Clean Diesel Technology for Snowmobile Applications

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INTRODUCTION

Bison Motorsports, the SAE collegiate chapter of North Dakota State University (NDSU), has been competing in the Clean Snowmobile Challenge (CSC) competition since 2012. NDSU helped pioneer the Diesel Utility class and has continued to innovate the area of diesel engine viability in snowmobiles to this day. For the 2019 season, the NDSU clean snowmobile team will continue this tradition while bringing state-of-the-art chassis and diesel engine design to compete against some of the most talented collegiate snowmobile design teams in the world.

INNOVATIONS

NDSU's 2018 competition snowmobile did not meet the standards of the current team and because of this, the 2019 team decided to redevelop the majority of the subsystems on the snowmobile. Several of the systems the team improved were also considered for innovation opportunities. These systems include a turbodiesel engine, the Polaris MessageCenter Gauge, the engine oiling system, and the steering system. Summarized below is each subsystem that was innovated to improve form or function. Further details of each component will be discussed in the 'Design Content' section of this report.

Turbodiesel Engine

One major innovation was acquiring and integrating a highly efficient turbodiesel engine into the snowmobile chassis. The team sourced a Mercedes-Benz OM660 engine developed specifically for the SMART ForTwo microcar. The 2018 NDSU team attempted to use a similar engine without success. The 2019 NDSU team overcame this by sourcing and purchasing a known running engine from Canada, converting it to a standalone engine management system, integrating it into the snowmobile chassis, and adapting an exhaust emissions aftertreatment system to it. Further details of this process and methodologies are discussed in the 'Snowmobile Components' and 'Design Content' sections.

GPS-Based Graphical User Interface (GPS-GUI)

The Mercedes turbodiesel engine requires a completely different ECU from the factory Polaris ECU. This means that the Polaris MessageCenter Gauge is not capable of displaying the new engine parameters. To solve this issue, the team developed a unique colored LCD touchscreen display with remote tuning and data logging capabilities. It should be noted that due to competition rules, all remote tuning features and telemetry will be disabled for the entirety of the competition (GPS speedometer excluded).

The GPS speedometer was integrated into the display system through use of a GPS breakout board that can parse GPS data accurately at up to two times per second. The display reads out in bar gauges that are easy to read at a glance but also outputs the real time numerical sensor values for precision monitoring.

To house the new, larger display and supporting components, a custom case was modeled with CAD software and 3D printed. The case was designed to house the graphical user interface as securely as possible without limiting its functionality all while fitting into the OEM display location.

Dry-Sump Oil System

After experimenting with a total redesign of the steering system last season, it was concluded that the most practical solution was to retain the OEM steering geometry and mounting locations. A low center of mass was also important due to the increased weight of the diesel engine and supporting systems, making it necessary to mount the engine as low as possible in the chassis.

To facilitate this, a dry-sump oiling system was developed. This lowered the engine's center of mass by four inches and allowed the retention of the OEM steering geometry. It also lowered the primary sheave of the CVT, placing it closer to the OEM location and allowed the retention of the OEM sheave-to-sheave centerline distance. This creates better stock body panel fitment and reduces chassis interference. The volume of the system was maximized from 2.9 quarts to 8.7 quarts to reduce oil foaming, increase heat capacity, and provide engine protection in the event of a system failure. An oil drain plug was also added to the bottom of the reservoir. This gives the dry-sump oiling system the added benefit of allowing a complete change of engine oil without removing the engine from the chassis. Finally, a theoretical benefit of the dry sump system is that the OEM Mercedes oil cooler may be used in reverse as an engine coolant cooler if the engine coolant temperature exceeds the engine oil temperature.

The disadvantage of the dry-sump oiling system is that it adds an additional 45 pounds to the snowmobile over the stock diesel engine oiling system. 53% of this this weight is positioned in the furthest forward cavity of the snowmobile behind the front bumper. This is a weight and handling disadvantage; however, the diesel utility class focuses on durability rather than handling. Therefore, the benefit of the additional oil system capacity outweighs the weight and handling penalties.

Electric Power Steering

Electronic power steering (EPS) is a new trend in the automotive sector and has recently found its way into the power sports market. After studying the implementation and construction of various EPS units, it was decided to implement a system in the snowmobile. The main components of the EPS system include a power steering motor from a 2012 Saturn Vue, a universal DC motor controller, and hand fabricated parts.

The EPS system is fully adjustable for assist level via gain knob on the dash. This allows very sensitive and precise power assisted steering during slow speed maneuvers where required handle bar effort is greatest. The rider is also able to dial in the assist they want or turn the system completely off depending on their preference.

The EPS system was specifically designed to be bolted into the snowmobile without any modifications to the snowmobile chassis. This was done to showcase the fact the system can be implemented in different models and across a company's lineup. Some minor fitment accommodations needed to be made but the overall system is very compact and adaptable.

TEAM ORGANIZATION AND TIME MANAGEMENT

NDSU is very familiar with the SAE Clean Snowmobile Challenge. 2019 will be the seventh competition for the university. To be competitive at any of the SAE Collegiate Design Series (CDS) events, effective project management and team organization is critical.

For a traditional project in a company or organization, project management is very structured. Each team member has a specific job title and a set of responsibilities. Strict timelines are set and the process of how things are completed is well documented. This increases efficiency and furthermore, increases profit from each project.

SAE CSC is not a traditional project for many reasons, the main being that it is almost completely voluntary in nature. The NDSU team is made up of five seniors who are completing the CSC snowmobile as their cap-stone project. They are considered the “project leaders”. The team also includes eight underclassmen SAE members that act as “technicians” as well as design and develop non-critical components and systems. This means most of the team is volunteering their free time to work on the project with no short-term incentives from the university and makes having a traditional method of project management very difficult. To mitigate this, a non-traditional method of project management called “Kanban” was selected to use.

Kanban is a popular framework that uses visualization to organize collaborative and self-managing teams. High level objectives were established for the entire team. From there, subgroups of interested team members chose their responsibilities from the list as seen in table 1. Each subgroup had complete freedom in their methods of completing their part of the project and the team met up once per week to update the entire team on progress and issues. The design team participated in the subgroups and gave direction as needed for the entirety of the team. The subgroups can be seen in Table 1 below.

Table 1. Team Organization and Responsibilities

Subgroup Responsibility	Subgroup Members
Engine Diagnosis	Mike, Kai, Luke, Jonah
Dry Sump Oil System	Bill, John, Mike
Part Modeling, FEA, Paperwork, Static Display	Mehrnoosh, Luke, Jonah
Engine and Chassis Electronics	Jason, Trent, Jonah
Display	Jonah, Luke, Trent
CVT	Brett, Bill, Jeff
EPS	Jeff, Matt, Caleb
Bodywork Modifications	Brett, Kai, Ben, Luke
Exhaust	Matt
Engine Mounting, Oil Reservoir, Overstructure Modification	Bill
Fundraising	Brett, Caleb, Kai, Mike, Jonah

To organize subgroup activities and ensure deadlines were met, a Kanban board and Gantt chart was created. A Kanban board is used to visualize what projects are ongoing, upcoming, and complete. It consisted of three columns labeled “To-Do”, “Doing”, and “Done” along with sticky notes with the tasks written on them that were moved accordingly. A Gantt chart was used to recognize which tasks could be done simultaneously and which tasks were waiting on other tasks to be completed before they could be started.

Fundraising and Team Building

The SAE CSC would be almost impossible to compete in without fundraising and sponsorships of some kind. Polaris Industries was generous in donating a working Titan snowmobile, along with many other parts the team needed. Team industries was also a large contributor to the team this year by donating a military grade clutch designed for diesel engines and their assistance in tuning the team’s CVT. Numerous other companies gave monetary donations that helped make the project possible.

To build the team’s comradery, the team took a trip to Roseau, MN to tour the Polaris Industries plant and pick up the donated snowmobile. Team building was essential because the team is composed of freshmen, sophomores, juniors and seniors from all different backgrounds. This Polaris tour united the team in a way that working in the shop could not by using a combined interest in snowmobile production. The trip was also very beneficial to the team by providing a visual representation of how snowmobiles are assembled as well as meeting with Polaris engineers to answer questions about planning and executing a project of this scope. The team also hosted a get together where members could take a mental break from the project and bond with each other. This was crucial to improve overall team moral and avoid burnout on the project.

SNOWMOBILE COMPONENTS

Chassis Selection

There are several utility class snowmobile chassis approved for competition. From that list, the NDSU CSC team decided to continue using the 2018 Polaris Titan XC chassis. This was partly due to Polaris' willingness to help support the 2019 CSC team through a new 2018 Titan chassis as well as continued resourcing of parts.

Figure 1. 2018 Polaris Titan XC

The new Polaris AXYS chassis has taken the utility snowmobile class to a new level. It blends the capabilities of a traditional utility class snowmobile with deep snow riding and maneuverability. It is a much more balanced package compared to its competitors and Polaris' previous utility snowmobile offerings. Because of this, the Titan offers many benefits for competition. Specifically, the 20-inch wide track and HI-LO range gearbox were a decided advantage in the "draw bar pull" and "acceleration plus load" competition events. The rider forward Chassis positioning follows modern snowmobile design convention and accurately portrays what is currently available on the modern market. This makes the Polaris Titan much more appealing to the majority of the snowmobile market.

One concern with the Polaris Titan chassis, however, was the limited amount of engine compartment space for packaging the turbodiesel engine and its subsystems. The team determined that it was possible to overcome this with strategic component placement and fabrication. Subsystem components, such as intercoolers and reservoirs, would also need to be optimized for size and efficiency in order to make everything fit correctly.

The turbodiesel engine also adds weight to the front of the snowmobile. To help compensate for this, Polaris Pro Float skis were used in place of the stock components to increase the ski footprint. This will provide 45% greater off-trail floatation and redistribution of the additional weight.

Engine Selection

The only engine currently available for the Polaris Titan is the 800cc Cleanfire® H.O. This is a twin cylinder, two-stroke, gasoline engine that produces an advertised 155 horsepower [1]. Two-stroke engines have a relatively high power-to-weight ratio, a desirable trait for a snowmobile engine, but lack combustion efficiency, have relatively high brake specific fuel consumption, relatively high noise output, and are less reliable. These traits were considered disadvantages for the Clean Snowmobile Competition Diesel Utility class.

Figure 2. Mercedes-Benz OM660 Diesel Engine

In comparison, diesel engines exhibit traits completely opposite of two-stroke gasoline engines. Diesel engines can have highly efficient combustion when injection timing, pulse width, and fuel pressure are optimized. Diesel engines can reach very low brake specific fuel consumption values due to higher compression ratios and the ability to run very lean without the risk of engine damage. Noise output can be greatly reduced with the use of a turbocharger, properly designed exhaust system, and the natural dampening effects of a robust engine block and cylinder head. Furthermore, the one characteristic "knocking" sound of a diesel engine can be eliminated with proper fuel injection timing and staged fuel injection events. Finally, diesel engines are generally more reliable than two stroke engines because they have a sealed and filtered oiling system, robust internal components, and operate at much lower speeds which reduces stress and friction on moving parts.

The disadvantage of using a diesel engine in a snowmobile application is their relatively low power-to-weight ratio. This is a result of their slow operating speed and robust construction. Modern automotive diesel engines also have electronic control systems that are generally more complex and sensitive to tuning than gasoline engine control systems. These tradeoffs must be considered during the engine selection process.

After weighing engine advantages and disadvantages, the NDSU CSC Team chose a Mercedes-Benz OM660 diesel engine. To the best of the team's knowledge, this is the smallest and lightest mass produced electronically controlled diesel engine available on the market today. It features an all-aluminum engine block with three cylinders, an aluminum cylinder head with a single over-head camshaft (SOHC), and two valves per cylinder layout. It displaces 799cc and has a compression ratio of 18.0:1. The engine has an electronically controlled direct fuel injection system with one fuel injector per cylinder. It is also turbocharged. With a Dyno-mite nine-inch dynamometer, the team measured a peak output of 39.1 hp and 48.9 lbf·ft at 4200 rpm.

Track Selection

The track chosen for the 2019 competition season was a Camso 9089U 1P Utility Track with Woody's traction studs installed in manufacturer's recommended pattern. The stock track had longer paddles that would lead to more noise generation. Instead, the team opted for a shallow paddle wide track that fit the competition regulations. Even though adding studs would create more noise, the team felt that, as a utility snowmobile, it was worth the added noise to gain points in the traction-based events.

Exhaust and Aftertreatment Selection

Since a car engine utilized in a snowmobile chassis was extremely rare, there was not any readily available exhaust systems available from an aftermarket supplier. This necessitated the team to design their own system from scratch. In designing the custom exhaust and aftertreatment system, the team tried to keep the inlet and outlet diameters the same as what a stock system would be if it were in a car. This was done to ensure that flow rates were not inhibited by the new design. The exhaust also had to be held as close to the engine as possible to get the catalyst up to operating temperature as fast as possible. The exhaust system will be ceramic coated, increasing exhaust system heat retention and further reducing catalyst light off time. A further explanation of the design of the exhaust system can be seen in the 'Exhaust system design' section.

In addition to nitrous oxides and sulfur oxides, diesel engines also produce a significant amount of soot under heavy loads and acceleration conditions. To mitigate this, a Diesel Oxidization Chamber (DOC, also known as a catalytic converter) and Diesel Particulate Filter (DPF) combination were used. This reduced the overall size of the aftertreatment system to aid in packaging and placed the components as close together as possible to optimize heat retention. Heat retention is necessary to "light off" the DOC and keep it at its proper operating temperature of approximately 900 degrees Fahrenheit. The DPF is passively regenerated, meaning there is no change to engine operation parameters or fuel delivery during the regeneration process after the engine has reached operating temperatures and is run at steady state.

Figure 3. Exhaust and Aftertreatment System

The Volkswagen part number *1K0-131-723-AD* is a proven DOC/DPF combination the team has used for several years. It is simple, robust, and works well with diesel engines in the 800-1000cc displacement ranges. For this reason, it was chosen again. To ensure proper function, a manual regeneration procedure was performed on it to eliminate any residual soot and hydrocarbons. The procedure was performed as follows, using a Thermal Systems TS 2022 OU oven:

Table 2. Manual Regeneration Procedure

Initial Temp (deg F)	**Final Temp (deg F)**	**Duration (hrs)**
Ambient	930	1
930	1020	1
1020	1020	3
1020	1200	0.2
1200	1200	3
1160	300	6
300	Ambient	6

Finally, a catalytic converter was placed after the DOC/DPF to further reduce any nitrous oxide emissions that may have been missed by the pre-catalyst due to soot buildup on the catalyst substrate prior to the generation process. This is a universal catalytic converter manufactured by Magnaflow (PN 60105) specifically for use with diesel exhaust systems. It is constructed with a stainless-steel body with a fiberglass mat insulated ceramic catalyst.

Oil System

The "semi-dry" sump engine oiling system utilizes a remote mounted oil reservoir that feeds the engine's internal gerotor pump via a flexible 0.625-inch I.D. collapse resistant hose. It is located at the front of the vehicle to facilitate easy filling, level checking, and draining. The reservoir also contains baffling to dissipate oil foam as well as chambers to prevent sloshing under extreme operating conditions.

Figure 4. Oil Reservoir Location

The bottom of the oil reservoir transfers oil directly into the internal pump of the engine. After the engine oil has passes through the cooler, remote mounted filter, and journal bearings it returns to the system's bed plate. This plate seals the bottom of the crankcase and collects oil to be transferred to two external gear electric scavenging pumps. From these pumps the oil re-enters the top of the oil reservoir. These pumps were flow tested at 2.2 gallons per minute. The pump housings and fittings were increased from 0.42-inch I.D. to 0.50-inch I.D. and clearance checked. This increased the flow rate by 20% for a total flow rate of 2.66 gallons per minute. Flow rate was tested using SAE 15W-40 oil through 0.625-inch hose at 62 degrees Fahrenheit and 12.54 battery volts. Pump flow is expected to increase as oil viscosity decreases with increased temperature.

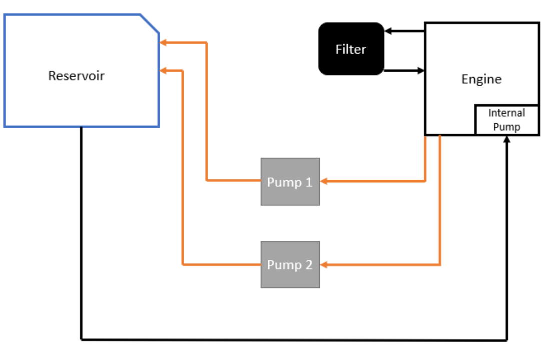

Figure 5. Dry Sump Oil System Schematic

The crank case bed plate and oil reservoir are made from 6061-T6 aluminum because of its high strength to density ratio, machinability, weldability, high thermal heat transfer characteristics, and relatively low cost. The oil transfer hoses are Parker 426 series high temperature rubber hose with stainless steel reinforcement. These hoses meet SAE 100R1AT specifications and exhibit excellent kink and collapse resistance characteristics. The scavenging pumps were selected strictly based on their affordability and simple design. Brass and steel fittings were used due to their low cost and availability.

Figure 6. Oil Reservoir Section View

Figure 7. Dry Sump Oil Pan

Control System

The OM660 diesel engine comes from a unique option of the Smart ForTwo only available in European and Canadian markets. This diesel engine option was not considered for the United States market and consequently has very little aftermarket support within the United States. The Bosch OEM ECU that came with the OM660 diesel is encrypted, making it virtually impossible to modify without proprietary software and hardware from Bosch. Therefore, the team had to look to foreign aftermarket support for a suitable engine controller.

SCS Delta, a company based in the United Kingdom, offers the SCS Delta 400 engine control unit (ECU) coupled with an SCS Delta Piezo injector driver module (IDM). The ECU and IDM were chosen because they are specifically developed to allow enthusiasts to operate the OM660 diesel as a standalone engine. It is also affordable and features the ability to modify and data log engine control parameters. Inputs such as rpm limiter, fuel pressure, and fuel injection pulse width and timing can be controlled manually by the user. Adjusting fuel injection quantity and timing is a large advantage because the engine can be tuned for the intended application. Increased fuel efficiency and reduced emissions are one of the goals for the Clean Snowmobile Challenge. With the SCS Delta equipment the engine can be tuned to reduce emissions and fuel consumption in all areas of engine operation while still maintaining adequate performance.

Because the stock engine was removed and the OM660 was installed, the stock display, which gives the rider snowmobile performance parameters like engine speed, rpm, etc., was no longer functional. A team member designed and built the new display as mentioned in the "Innovations" section to give the rider all necessary information on snowmobile performance.

Electrical System

The electrical system was designed to be both highly modular and safe. In past years, the electrical system was unorganized and fixed, making it difficult to diagnose problems and make minor adjustments. This year, the system was made to be adaptable using extension harnesses, a relay board, and easily accessible fuses.

First, an engine wiring harness was constructed along with an extension harness. The stock wiring map was used for reference [3]. The extension harness was necessary because the ECU and IDM are in the rear of the snowmobile away from potential risks like fires occurring at the front by the engine. The extension harness was constructed using two twelve-pin connectors, 3 two-pin high current connectors for the injector wires, and a single-pin high current connector for the glow plugs, which also require high current. The extension allows easy removal of the engine, ECU/IDM, or both as well as adaptability for dynamometer testing. For diagnostic purposes, a master engine wiring diagram and relay board diagram were constructed. The diagrams help the electronics stay organized and localize any electronics-based problems that arise and shown in Appendix A.

Second, a relay board was constructed to organize the relays and the power distribution for all engine and chassis components. The relay board contains six relays for the ECU, IDM, glow plugs, oil pumps, chassis components, kill switch, and five eight-pin distribution blocks for organizing the relays, powers, and grounds. With this setup, any damaged relay can be replaced in seconds, and the power and grounds are distributed in an organized fashion. Near the relay board is a fuse box that was mounted to the exterior of a battery box to replace broken fuses quickly and easily. The fuse box contains two rubber seals to remain waterproof while being mounted externally.

The glow plug controller was an expensive and unnecessary component for the electrical system, so a manual circuit was constructed. A manual toggle switch and indicator light on the dash power the glow plug relay, which in turn controls the glow plugs. The new setup is more reliable, effective, and affordable compared to the glow plug controller.

The wire gauges were determined based on previous wire gauges from the OM660 engine and the necessary current draw for each component. Any component transferred from the OM660 (engine sensor wires, injector wires, etc.) was wired with the same gauge wire used in the Smart car engine harness to maintain wiring safety. New components, such as the electronic display, were wired based on their current draw. For example, low current components were wired with sixteen-gauge wire and high current components were wired with fourteen and twelve-gauge wire, which was based on Figure 8. The ECU, IDM, oil pumps, headlights, taillights, fuel pump, glow plugs, and electronic display were all fused meaning all circuits are fused for safety. Crimped or soldered connections near the engine were covered with heat shrink. Also, wires were protected with plastic wire looming to protect them from the environment.

AMPS	3'	5'	7'	10'	15'	20'	25'
0 to 5	18	18	18	18	18	18	18
6	18	18	18	18	18	18	18
7	18	18	18	18	18	18	18
8	18	18	18	18	18	16	16
10	18	18	18	18	16	16	16
11	18	18	18	18	16	16	14
12	18	18	18	18	16	16	14
15	18	18	18	18	14	14	12
18	18	18	16	16	14	14	12
20	18	18	16	16	14	12	10
22	18	18	16	16	12	12	10
24	18	18	16	16	12	12	10
30	18	16	16	14	10	10	10
40	18	16	14	12	10	10	8
50	16	14	12	12	10	10	8
100	12	12	10	10	6	6	4
150	10	10	8	8	4	4	2
200	10	8	8	6	4	4	2

Figure 8. Wire Gauge Selection Table for 12 Volt Circuit

Vacuum Formed Body Panels

To accommodate for the larger engine and alternate clutch, the stock body panels needed to be modified. For last year's competition, a sheet metal patch was fabricated to cover the hole cut in the body panel. For the 2019 competition, to minimize weight and streamline the chassis, 3/8-inch ABS plastic was vacuum formed around a mold and attached to the body panel.

DESIGN CONTENT OF SNOWMOBILE

Engine Adaption

Given the larger size of the OM660, modifications were needed to integrate it into the Titan chassis. The first modifications done were the engine mounts. Three mounts were built to hold the engine in the optimal orientation. The mounts were then modeled in CAD and had finite element analysis (FEA) performed on them, confirming that they were as strong as the stock mounts. The fabricated mounts were then finalized according to the CAD models. Vibration isolation was used on each mount to reduce vibration transferred to the chassis.

Modification of the overstructure supports was unavoidable, due to the OM660 size. The optimal engine orientation of 55 degrees was selected to retain the OEM steering and overall overstructure shape. The stock overstructure supports were model in CAD and had FEA performed. Polaris Industries was contacted to determine the mechanical properties of the OEM supports. The supports were then tested to failure by increasing the applied force until the maximum principal stress surpassed the yield stress. To ensure that the new overstructure supports passed the competition standards of being as strong, if not stronger than the stock structure [2], the newly designed overstructure was tested with the same loads that caused failure in the stock supports. It was determined that AISI 4140 Chromoly with .125-inch thickness was needed to pass the FEA.

GPS Integrated Display

The display is made using a raspberry pi microcomputer to handle engine sensor data passed from through the controller area network bus coming from the engine control unit. Once received the computer decodes the CAN messages according to the OBDII standard and displays them on a GUI designed for readability in both high and low light situations. We also integrated our GPS speedometer into the display system through use of a GPS breakout board that can parse GPS data accurately at up to 2 times per second. The display reads out in bar gauges that are easy to read at a glance but also outputs the real time numerical sensor values on top for precision monitoring.

In addition to providing digital gauges the computer also stores the sensor values in comma separated value format in text files named for the time and date at which the program is run. The program logs the time, the GPS speed, and all programmed engine sensors. This gives us the ability to log engine sensors during dynamic testing and diagnose engine issues based off the sensors without being in the lab.

The display was designed with the operating environment at the forefront of our minds. To function properly all components must be able to operate in the cold weather, withstand the snowmobile potentially slamming on the ground, and hold up against the constant vibrations generated from the dynamic mechanical components of the snowmobile. To design to meet these requirements, research was conducted in all computer and electronic components obtained to assure that they can withstand the harsh environments. It was found that that the manufacture's recommendation of temperature range for the Rasberry Pi used is -40-80 degrees Celsius. This will be more than satisfactory for competition.

Exhaust System Design

In designing an exhaust system that would work in conjunction with an engine designed for an automobile, albeit a small one, some challenges had to be overcome. These included component selection and availability, packaging within the chassis, and ease of configuration.

To start, the team decided on 2" diameter tubing at the base of this exhaust system after doing flow rate analysis given the parameters of the engine and its requirements. This gave us an ideal size of 1.75" I.D. tubing or 1.875" O.D. 2" tubing was selected because of availability of components like V band flanges, mandrel bends, and DPF.

With a background in exhaust design and fabrication, the location of each component was carefully chosen considering multiple variables. This left the team with a DPF located near the turbo outlet with a secondary catalytic converter following. A spark arrestor and finishing outlet aid in exhaust exit from under the lower right-side kick panel. This design will demonstrate exceptional performance while assisting in the goal of cleaner exhaust emissions.

Continuously Variable Transmission (CVT) System

The OEM Polaris Titan CVT configuration was not suitable for use with the turbodiesel engine. This is because its engagement, shift rate, and maximum shift rpm points are tailored to work optimally for a 155 horsepower 800cc two-stroke gasoline engine which is capable of operating at sustained engine speeds able 8,000 rpm. Instead of modifying the OEM 800cc primary clutch assembly and risk rider safety, the NDSU team decided to contact TEAM Industries for assistance. With their help, it was determined that the ideal clutch for this specific diesel application would be a TEAM Industries Rapid Response clutch.

The Team Industries Rapid Response primary clutch features the ability to safely add heavier weights to improve belt engagement at lower engine speeds under high torque conditions. This clutch will also improve torque response in the powerband while limiting engine speed to prevent over-revving and possible engine failure. Engine to transmission power transfer will be improved as well, reducing the amount of power loss due to belt slip. Finally, it should be noted that the Rapid Response clutch is 0.25-inches larger in diameter than the OEM AXSY primary clutch, giving the snowmobile a theoretically higher top speed.

There is a 4,050-rpm difference in peak power between the stock 800cc gasoline engine and the OM660 turbodiesel. Due to these extensive operation ranges, a primary clutch with broad tunability and available component options was needed. The Rapid Response primary clutch provided availability of custom weights and springs. Due to unforeseen delays in engine performance testing, primary clutch testing data was note available at the time of this report.

It should also be noted that an EPI Performance belt was used with the CVT system. The belt is composed of a more durable compound that will provide greater durability over OEM offerings. The dual cog design of the belt provides increased cooling to the clutches and belt by increasing air circulation within the clutch shroud.

Electronic Power Steering (EPS) System

Due to the added weight of the turbodiesel engine and supporting subsystems as well as the increased surface area of the Polaris Pro Float skis, steering effort while the snowmobile was at rest or at very low speeds was significantly increased. Because of this, a power assisted steering solution was developed. The system needed to be compact to allow room for other snowmobile components, light weight, able to have an adjustable assist rate, and maintain complete steering control during a system failure condition.

After researching different steering assisting methods, the team weighed the pros and cons between two common systems: hydraulic and electric. Hydraulic systems were immediately eliminated because they require a working fluid, a pump, relatively higher maintenance, are affected by cold weather, and are relatively complex. In contrast, electronic power steering is relatively compact, simple, robust, and is less affected by cold weather. It can also we easily adjusted and manipulated with a simple microcontroller and does not require a direct mechanical connection to the engine. For these reasons, the team chose to develop an electronic power steering system.

The components used to build the system were a power steering assist motor/gearbox/steering shaft assembly from a 2012 Saturn Vue (Figure 9). The stock steering post and linkage were adapted using a single u-joint, a steering drag link (Figure 10), and a short adapter shaft. The motor assembly is attached to the snowmobile belly pan using custom made mounting brackets with oil impregnated bronze bushings and the stock steering block mounting holes.

Figure 9: Saturn Vue electronic steering assist motor assembly

Figure 10: EPS drag link

Initially, the team developed the electronic power steering (EPS) system to return the steering performance back to stock levels. It was quickly discovered that the EPS system could be made fully adjustable to tailor the steering effort to suit the preferences of any rider using a simple motor controller. In the future, the steering assist rate will be computer controlled and integrated into the GUI computer to allow full steering assist when the snowmobile is completely stopped and then bleed off assist to zero as the snowmobile picks up speed. This will provide minimal steering effort when the snowmobile is at rest and maximum steering feedback and rider safety at high speeds.

Sound Reduction

To test the sound reduction of the competition snowmobile, the team conducted "A/B Testing" with a stock Polaris Titan XC. A/B testing consists of testing both a stock snowmobile and the team's modified snowmobile and comparing the results. SAE J192 testing standard was followed to the best of the team's ability with and the results were compared. The standard stated that a test course be set up like the one shown in the figure below, and three tests were conducted: an acceleration test, steady state test, and stationary test. For the acceleration test, the snowmobile was brought up to 15 mph before applying full throttle for 150 feet. The microphone was located 75 feet up the line of the path and 50 feet away, positioned perpendicularly to the path. For the steady state test, the snowmobile was held at 15 mph for the entirety of the path and the sound was measured with the same process of the acceleration test. For the stationary test, the snowmobile was slowly brought up to 4000 ± 200 rpm while remaining stationary. The microphone was located 12 feet out from the exhaust port and four feet off the ground.

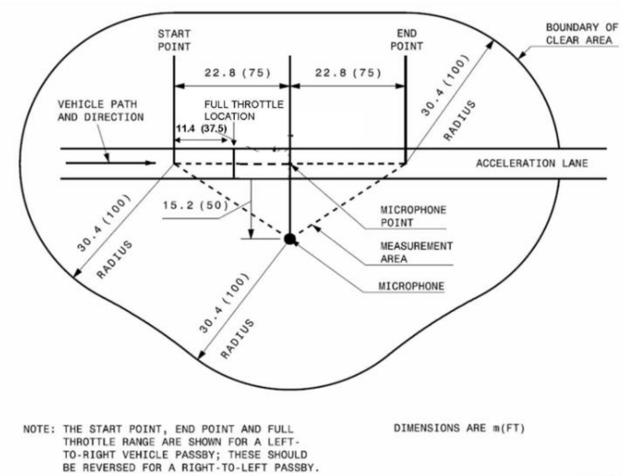

Figure 11. Track setup for SAE J192 sound testing

Due to the complications with engine startup, sound testing on the OM660 engine could not be completed. Testing on the stock Titan was conducted and the results are displayed in Table 3 below. The team plans on using competition results to compare the stock snowmobile to the competition snowmobile.

Table 3. Sound Testing Results for 2-Stroke Engine

	Average Results (dBA)
Acceleration Test	95.57
Steady State Test	72.72
Stationary Test	83.80

Emissions Reduction

To perform a thorough analysis of exhaust gas emission improvement from the 800cc Polaris two-stroke engine to the Mercedes OM660 common rail diesel, a standardized test had to be developed to compare each engine. The exhaust emissions data was recorded using a Horiba MEXA-584L Automotive Emission Analyzer. Carbon Monoxide (CO), Carbon Dioxide (CO_2), Hydrocarbon (HC), Nitrous Oxide (NO_x), and Oxygen (O_2) exhaust constituents were recorded.

For cold start emissions, the engine was cooled as much as possible via the wall mounted heat exchanger in the dyno lab. Emissions data was recorded under a 0% engine load condition through the entire engine speed operating range (idle to redline) in 100 rpm increments. Each data point was recorded when engine coolant temperature (ECT), intake air temperature (IAT), exhaust gas temperature (EGT), intake manifold absolute pressure (MAP), fuel absolute pressure (FAP), and fuel supply temperature (FST) have stabilized.

For the engine operating emissions testing, the engine was brought to normal operating temperature. Emissions data was recorded from 0%-100% engine load through the entire engine speed operating range (idle to redline) in 10% increments using throttle position and 100 rpm engine speed increments. Again, each data point was recorded when engine coolant temperature (ECT), intake air temperature (IAT), exhaust gas temperature (EGT), intake manifold absolute pressure (MAP), fuel absolute pressure (FAP), and fuel supply temperature (FST) have stabilized. Here, multiple tables were generated. Each will have %Load/rpm data for O, CO_2, HC, NO_x, O_2, MAP, EGT, AFR, and Torque. The results are shown in Appendix B.

Due to the complications mentioned previously, emissions testing on the OM660 was not conducted. The team plans on performing emissions testing on the OM660 prior to competition.

CONCLUSIONS

The NDSU team goals for 2019 SAE CSC were to modify a snowmobile to increase fuel efficiency and performance while decreasing noise and exhaust emissions. The team accomplished this through design considerations of the following.

- A three-cylinder Mercedes Benz OM660 0.8L turbodiesel engine was placed in a 2018 Polaris Titan XC Chassis. The OM660 engine was chosen for its relatively small size, low speed torque production, high efficiency, and electrical optimization system.
- To reduce the exhaust emissions, a DPF and a catalytic converter were installed. The DPF filters exhaust soot and the catalytic converter transforms harmful gases, such as hydrocarbons, nitrogen oxides and carbon monoxide into innocuous compounds of gaseous nitrogen, carbon dioxide, and water vapor.
- To make room for the larger engine in the chassis, a semi-dry sump oil system was developed using two scavenger pumps in parallel and an oil reservoir mounted near the front of the chassis.
- The team chose to install a GPS-based display that can provide live readouts of various engine parameters, while logging data for optimization purposes.
- The electrical work for the project included improving safety and making the entire system more modular. A relay board was added for easy diagnosis and quick replacement of relays if necessary.
- A CVT that is capable of functioning optimally over the new engine's powerband and lower speeds
- An electronic power steering system to overcome the effects of added weight from the turbodiesel engine and its subsystems.

With the above points, the 2019 NDSU CSC team proved the viability of diesel-powered snowmobiles for utility applications. The combination of environmental, manufacturer, and customer benefits makes the 2019 NDSU CSC snowmobile an ideal diesel utility vehicle.

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- All Terrain
- Midland Diesel Service
- EPI Performance
- CastleX Racing
- Autozone
- EVS Sports

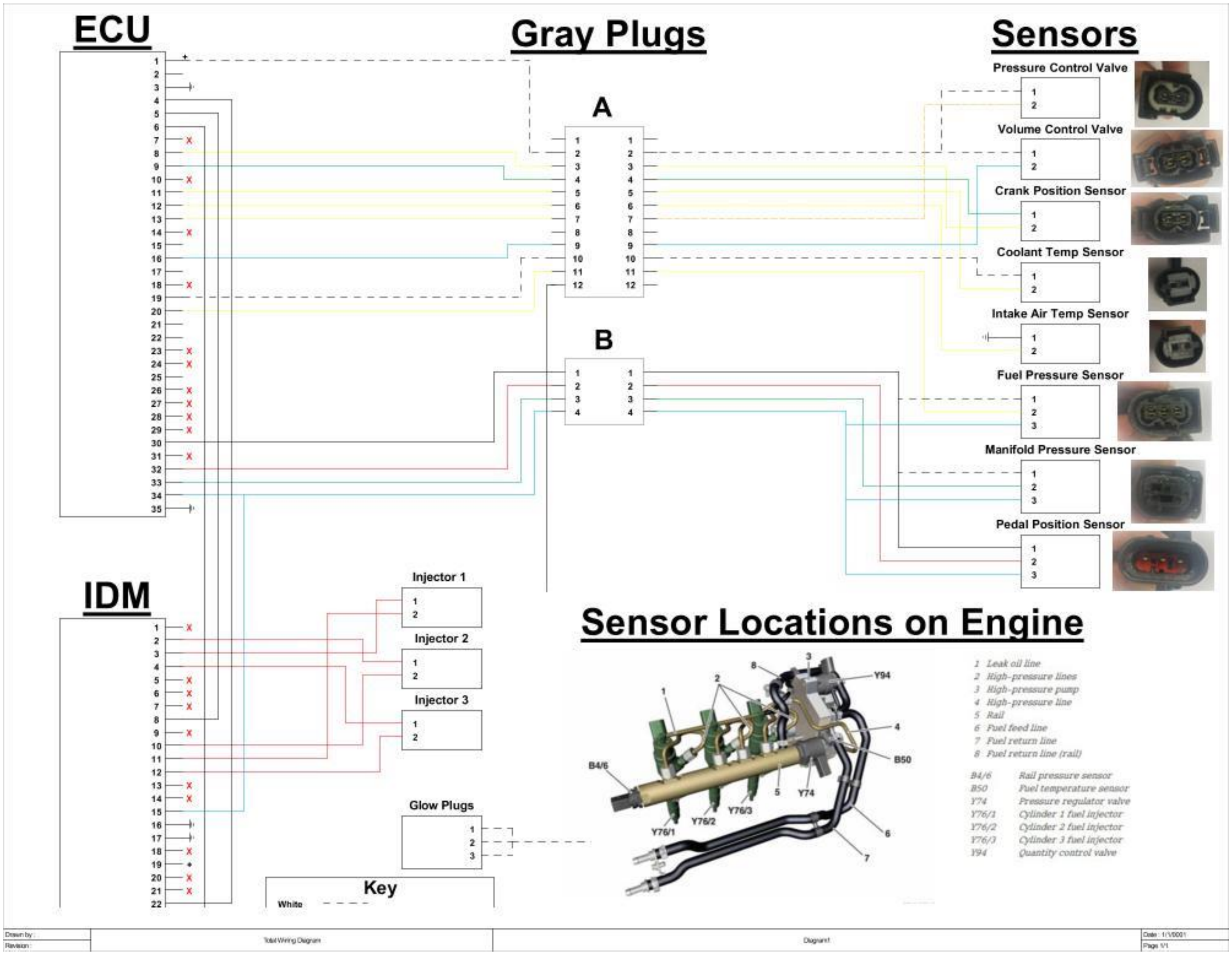
DEFINITIONS / ABBREVIATIONS

NDSU	North Dakota State University
CSC	Clean Snowmobile Challenge
GPS	Global Positioning System
GUI	Graphic User Interface
ECU	Engine Control Unit
LCD	Liquid Crystal Display
CAD	Computer Aided Design
OEM	Original Equipment Manufacturer
EPS	Electronic Power Steering
DC	Direct Current
CVT	Continuous Variable Transmission
CDS	Collegiate Design Series
H.O.	High Output
SOHC	Single Overhead Camshaft
DOC	Diesel Oxidization Chamber
DPF	Diesel Particulate Filter
I.D.	Inside Diameter
O.D.	Outside Diameter
SCS	Specialist Control System
IDM	Injector Driver Module
ABS	Acrylonitrile Butadine Styrene
FEA	Finite Element Analysis
AISI	American Iron and Steel Institute
CAN	Control Area Network
ECT	Engine Coolant Temperature
IAT	Intake Air Temperature
MAP	Manifold Absolute Pressure

EGT	Exhaust Gas Temperature
FAP	Fuel Absolute Pressure
FST	Fuel Supply Temperature
CO	Carbon Monoxide
CO_2	Carbon Dioxide
HC	Hydrocarbon
NO_x	Nitrous Oxide
O_2	Oxygen

Appendix

Appendix A. Wire diagram for Competition Snowmobile



Appendix B. Emissions Results for Stock Polaris Titan

Cold:

Engine Speed (RPM)	ECT (°F)	EGT (°F)	IAT(°F)	CO (%Vol)	HC (ppmVol)	CO2 (%Vol)	Lambda
Baseline				0	25	0	9.999
IDLE (1,700 ±200)	71.6	331	78.8	3.26	11280	4.86	0.933
3,600	75.2	483	78.8	3.18	8570	5.86	0.986
4,800	75.2	522	78.8	3.45	7360	5.42	1.05

Operating:

CO (% vol)

	IDLE	4,000	5,000
0%			
10%			
20%		3.05	0.60
30%		3.87	0.64
40%		3.81	0.67
50%		2.61	0.71
60%		1.77	0.75
70%		1.52	0.80
80%		1.37	0.83
90%		1.23	0.88
100%		1.11	0.96

Lambda

%Load/RPM	IDLE	4,000
0%		
10%		
20%		0.631
30%		0.682
40%		0.682
50%		0.701
60%		0.656
70%		0.636
80%		0.622
90%		0.607
100%		0.593

HC (ppmvol)

%Load/RPM	IDLE	4,000	5,000
0%			
10%			
20%		7510	2810
30%		4900	2860
40%		4940	2900
50%		4430	2950
60%		393	3000
70%		3750	3060
80%		3630	3110
90%		3510	3160
100%		3400	3250

CO2 (% vol)

%Load/RPM	IDLE	4,000
0%		
10%		
20%		8.42
30%		8.06
40%		8.08
50%		7.58
60%		5.08
70%		4.32
80%		3.88
90%		3.44
100%		3.10

Nox (ppmvol)

%Load/RPM	IDLE	4,000	5,000
0%			
10%			
20%		96	81
30%		290	84
40%		444	87
50%		283	93
60%		224	97
70%		198	104
80%		179	109
90%		159	119
100%		145	127

EGT (deg F)

%Load/RPM	IDLE	4,000
0%		
10%		
20%		805
30%		886
40%		928
50%		880
60%		890
70%		879
80%		870
90%		870
100%		867

Torque (ft.lb)

%Load/RPM	IDLE	4,000	5,000
0%			
10%			
20%		30.0	29.0
30%		45.0	41.0
40%		51.0	49.1
50%		55.0	54.0
60%		56.0	57.0
70%		57.0	58.7
80%		57.0	60.0
90%		58.0	61.5
100%		57.0	62.0

O2 (% vol)

%Load/RPM	IDLE	4,000
0%		
10%		0
20%		0
30%		0
40%		0
50%		0
60%		0
70%		0
80%		0
90%		0
100%		0