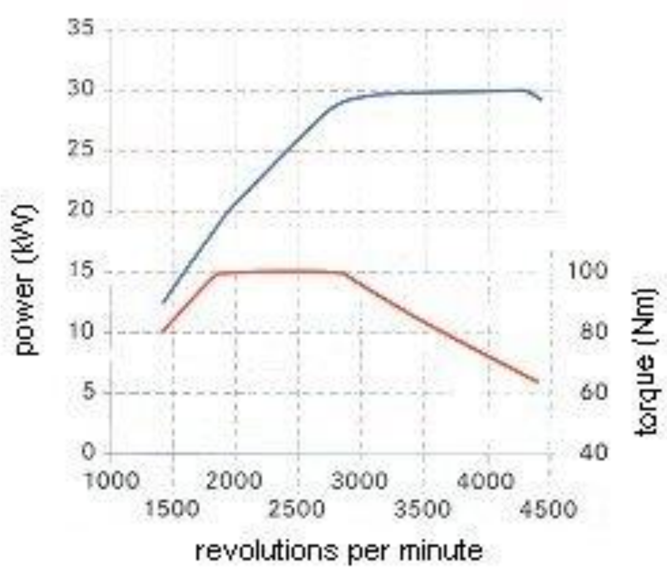

Figure 2. Power & Torque Curves [2]

Chassis Selection

The Polaris Titan SP, pictured in Figure 3, was the right choice for the diesel utility class. Due to the size of the Mercedes-Benz OM660 engine, it was clear that a chassis with enough space to fit the engine and the additional components that to go with it, was needed. A sled with great control, balance, handling, and performance while also being able to support the weight of the OM660 was also required. The Polaris IPF shocks provide enough stiffness to compensate for the added weight to the sled, and still allow for smooth ride at no loss of performance. The Titan SP comes with a 20 x 155 x 1.375 Ripsaw Full Track to give enough traction while towing heavy loads. Another feature that lead to the choice of this chassis is the Titan Alpha transmission. This transmission offers a high, low, reverse, and neutral drive ranges with the high gear having a towing capacity of 1200 lbs. These features were found to be desirable because of the need for a high-performance sled, while still falling into the utility chassis class laid out by the CSC rules.

Figure 3. 2018 Polaris Titan SP

Drive Train

The Mercedes-Benz OM660 was designed to be used in a small smart car which utilizes a semi-automatic transmission that is bolted directly onto the bell housing of the engine. That is much different that the continuously variable transmissions (CVT) that are used on most snowmobiles, and required for the CSC [1]. Production snowmobile engines come with a taper that protrudes from the engines output shaft so that a primary CVT can be placed on. The primary CVT utilizes weights and springs to compress on the drive belt when the desired engine RPM is reached, and spins the belt. The belt then spins the secondary CVT which is connected to the jackshaft that goes into the Titan Alpha Transmission.

Taper Adapter

To connect to the required CVT to drive the snowmobile, a taper was made that attached to the flywheel of the engine. The taper was designed with careful consideration because it is much longer than typical tapers due to where the engine sits in the chassis. The extra length increases the moment that is applied to the taper when the clutches engage. An engineer at Carlisle Belts gave a verbal estimate of 4003.4 N (900 lbf.) of tension within the belt, so that was the applied linear force that was used during the design and analysis. The taper was carefully designed to avoid stress concentrations, utilize the current bolt holes in the flywheel, and to eliminate unnecessary mass that could cause it to be unbalanced. Figure 4 shows the finite element analysis (FEA) that was conducted during the design. The 4003.4 N force was placed where the clutch sits, and the model was fixed through the bolt holes. A maximum stress of 188.6 MPa was found and confirmed through an error analysis by changing the mesh size by a factor of 2. There was also a .2483mm maximum displacement at the tip that was deemed acceptable. The taper is made of out AISI 1045 steel which has a yield strength of 310 MPa [6]. This gives the taper a theoretical safety factor of 1.64. The maximum stress does occur at the weld point between the taper and plate. AISI 1045 is readily welded and the machinist said the weld was at least 80%, which decreases the safety factor to 1.32, which is lower, but still okay for a worst-case scenario. There is also a 44.48N (10lbf.) force added to the model where a pulley is mounted to spin the alternator. The pulley is hidden in figure 4 to display the peak stress area. The pulley has a diameter of 177.8mm (7 inches) so that the alternator will spin at about 2400 RPM when the engine is idling at 800 RPM.

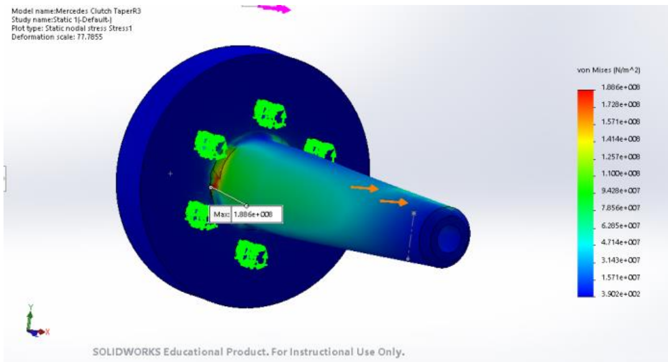

Figure 4. Clutch Taper FEA

Engine Management

Utilizing the OM660 within the snowmobile required a system that could utilize the controls on the snowmobile to safely control the engine and get the desired output of a clean and powerful snowmobile.

Engine Mounts

To support the greater weight of the OM660 engine and to ensure proper engine alignment the stock chassis engine mounting locations could not be used. New engine-to-chassis mounts and mounting locations had to be designed to coexist with the existing mounting locations on the engine block. All of the mounts were made with AISI 1045 Steel which is readily weldable and has a yield strength of 310 MPa.

Front Mount

The lower front crossmember on the bulkhead was redesigned to create a new mounting location

The front engine mounts purpose is to solely support the weight of the engine and not to counter act any horizontal forces created by the CVT. In the FEA a force of 7165 N was used. This value was determined by calculating the force on the mount assuming the mount supports 50% of the weight of the engine and the snowmobile was dropped at a height of 1 meter and considering the front suspension has .15m of travel. The calculations can be found in the Appendix. Figure 5 is the FEA of the front mount.

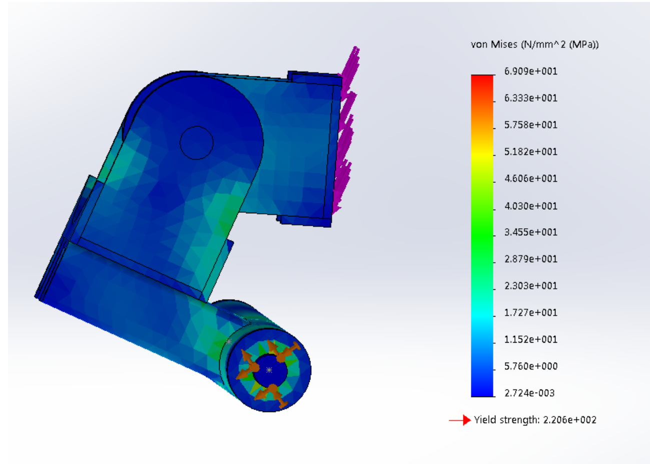

Figure 5. Front Engine Mount FEA

Rear Mount

The rear engine mount was designed to attach to the chassis along the forward heat exchanger. This location was chosen due to its alignment with the mounting location on the engine block and due to the geometry of the heat exchanger. The stock mounting location also utilized the heat exchanger to support the engines weight, the design built off that, but added more points of contact to further support the greater weight of the OM660 engine.

The rear mount not only has to support the force exerted by the mass of the engine, but must also counter balance the force created by the tension in the belt by the CVT. In the FEA the same value as the forward engine mount was used for downward force. The force created by the CVT was than calculated and added to FEA.

Calculating Moment Force:

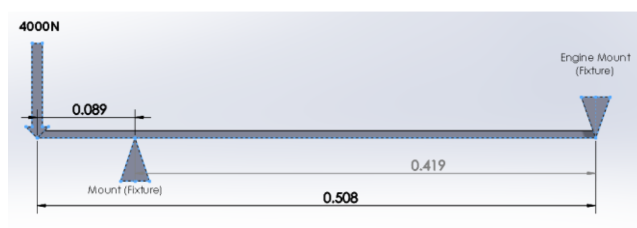

Figure 6. Free Body Diagram of Engine Mounts and Belt Tension

$$\sum M = .089m * 4000N - (.419m * F) = 0$$

$$F = \frac{.089m * 4000N}{.419} = 841.64N$$

Equation 2. Force Calculation of Rear Mount Using Equilibrium Moments

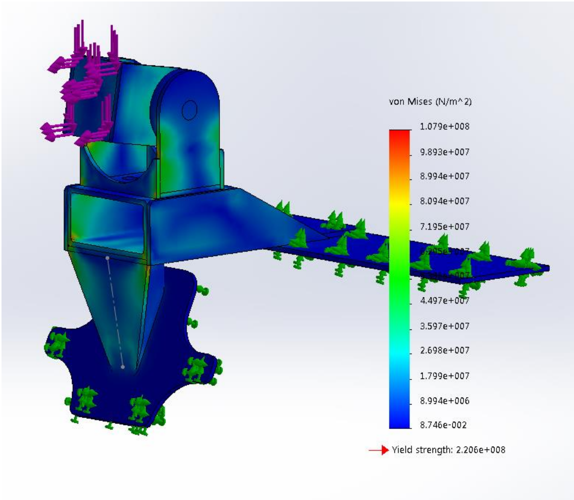

Figure 7. Rear Engine Mount FEA

Side Mount

The front and rear mounts are softer than the side mount, so the side mount needs to keep the engine square during clutch engagement. The side mount utilizes the strong bell housing of the engine and two stock bolt holes on the side of the chassis bulkhead. 1045 carbon steel was used for the mounts, and the pieces were cut using a water jet to make them precise and accurate to the SolidWorks model. In a worst-case scenario where the side mount had to support the entire linear force of the clutch engagement of 4003N, the mount experienced a peak stress of 48.26 MPa, which is much lower than the 310 MPa yield strength that 1045 steel has [5]. Figure 8 is a screenshot of the FEA using SolidWorks.

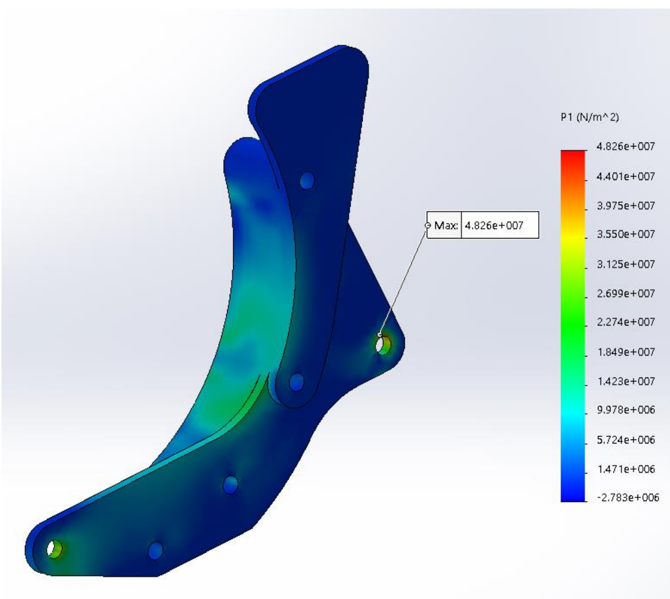

Figure 8. Side Mount FEA

Wiring

The wiring harnesses from the engine and chassis were carefully modified and conjoined to deliver power to the display, fuel pumps, fans, and other accessories on the snowmobile. The OM660 used an electronic throttle, while snowmobiles use a mechanical one, so a converter, manufactured by Audi, was wired in.

ECU

An Engine Control Unit (ECU) and Injector Driver Module (IDM) were also connected in, and coded to tune the engine. The ECU is a Delta 400 which pairs well with the Delta Piezo IDM. The customizable abilities allow the team to maximize the efficiency of the engine by controlling the air to fuel ratio and injector timing, and will play a big role in the future when heavier modifications are made.

Fuel Management

The fuel system on the OM660 is required to deliver diesel fuel to the injectors and provide an injection pressure above 130 MPa [3]. The fuel system incorporated in the snowmobile has an in-line electric fuel pump that delivers fuel to the injection pump at a constant 413 KPa of pressure. The entire system consists of a lifter pump to draw fuel from the tank and into the line, a pre-filter to entrap particles before passing through the electronic fuel pump, which draws fuel and forces it through the fuel-water separator and fuel filter, where it is finally fed into the injection pump, which is chain and gear driven from the crankshaft, and supplies an equal and even high-pressure fuel distribution to the fuel rail. The injectors used on the engine are stock with direct input signals coming from the Injector Driver Module that is paired with our ECU. The system is also equipped with a bleed valve, as well as standard flow valves, to provide for the ease of switching over fuel supply lines, and for purging air from the lines after switchover.

Coolant System

For the design of the coolant system, exceeding the cooling characteristics of the stock engine configuration of the OM660 Mercedes engine, was the goal. Being that the vehicle is a utility class snowmobile, it was taken into consideration that the stock heat exchangers on the chassis would not perform well enough under the amount of stationary and low speeds that the sled would expect to experience under a work environment. Whether the vehicle was in motion or stationary, the engine needs to stay at a comfortable operating temperature without worries of it overheating. To accomplish this, a very space efficient cooling package in the front of the sled, consisting of a fan, dual pass radiator and intake intercooler, were designed by Bell Intercoolers, and installed. A rendering of the cooling pack is shown in Figure 9. The cooling pack was then supplemented by plumbing the tunnel heat exchanger in parallel with the radiator. Due to the angle at which the cooling package had to be mounted, the direct airflow was cut down considerably, so to make up for this lack of airflow, a fan with a flow of 69 cubic meters per minute with a minimal current draw of 4.50 amps was installed [7].

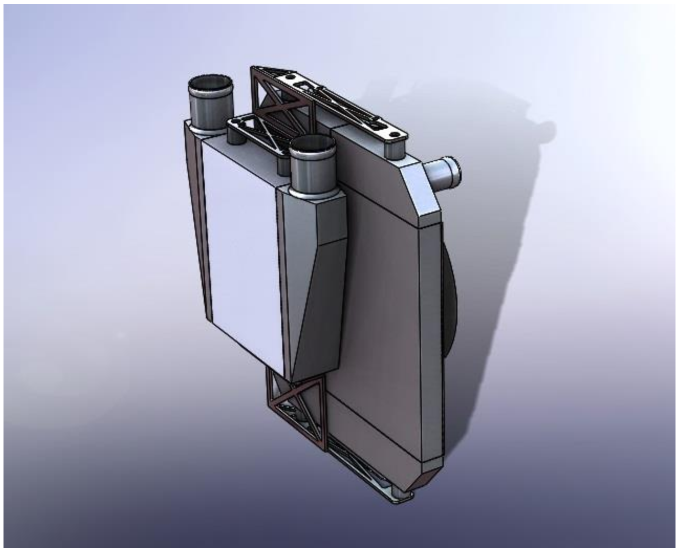

Figure 9. Bell Intercooler and Radiator

The second heat exchanger on the bulkhead was determined to be unnecessary and would have been in too close of proximity to the exhaust, so it was removed. Figure 10 displays the coolant track that is implemented in the sled.

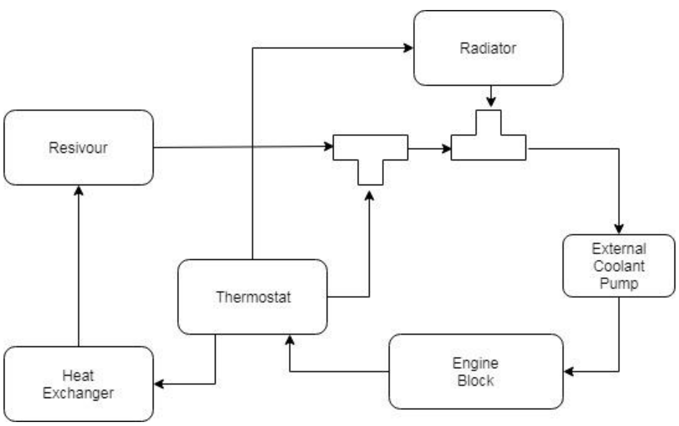

Figure 10. Coolant System

By setting up the coolant system in parallel, the flow of the system and the capacity of the coolant was increased. Due to the increase of the coolant capacity it was decided to use a remote electric water pump that was better suited for the increased volume of coolant. This also allowed the pump to be placed more efficiently in the chassis by making room for other components. Not only has the external coolant pump benefited the sled in the current design for the coolant system, but it will be highly beneficial next year where the coolant capacity will have to be increased even further to accommodate for a liquid cooled EGR and turbo.

Air Intake

To save space, the stock air filter and airbox were elected to be used as much as possible. To do this, an adapter was made to go from the custom shape of the Polaris intake tubing to the 38mm diameter turbo inlet. SolidWorks was used to model and simulate a flow analysis of the part to develop a gradual decrease in the cross-sectional area of the flow that fit within the available space in the bulkhead. Figure 11 is a screenshot of the analysis. All sharp corners were avoided to maintain laminar flow into the turbo inlet

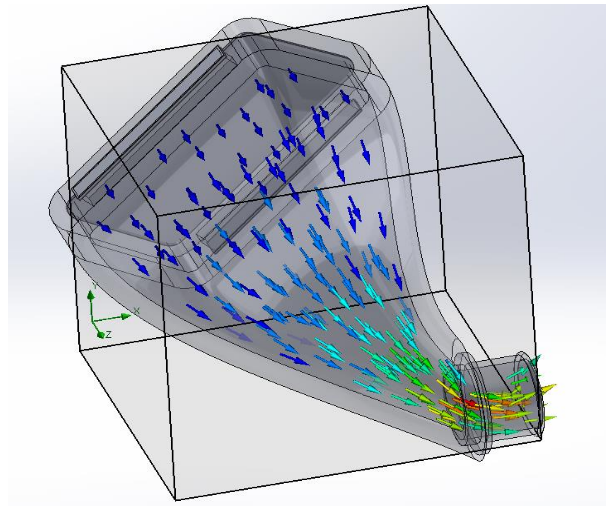

Figure 11. Air Intake Flow Analysis

The air intake was 3-D printed at the National Resources Research Institute (NRRI) in Duluth, MN, using carbon reinforced nylon 11.

Figure 12. Air Intake Rendering

Emission Controls

Controlling emissions is a large part of the Clean Snowmobile Challenge and it is also very important for the continuation of the sport of snowmobiling. The Mercedes-Benz OM660 has relatively low emissions due to its use of a turbocharger and direct injection, but further steps were taken by the UMD Diesel Team.

A catalytic converter and diesel particulate filter (DPF) were installed in the post-turbo after treatment portion of the exhaust. Catalytic Exhaust from Ontario, Canada supplied a purifier catalyst. This catalyst is designed to reduce Carbon Monoxide (CO) levels by 90%, Hydrocarbons (HC) by 80% and particulate matter (PM) by 20% [8]. A DPF was added after the catalytic converter to reduce the amount of particulate matter (commonly referred to as soot) that exits the tailpipe. The DPF that was used is also designed to decrease back pressure by 50% compared to other DPFs [9].

Exhaust temperature is very important to the efficiency of the catalytic converter and DPF. The catalytic converter requires temperatures around 260 ˚C for the pollutants to react with the oxygen to produce harmless product like it is shown in equation 3 [8]. The DPF requires temperatures between 300 and 800 ˚C to be able to burn off the particulate matter [9]. To obtain these high temperatures, the catalytic converter and DPF were placed as close to the turbo outlet as possible. The exhaust was also wrapped with exhaust wrap and shielded with heat shields composed of aerogel to keep the heat within the exhaust pipe, and to protect other components within the engine bay that are heat sensitive.

$$\text{Carbon Monoxide: } 2CO + O_2 \rightarrow 2CO_2$$
$$\text{Hydrocarbons: } HC + O_2 \rightarrow CO_2 + H_2O$$

Equation 3. Catalytic Converter Reactions [8]

Team Management

The UMD Diesel Team is composed of multidisciplinary engineering students that are looking for a hands-on experience to accompany their classroom education. The club is completely based on the members volunteering their time to do projects. The team is also unique in the fact that the club was originally made to perform research and development on diesel engines. So, the process of building a snowmobile to compete in the SAE CSC has been a complete learning experience for most of the members.

Outreach

Engineering is about looking at the future and thinking of how a better world could be created. In that sense, it’s important to reach out to the future generations, and get them interested in the mathematics and sciences. The UMD Diesel Team has participated in science and engineering nights open to the public, and spent a Saturday at the Barnes & Noble Mini Maker Faire talking to parents and children about the project and what got them interested in engineering. The kids were particularly interested in the 3-D printed prototypes of parts that were made.

After competition, the UMD Diesel Team will be spending time going to high schools in the Duluth area to showcase the finished snowmobile and to introduce the world of engineering to them.

Conclusions

Implementing a diesel engine in a snowmobile is unorthodox and provides many challenges, but if done properly, can create a workhorse that a gasoline engine can’t compete with. The UMD Diesel Team has implemented the following innovations to make the snowmobile possible:

- Selected the Mercedes-Benz OM660 for its size, efficiency, turbocharger, and direct injection
- Selected the Polaris Titan SP for its large size and durability, as well as its dynamic gear box
- Created a taper that would reach out to the CVT and be strong enough to withstand the large moment
- Designed engine mounts to support the weight of the engine and to keep the engine square during clutch engagement
- Implemented a cooling system capable of maintaining desired engine temperatures
- Utilized the stock air intake a created an adapter to provide sufficient flow for the turbocharger
- Reduced emissions with the use of a catalytic converter and diesel particulate filter.

The UMD Diesel Team has created a diesel utility snowmobile that conforms to the SAE CSC 2018 rules, and is a viable option for those in need of a utility snow vehicle. [1]

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Abbreviations

UMD	University of Minnesota Duluth
SAE	Society of Automotive Engineers
CSC	Clean Snowmobile Challenge
CC	cubic centimeter
CO	carbon monoxide
CVT	continuously variable clutch
DPF	diesel particulate filter
DUC	Diesel Utility Class
ECU	engine control unit
FEA	finite element analysis
HC	hydrocarbons
PM	particulate matter (soot)

Appendix

Force on Rear and Front Engine Mounts

Velocity at impact

$$V = 9.81\, {}^{m}/_{s^2} * 1m = 9.81\, {}^{m}/_{s}$$

Average velocity after initial impact

$$V_{avg} = \frac{\left\{9.81\,\frac{m}{s} - 0\,\frac{m}{s}\right\}}{2} = 4.91\, {}^{m}/_{s}$$

Determining Time Period of Negative Acceleration

$$t = \frac{.15m}{4.91\, {}^{m}/_{s}} = .031s$$

Determining Acceleration

$$a = \frac{4.91\, {}^{m}/_{s}}{.031s} = 158.1\, {}^{m}/_{s^2}$$

Force on Engine Mount

$$F = 45.2kg * 158.1\, {}^{m}/_{s^2} = 7146.1N$$