North Dakota State University – Clean Snowmobile Challenge 2016

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Abstract

North Dakota State University chapter of the Society of Automotive engineers (SAE) has developed a cleaner, quieter and more efficient snowmobile. This year's snowmobile is built around a 2014 Polaris 550 Indy Voyageur chassis. The snowmobile is powered by a rebuilt 904cc Yanmar diesel engine to increase fuel economy and towing performance. Due to excessive engine temperatures in last year's competition the reliability of the engine was in question and was rebuilt to ensure performance at the 2016 Clean Snowmobile Challenge. To increase power and efficiency the engine will be run with an IHI RHF3 turbocharger. In order to meet Tier-4 emission standards and further reduce the emissions of the diesel engine, a 2009-2014 Volkswagen TDI DPF and DOC has been implemented into the snowmobile. Several major modifications to the stock Polaris Indy chassis were made in order to incorporate the diesel engine. These modifications include a u-joint steering system, a tunnel-mounted liquid cooling system, and an over-structure modification.

Introduction

Exhaust emissions is an area of concern for engineering because of the potential damaging effects to the environment. The Clean Snowmobile Challenge (CSC) is a competition and learning experience where students can create innovative prototypes that could potentially help eliminate harmful emissions and increase fuel economy. The Clean Snowmobile Challenge, sponsored by SAE, is an international design competition that focuses on several environmental areas. These areas include increasing fuel economy, lowering emissions, decreasing noise levels while maintaining the industry standard performance levels. By competing in this competition, students gain hands-on experience and contribute to developing technology that can reduce the harmful effects caused by burning petroleum-based fuels. The CSC allows engineering students and snowmobiling enthusiasts to come together and initiate progress through competition.

Marketing Standpoint

A product that has great marketability is more likely to succeed in any industry. This being said, NDSU's snowmobile was designed for use as a utility vehicle. The implementation of a diesel engine has increased the fuel economy compared to that of a stock sled. Last year at competition, the snowmobile achieved 19.1 miles per gallon (mpg). However, two years ago, with the same engine and a similar chassis, 28.7 mpg was achieved. The added torque produced by the diesel engine provides the snowmobile with greater towing capabilities. To take advantage of the increased towing capabilities, a receiver was installed to the rear bumper of the snowmobile that is able to accommodate any standard two-inch receiver hitch.

Engine/Turbocharger

Due to overheating of the engine at competition last year at temperatures in excess of 320 degrees Fahrenheit, an engine rebuild was required.

Engine Rebuild

The rebuilt engine is a 904 cc three cylinder Yanmar 3TNM72-APL out of a Polaris Ranger 900D. During the disassembly of the engine, damage was evident in the number two cylinder. The damage included water and oxidation in the piston head and a small gouge in the cylinder wall. A bad head gasket caused the water damage and was replaced. Light honing was used to removed the gauge in the cylinder wall. Other parts replaced during the rebuild include the piston rings, journal and main bearings, head bolts, and all gaskets.

During further inspection 5 of the 6 valves were not seating completely. Valve lapping was successful in eliminating leaks in two valves and reduced leaks in the rest. After the rebuild was completed the engine was run on a water break dynamometer to break in the engine. After approximately 5 hours of break in time, the oil pressure started to decline. The engine was disassembled and inspected for the cause of the declining oil pressure. The root cause was a score mark on the pressure release valve in the oil pump. This caused the pressure release valve to remain open. The main bearings were significantly damaged and unsalvageable. Due to the limited time remaining until competition, it was decided to use the backup engine, which had been rebuilt as well.

Turbocharger

The turbocharger selected for this application is an IHI RHF3 turbo, which is designed for diesel engines with a displacement range of 1000-4000 cc and power output of 20-100 hp. This turbocharger was chosen based on a chart from the manufacturer shown in Figure 1 [1]. The main aspect that needs to be considered when choosing a turbocharger is the displacement of the engine. Although the actual engine displacement of 904 cc is slightly under the recommended range of 1000-4000 cc, the engine is rated for 23.8 horsepower, which is within the recommended power output range.

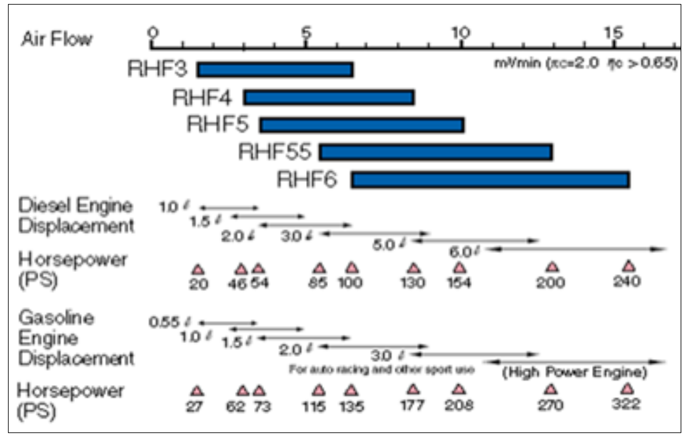

Figure 1 IHI turbocharger selection chart [1]

Chassis

Polaris Industries generously donated a new chassis. As entry will be in the diesel utility class, a utility style chassis was deemed as being the best option for this particular application. A 2014 Indy Voyageur with a 144-inch track was selected for the competition. This chassis is almost identical to the chassis that was used at competition last year. The team decided to select a similar chassis in order to improve on some designs from the previous year.

Chassis Modification

The stock chassis had to be modified in order for the team to be eligible to compete in this year’s competition. These modifications will be outlined in the following sections.

Over Structure

The Yanmar 3TNM72-APL is larger in overall size compared to the stock gasoline engine that was originally equipped in the snowmobile. Due to the increased height of the engine, a modified over structure was implemented. The new over structure is made from 1.25 inch OD A36 structural steel tubing with 0.25 inch walls in order to match the strength of the stock over structure. The new design also allows for the castings attached at each end of the stock over structure to be reused. By rotating the lower casting 30 degrees, the lower casting was left unmodified. Figure 2 shows a CAD representation of the modified over structure, while Figure 3 shows the modified over structure assembled into the chassis. The original aluminum over structure was evaluated to determine when failure occurs. It was determined that axial compressive failure occurred at 3750 lbf. The new over structure was then evaluated using a compound load to account for the 30 degrees of rotation. The magnitude of the load was 3750 lbf. Figure 4 shows the FEA results of the compound loading. The new over structure provides a factor of safety of 1.23.

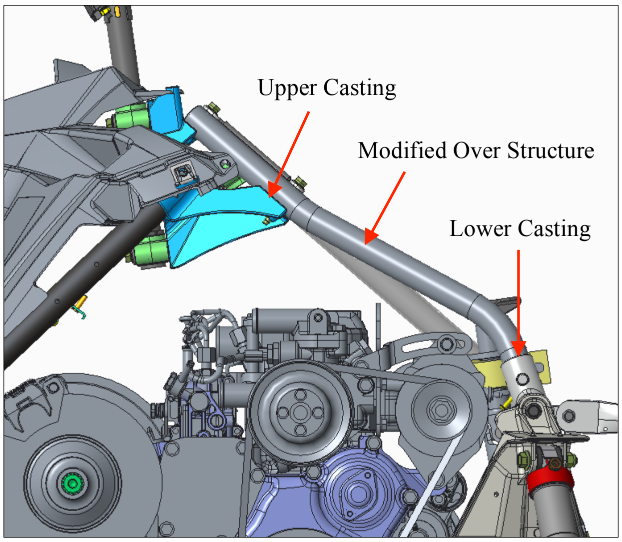

Figure 2 CAD model of the modified over structure

Figure 3 Modified over structure assemble in chassis

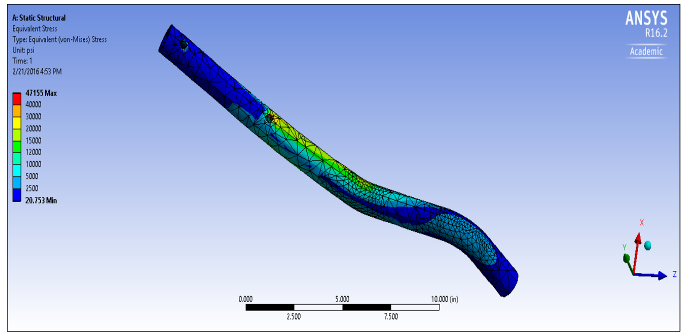

Figure 4 FEA of modified over structure

Engine Mounts

The engine mounts from last year's competition snowmobile will be utilized to accommodate the Yanmar engine. The Yanmar engine has much higher mounting points than the stock engine, so the original mounting points in the chassis cannot be used. CAD models of the complete engine mount assembly are shown in Figure 5 below.

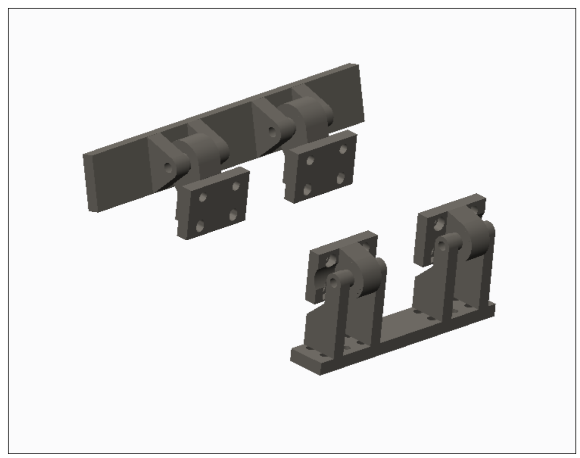

Figure 5: CAD assembly models of the engine mounts

Plates were attached to the chassis behind the engine and to the bulkhead under the engine. Brackets were bolted to these plates. The 2013 NDSU Clean Snowmobile team performed FEA analysis on the mounts to ensure that 321 stainless steel would be a sufficient material. Figure 6 shows analysis of the brackets used to attach the engine mounts to the rear plate. A load of 250 pounds was applied to the bracket during the simulation. This loading was determined by considering the weight of the engine and the torque output of the engine. Figure 6 shows the maximum von Mises stress in the part is considerably less than yield strength for the 321 stainless steel. The bracket resisted deformation and maintained a factor of safety of 27.2 based on von Mises stress.

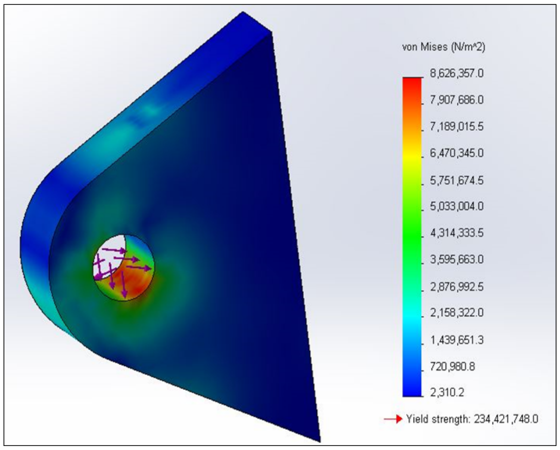

Figure 6 FEA analysis of the rear engine mount brackets

The front and rear engine mount blocks were analyzed as well to ensure that 6061 aluminum would be sufficient. Analysis of the mounts was performed by applying a load of 500 pounds to each block. This load was determined by considering the weight of the engine and torque output of the engine. Figure 7 shows the analysis of the rear engine mount had a factor of safety of 2.86. The front engine block had a factor of safety of 3.02 using Von Mises which can be seen in Figure 8.

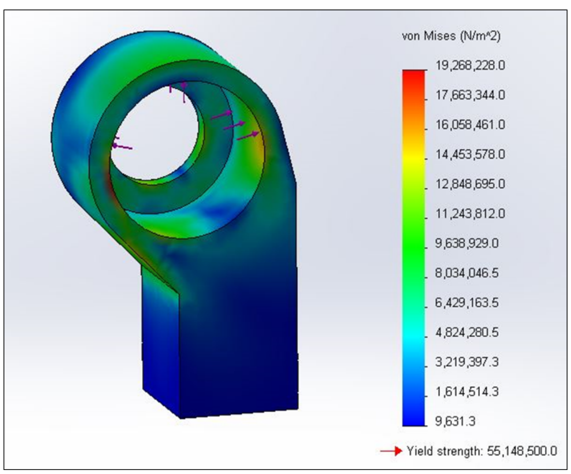

Figure 7 FEA analysis of the rear engine mount blocks

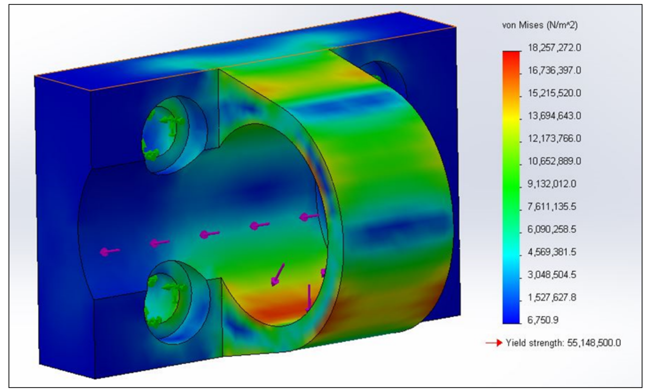

Figure 8 FEA analysis of the front engine mount blocks

Tunnel

Very few modifications were made to the tunnel, as structural integrity could not be compromised. A receiver hitch was attached for the two events that involve towing. Also, new holes were drilled on the sides of the tunnel to bolt on the rail mounts.

Cooling System

The chassis acquired from Polaris Industries is for a fan-cooled snowmobile. This type of cooling system would not suffice to keep the diesel engine cool so a new cooling system had to be designed. The new cooling system for the sled consists of a heat exchanger that has been modified to fit between the two stock tunnel protectors. The heat exchanger was taken from last year's snowmobile, a 600 Indy Voyageur. Simple welds were used to patch up a leak in the heat exchanger. In order to fit between the two tunnel protectors, the pipe connecting the two halves of the heat exchanger needed to be substantially shortened. The cooling system was taken to a welding shop to have the new design properly welded. The coolant lines run from the heat exchanger through holes that are drilled at the front of the tunnel and then to the engine. This design allows for snow to be kicked up from the track to hit the heat exchanger and cool down the coolant running through it. Leaving the stock tunnel protectors on the sled will also protect the heat exchangers from being damaged. Below Figure 9 shows a CAD model of the new cooling system. The red highlighted part is the added heat exchanger.

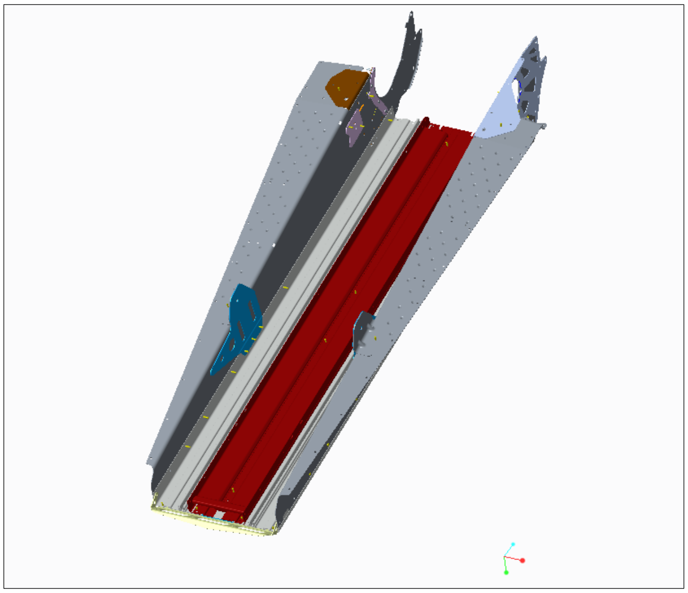

Figure 9 Cooling system mounted under tunnel

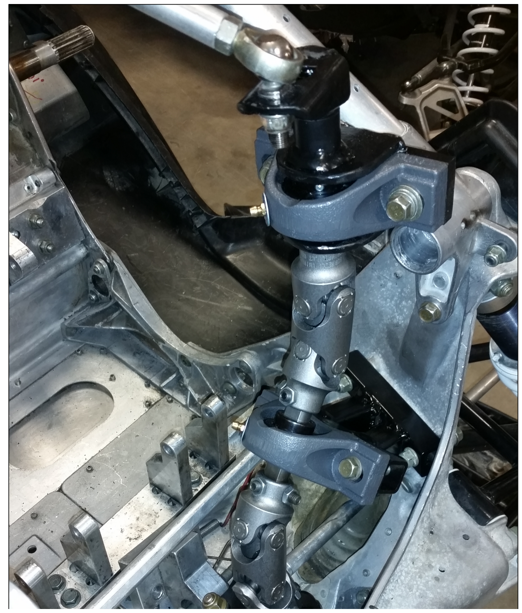

Figure 10 Steering joining linkage

Steering Modifications

Due to the limited space available in the engine cavity, a new steering system that incorporates aspects of the 2014 550 Indy Voyager and the 2014 600 Indy Voyager steering systems was implemented. Components reused from the 2014 550 Indy Voyager steering system include the tie rod mounting plate which acts as a lever arm forcing the tie rods to turn the skis and the lower mounting plate for the steering shaft. Aspects reused from the 2014 600 Indy Voyager steering system include the upper steering post and linkage. The joining linkage between the two steering systems was assembled using Borgeson double u-joints, 3/4-inch DD steering shaft, and NTN mounted bearings. Figure 10 and Figure 11 show the joining linkage and the completed steering assembly, respectively.

Figure 11 Complete steering assembly

Emissions Control

Due to the high point values associated with emissions and failure to meet lab emissions at last year's competition; a large amount of research went into finding the best possible exhaust system. The starting point of the research was looking at the lab emissions from the 2015 competition. The team met all emission standards except for soot.

Running a diesel engine in a snowmobile provides unique emission system challenges. Diesel engines release several compounds that are harmful to the environment. The primary pollutants created are nitrous oxides (NO_x), carbon monoxide (CO), particulate matter and Hydrocarbons. To prevent the release of these pollutants several exhaust after-treatment components are being used in the snowmobiles exhaust system. The exhaust system has both a Diesel Oxidation Catalyst (DOC) and Diesel Particulate Filter (DPF). The DOC and DPF are packaged together in a single can. The exhaust first flows through the DOC and then through the DPF before being emitted into the air.

DOC

The DOCs purpose in the after-treatment process is to reduce the release of CO, HC and PM. The catalyst is formed of a substrate that is coated with a precious metal. When the metal is heated to high temperatures a catalytic reaction occurs. This reaction oxidizes CO, HC and PM to the compounds CO_2 and H_2O. If selected properly, a functioning DOC can result in reductions of PM by 20 to 40 percent, HC by 40 to 75 percent and CO by 10 to 60 percent according to the EPA [2]. In order to burn to create the desired amount catalytic reaction high levels of temperature need to be reached. The exhaust temperature must exceed 300°C in order to reach the desired 90% efficiency level.

DPF

After the exhaust passes through the DOC it enters into the DPF. The primary function of the DPF is to remove particulate matter (PM) or soot from the exhaust stream. The DPF is similar to most filters in the sense that it traps the undesired PM before it can be emitted into the environment. The DPF is typically made out of a ceramic material that can withstand high temperatures. When the PM is trapped in the ceramic material it is burned into ash and converted into non-harmful emissions. This is called a regeneration process.

There are two types of regeneration, passive and active. Active generation requires a fuel additive to be released into the DPF. By adding fuel to the DPF, ignition occurs, creating high enough temperatures to cause regeneration. Passive regeneration requires no fuel additive. Instead the temperatures created by the engine are high enough to burn the PM trapped in the DPF. Proper application of a DPF can result in particulate matter reductions greater than 85% [3].

Last year's snowmobile operated using a prototype exhaust system from Emitec. This system used a partial-flow DPF which caused large spikes in the PM being emitted from the exhaust. To fix this problem, a wall-flow filter will be implemented into the exhaust system. Using an active regeneration process was considered to ensure total burning of soot. After weighing the pros and cons active regeneration seemed to complex and would cause loss of fuel economy. Instead, the temperatures created by the engine and insulating the exhaust routing will be used to cause passive regeneration.

Partial-flow filters allow some PM to pass through the DPF without passing through the filter. When the soot builds up to a certain level, it is ejected from the DPF, through a valve, before it can be properly treated by the system. A wall-flow filter forces every bit of PM through the filter before it can be released into the environment. This causes a much more efficient regeneration process and cleaner emissions. Depending on the system exhaust temperatures must be between 250°C and 600°C to cause active regeneration [4].

Finding a wall flow filter small enough to be used in a snowmobile was very challenging. Most Diesel applications are for much larger vehicles and will not fit in the snowmobile chassis. The team has been working closely with BASF The Chemical Company to obtain a custom system small enough to function in a snowmobile. Due to time restraints the BASF system could not be installed and a 2009-2014 Volkswagen TDI DPF will be used as seen in Figure 12 below.

Figure 12 DOC and wall flow DPF

Track Selection

A 144-inch track was selected because of the new towing category introduced in the 2015 competition. The snowmobile towed the sleigh easily at competition last year so it was decided that the team would continue with this selection.

Two tracks were considered from Camso, formerly Camoplast; the Cobra track and the Ripsaw II track. Both tracks focused on noise reduction and excellent traction through specialized lug designs. The Cobra track has cupped, flexible lugs, whereas, the Ripsaw II track has sharp, angled lugs [5]. Figure 13 shows a close-up of the lug designs of each track.

Originally the Ripsaw II track seemed to be the better track for competition since its lug design targeted hard-packed groomed trails, which is the main terrain that would be driven on at competition. But after discussing the desired characteristics for the track, it was decided that the most important item to focus on is finding a track that contributes to reducing the noise of the snowmobile. A representative of Camso informed the team that the best route to go for noise reduction would be to use the Cobra track [6]. Therefore the team has selected the Cobra track for competition.

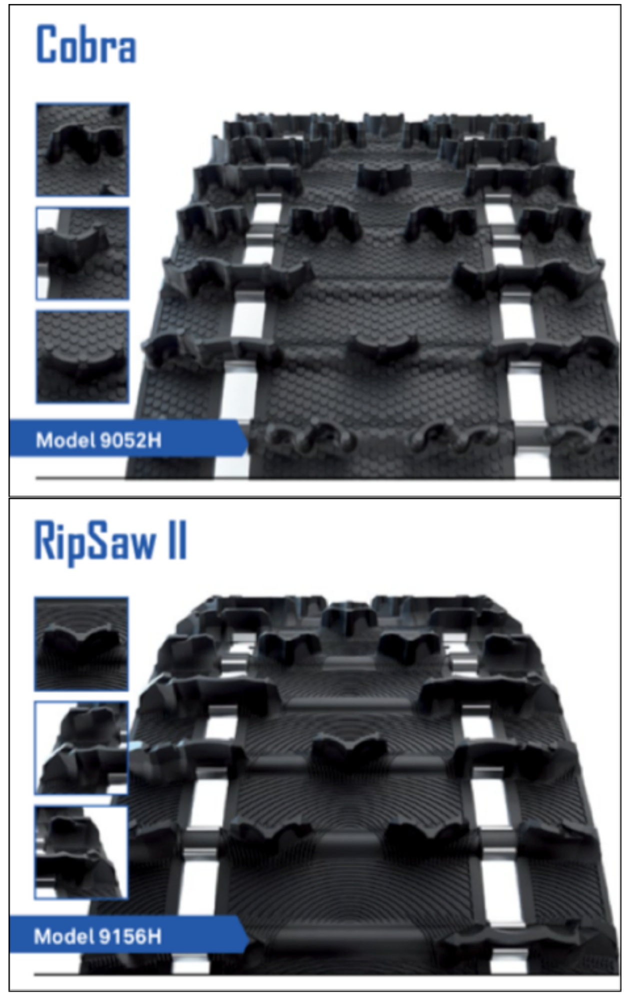

Figure 13 Track options from Camso [5]

Drivetrain

Continuous Variable Transmission (CVT)

The Indy Voyager snowmobile is propelled with two different clutches, the drive (primary) clutch and a driven (secondary) clutch. These make up the continuous variable transmission, more commonly known as a CVT. At rest when the drive clutch is spread all the way out and the driven clutch is clamped shut there is a 3:1 ratio from the drive to the driven. This 3:1 ratio continuously changes as engine speed changes. As engine speed increases the drive clutch starts to close while the driven clutch starts to open. Once the engine is at full speed, the drive clutch is fully closed, and the drive clutch is fully spread out, causing the ratio to change to 0.75:1, this gives an overall ratio of 4:1 for the CVT [7]. This is depicted below in Figure 14. The secondary clutch was replaced due to damages at last year's competition.

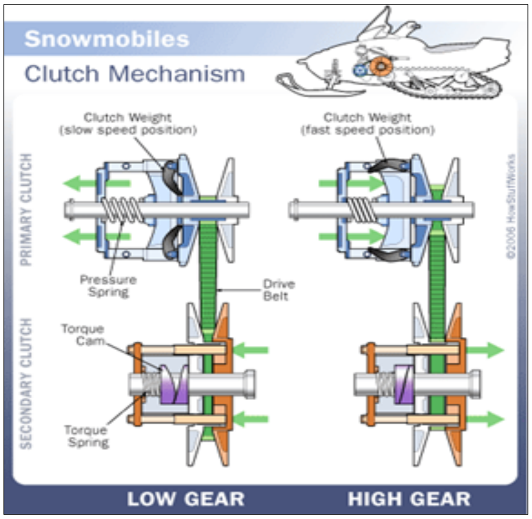

Figure 14 CVT schematic [7]

Output Shaft

The same engine and a comparable snowmobile chassis to the previous year's design will be used for competition this year. Therefore, the output shaft and spacer from the previous year's snowmobile will be reused. The output shaft allows the primary clutch to mate with the Yanmar engine. The material used for the output shaft was 321 annealed steal which has a yield strength of 234.42 MPa. Finite element analysis (FEA) was performed on the output shaft and spacer by the 2013 NDSU Clean Snowmobile team. Each of the components was analyzed based on an applied torque of 160 ft-lbf which was calculated by multiplying the max torque output of the modified engine by a factor of safety of 2.5. The highest stress on the spacer was 10.42 MPa giving a factor of safety of 22.5 based on the yield strength. The highest stress induce on the output shaft was 85.69 MPa giving factor of safety of 2.74. FEA results for the output shaft and output shaft spacer have been included in Figure 15 and Figure 16, respectively.

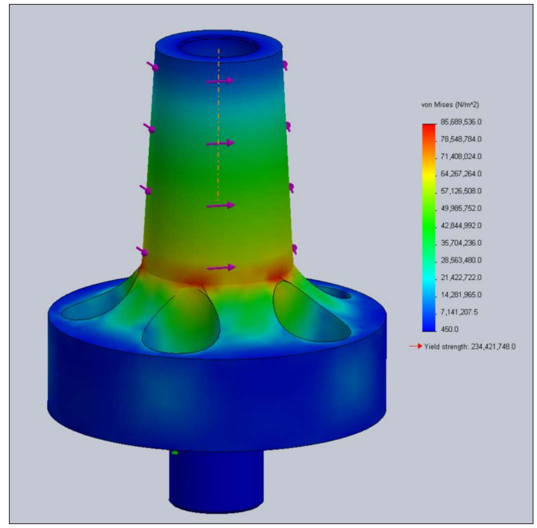

Figure 15 FEA analysis on the output shaft

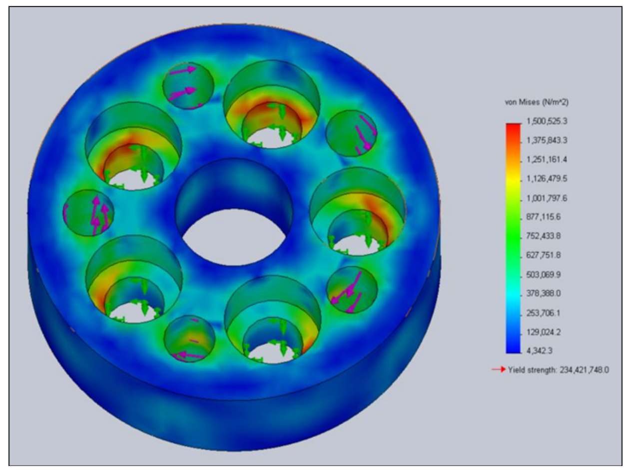

Figure 16 FEA analysis on the output shaft spacer

Sound Treatment

Exhaust

The path of the exhaust system is routed such that it will exit the bottom of the snowmobile directly ahead of the chain case. The sound created by the exhaust will be dampened by the snow underneath the snowmobile's engine cavity. The exhaust system will also be routed so that as the exhaust exits it is pushed more towards the center of the sled. This will help even out the sound so that the right side of the sled will not be substantially louder than the left side during the sound testing portion of competition.

Track

As stated before, when selecting the track, noise reduction was the team's main focus. The Cobra track will help contribute to reducing the snowmobile's noise.

Summary/Conclusions

The NDSU Clean Snowmobile Team's focus this year was to build a reliable snowmobile that was focused on the key values of the competition. The world is constantly changing and as engineers it is important to address the issues that these changes cause. Each year stricter regulations are being put on original engineering manufacturers (OEMs). Regulations on lowering emissions and increasing safety are of constant concern to the public. For the 2016 competition, NDSU implemented a diesel engine into a Polaris Indy Voyageur chassis. The Diesel engine provided increases in both fuel economy and in the towing capability of the snowmobile. The Diesel engine also provided some drawbacks that needed to be resolved. There isn't an OEM in the snowmobile industry that uses a diesel engine. Due to this, a lot of time and energy was focused on making the snowmobile chassis compatible with the Diesel engine. Engine mounting was replaced, steering had to be redesigned and a new cooling system was run under the tunnel. Due to the large amount of soot levels of the previous exhaust system, a wall flow DPF was implemented. These challenges gave team members engineering experience that can be used later in industry. Although running a diesel engine is uncommon, it provides unique opportunity for new design in an industry dominated by two stroke engines. This year the NDSU team hopes to improve in all areas of the competition, specifically the endurance run and lab emissions. When designing this year's snowmobile, a large amount of attention was on making a reliable machine. By having a snowmobile that can be run multiple years, more time can be spent on innovative design and improving performance at the SAE Clean Snowmobile Challenge.

References

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Definitions/Abbreviations

CSC (Clean Snowmobile Challenge)

CVT (Continuous Variable Transmission)

DOC (Diesel Oxidation Catalyst)

DPF (Diesel Particulate Filter)

NDSU (North Dakota State University)

OEM (Original Engineering Manufacturer)

PM (Particulate Matter)

SAE (Society of Automotive Engineers)