Design and Development of a Clean Diesel Snowmobile

Owen Maginity, Jordan Taylor, Sean Rabenaldt, Karl Zometa, Greg Davis
Kettering University

Innovations

While Kettering University has been attending the Clean Snowmobile Challenge since the beginning, it has focused on spark ignited (SI) engines throughout much of its history. In 2017 the team started to transition into the Compression Ignition (CI) class and now we are in our third year competing in the CI class. This year, the team has focused on refining and optimizing the powertrain developed in the 2017 and 2018 seasons, by improving the cold start capabilities of the sled with a new pilot injection mapping mode and fixing open issues with the Urea SCR Catalyst system that started in previous years. Kettering has chosen to use the Mercedes Benz OM660 'Smart Fortwo' (Figure 1) CDI Diesel engine. A custom Simulink based engine control model was developed to allow for flexibility in engine management and the development of specific vehicle features. Our control model is fully torque based, including a number of torque requesters and a torque arbiter to determine the demand on the engine, and a combustion manager to coordinate combustion and emissions related parameters while achieving the demand torque. The initial control development was done primarily during the 2017 season, but it was heavily expanded and improved throughout the 2018 and 2019 seasons based on feedback from users and the calibration process. New software features have been added to nearly every subsystem in support of more advanced after-treatment and combustion management. The soot limiting and targeting software has been restructured to control a fuel to air ratio objective, better managing engine out soot emissions. The control system is now able to accept manually triggered particulate filter regenerations, as is required for the particulate filter. The injection advance has been recalibrated for better starting conditions. Traditionally, Diesel engines produce significantly more NOx emissions than other constituents. This mixture is difficult to catalyze. The SCR catalyst, a urea system with freeze protection systems, and a dosage control model were added in 2018 and further refined for the 2019 reason. The OM6600 was not designed for a snowmobile, as such many changes were required to be done to the engine and chassis for packaging purposes.

Figure 1: Mercedes-Benz OM660 Diesel Engine

Team Organization and Time Management

For the 2019 Clean Snowmobile Challenge season the Kettering University team was formed by students that had stayed from the 2018 season and by recruiting other members from other teams and from various first year student events held by Kettering. Recruiting students from the SAE Baja and Formula teams allows us to gain new team members that have had experiences in related and diverse disciplines. While freshmen and first year students to Kettering gives us the opportunity to have a person with a fresh perspective on any problems we may have been dealing with. Our main recruiting event was at Kettering's New Student Orientation "Festival of Clubs" event for prospective recruits to get a chance to learn about the team. We were able to successfully recruit several freshman and upperclassmen.

The Kettering University 2019 Clean Snowmobile Challenge Team attended the Detroit Maker's Faire from July 28 to July 29 of 2018. This gave the team a chance to introduce new members to how to present information about the snowmobile and a chance to learn more about the snowmobile from hearing what senior members explained to attendees of the event. This event also gave new members a chance to spend time with and get to know more senior members of the team.

The team also attended a Denso event showcasing employee vehicles and collegiate vehicle design teams. This event gave the team a chance to make an impression on the Denso Corporation and to build connections within the organization. The event also gave younger members another chance to practice presentation and public speaking skills.

Time management was accomplished by using a Gantt Chart (Figure 2) schedule to lay out what was to be accomplished at each week meeting and to set due dates. This schedule was set by the senior members of the team, who had knowledge of what to accomplish at different points throughout the season. In addition to this, items were ordered ahead of time such that they arrived in time for their scheduled installation. A more senior member was always present to guide and instruct new members on the intricacies of working on the snowmobile.

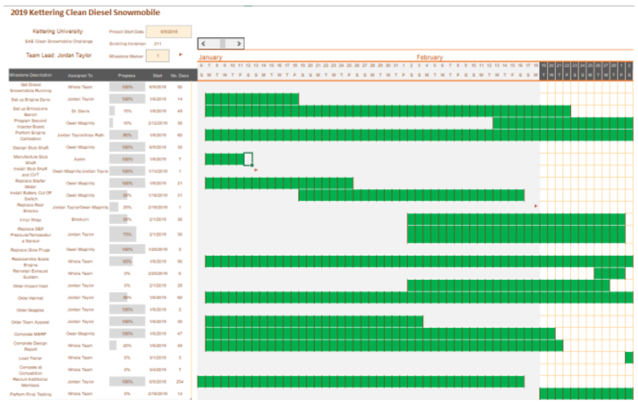

Figure 2: 2019 Kettering CSC Gantt Chart

Build Items of the Snowmobile

- Chassis – Ski-Doo, Tundra Sport, 2016
- Engine – Mercedes-Benz OM660, Diesel, 4-stroke,799cc, 43 Hp.
- Track – Camso Cobra, 137”
- Muffler –Student designed, Absorptive
- Aftertreatment – DOC/DPF Catalyst – Faurecia DOC + DPF from a Volvo XC70 with Periodic regeneration
- Aftertreatment – SCR Catalyst – Faurecia catalyst from a Fiat 500 with a Bosch supply system
- Skis – Stock

Design Content of Snowmobile (Author’s discretion)

Design Objectives

The goals of the competition are to improve the emissions, fuel economy, and noise of a production snowmobile while maintaining or improving on performance. Kettering has gone beyond the competition minimums and set the following design goals for 2019:

1. Lower fuel consumption to reach 30 miles per gallon at a cruising speed of 35 miles per hour.
2. Active DPF regeneration cycles.
3. Reliable cold start with a new pre-injection mapping.

With these goals in mind we had a few sleds to choose from that met our volumetric requirements that had been set, a 2016 Ski-Doo Tundra Sport Utility sled and a Mercedes-Benz OM660 with common rail fuel injection was chosen for the 2019 Kettering University team.

Snowmobile Selection

The process of choosing the base snowmobile for the CI entry involved many factors, including the packaging volume available for the engine, the acoustic properties of the sled, and the suspension design. When considering the packaging volume available, we wanted the largest size possible while still remaining manageable. Next, we studied track length. The longer the track, the more noise it will make and the less fuel efficient it will be. Knowing this, we selected a utility sled with the shortest possible track length. The Ski-Doo Tundra Sport, originally equipped with a Rotax 600 ACE engine, was selected due to it having the best combination of these two attributes as well as a widened engine bay due to the Rev-XU suspension design. All of these factors lead to this sled being deemed the most suitable for the transplantation of a diesel engine.

Engine Selection

For the 2019 Clean Snowmobile challenge the Kettering team chose a Diesel Compression Ignition engine featuring a common rail direct injection fuel system. This powertrain shines in the utility market, where high toque, towing capacity, reliability and fuel efficiency are required.

The Mercedes-Benz OM660 engine, was used in the Smart Fortwo model 450, was chosen due to its common rail fuel injection system, full aluminum block construction, and compact size. The aluminum block construction is a common design in most gasoline engines, but it is much less common in diesel engines due to the high cylinder pressures. Even with having such a compact and lightweight diesel engine there is still a weight increase over the stock 600 ACE engine that came with the Tundra, but the weight difference is less than 50kg.

A common rail engine allows for a full electronic control over fueling, which provides flexibility to the engine calibrator to modify injection system parameters to balance performance and emissions. This system runs at up to 1400 bar injection pressures allowing fuel to be delivered extremely fast which allows better control of the combustion rate for ideal emissions. This common rail system also allows for 4 injections per cycle which allows for the combustion rate to be shaped through software, improving emissions. Electronic injection has many tertiary benefits as well. They allow for better fuel scheduling in transient conditions, software-based soot limiting, and for pedal feel to be shaped based on CVT ratio.

Table 1: Specifications for 2016 Tundra Sport Snowmobile

Snowmobile Model	Ski-Doo Tundra Sport
Model Year	2016
Track	137" Camso Cobra
Engine Model	Mercedes-Benz OM660
Cylinder Configuration	3 In-Line
Fuel	B0-B9 Diesel
Displacement	799cc
Compression Ratio	18.0:1
Peak Power	32kW @ 4200 RPM
Peak Torque	95 Nm @ 3600 RPM
Fuel System Type	Common Rail
Fuel System Model	Bosch CRSI w/ CPI Pump
Fuel System Pressure	1400 Bar

Diesel Particulate Filter and Oxidation Catalyst

The Diesel Particulate Filter is in place to trap and store particles of soot in order to prevent them from exiting the exhaust system. These filters must be "regenerated" periodically to ensure the soot is fully oxidized into carbon dioxide. There are systems designed to regenerate purely from the temperature of the exhaust, but these systems operate at a lower level of efficiency compared to a "full-flow" system. We chose a Faurecia combined DOC + DPF assembly due to its ability to capture soot efficiently and its appropriate sizing for our engine. A 1.7L and 3.5L brick was used for the DOC and DPF monoliths, respectively. Due to the DPF being a "full-flow" type, it requires periodic regenerations. In order to induce oxidation and to raise the temperature to the regeneration point, we developed a new control model. This model is designed to request fuel injections into the exhaust via a post-injection.

The efficiency of the DOC was measured (see the section on 'Emissions Test Procedure') and was found to have a conversion efficiency of 99.3% for CO and 82.6% for the HC. In our testing, an instrumental grade soot measurement was not available. Instead accumulator type sensors showed no measurable soot post DPF in any mode. Soot was readily measured before the DPF when in modes 1, 2, and 3.

Selective Catalytic Reduction

Gasoline engines with a stoichiometric tune are able to rude the NOx emissions through a three-way (oxidation-reduction) catalyst. This catalase catalyzes NOx into N2 in the presence of CO and HC in the oxygen-poor environment present. In diesel exhaust, the oxygen mixture is rich and the ratio of NOx to CO and HC is very high. Due to this, it is not possible to catalyze NOx without an additional chemical process. It counteracts this, mobile diesel engines use a SCR system which injects aqueous urea as the reducing agent, which decomposes into ammonia in the high temperatures present in the exhaust environment

We selected a Faurecia SCR catalyst and a urea dosing system was designed using off-the-shelf components in addition to custom control models to build a complete system. The SCR monolith has a volume of 2.2L and its housing integrates a urea injection port, urea mixer, and a temperature sensor. The development of this system presented many challenges, much like those limiting the use of the SCR system in automobiles. Aqueous urea (sold commercially as DEF) has a freezing point of -11℃, which presents challenges in cold weather environment. To alleviate this concern, a Bosch solenoid driven urea supply/return system was implemented on the sled. The pressure in the system is monitored by the computer and is software controlled to maintain optimum pressure. The urea system was designed such that the engine coolant is able to thaw it, inhibit dosing until the thawing had occurred, and to purge any excess urea in the system upon shutdown. A urea capacity of 3L ensures that the system does not require frequent refills.

Atomization of the urea into the exhaust environment is vital, since the urea must be able to decompose into ammonia in the high temperature environment before it deposits onto the catalyst monolith. The catalyst-provided exhaust mixer is used to enhance the mixing of urea and provide a surface on which the decomposition can occur. A Bosch air cooled urea injector was selected due to its relatively low cost and ease of operation. To set up a profile for the injector and the pump, they were tested together on a flow bench.

Common Rail Fuel System

The OM660 engine was provided with a Bosch CRS1 injection system with CP1 pump. The injection system hardware was not modified, to ensure fuel system integrity. Rail pressure is controlled primarily through the Rail Pressure Control Valve (PCV), a variable force solenoid which bleeds high pressure fuel from the common rail to the return line. This pressure control method results in very fast pressure response but increases the mechanical work done the high-pressure pump, compared to inlet metered or variable displacement pumps. The CP1 pump also has a binary solenoid to deactivate one of the three pistons, and this solenoid is used at light loads to reduce the mechanical work done by the pump by reducing the flow rate through the pump.

The Mercedes-Benz OM660 engine came stock with a Bosch CRS1 injection system with a CP1 pump. The injection system hardware was not modified in order to ensure fuel system integrity. The Rail Pressure Control Valve (PCV), a variable force solenoid which bleeds high pressure fuel from the common rail to the return line, is used to control the rail pressure. This method of pressure control results in very fast pressure responses but increased the amount of mechanical work done by the high-pressure pump, compared to inlet metered or variable displacement pumps. The CP1 pump is equipped with a binary solenoid to deactivate one of the three pistons and this solenoid is used during periods of light load to reduce the level of mechanical work performed by the pump by reducing the flow rate through the pump.

For the 2019 season we worked heavily on injection techniques for a more reliable cold start. To accomplish this, we had added a pilot injection to the cracking process so that we are able to have a small fuel injection towards the beginning of the stock so that we are able to start heating up the cylinder for a full injection further on in the stock making it so the larger injection should combust more completely.

Figure 3: Woodward SECM70 Engine Control Unit

Control System

The Mercedes-Benz OM660 engine came stock with a Bosch EDC16 control system. However, this control system was not provided with the engine and would have presented many difficulties in modifying the programming to suit a snowmobile setup.

In addition, our engine control system, the base snowmobile was originally equipped with an engine control unit (ECU) for the gasoline engine. This ECU, along with the original gauge cluster from the factory, was intended to control many non-engine functions of the sled. This includes the heated grips and main power controls. These functions must be provided in the new ECU.

Due to the limitations of the original engine and the Ski-Doo ECU, a new control system was developed for our sled. This control system is based on the Woodward MotoHawk rapid prototype control system hardware, alongside student developed code inside of the MATLAB Simulink environment.

Under hood Noise, Vibration, and Harshness

Sheet metal and flat surfaces are known to have noise reverberation properties. To reduce those properties within an enclosed engine bay we covered as much of the sheet metal and flat surfaces as we could with a tar paper called Dynamat Xtreme. To protect the sound dampening material in high temperature locations we had used foil mylar to deflect the heat.

The Dynamat Xtreme had also been added to the inside of the tunnel in the attempt to lessen the noise of ice and rocks being thrown up and hitting the sheet metal making noise. Adding the Dynamat to this area also lessens the noise reverberation off the track. The is unstudied this year to lower the noise coming from the snowmobile.

Summary/Conclusions

The primary work done this year was to develop and refine the Snowmobile from last year, focusing on calibrations, cold start, and the reduction of emissions by adding a SCR system to the sled. The majority of our mechanical design has remained the same from the previous year since Kettering's team has undergone a massive team change with only one full time member remaining from the 2018 season. Most of the season was spent trying to learn the controls system that had been made over the previous years and learning more in depth on how snowmobiles function and the components they use since most of the new members had not even ride a snowmobile before.

A three-cylinder, four stroke Mercedes-Benz MC660 CDI Diesel engine, sourced from a Diesel Smart Fortwo model 450, was chosen for its common rail design, all aluminum construction, and compact size. The common rail fuel system allows for flexibility when calibrating the engine as well as for flexibility when programming fuel injection.

Tailpipe emissions were reduced through the use of a Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF), and a urea-dose Selective Catalytic Reduction (SCR). Noise was reduced through the use of an exhaust silencer and the careful distribution of noise dampening padding throughout the vehicle.

All goals were achieved using the most cost-effective methods and technology.

References

Contact Information

Greg Davis

gdavis@kettering.edu

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Definitions/Abbreviations

CI	Compression Ignition