Clean Diesel Technology for SAE Clean Snowmobile

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Abstract

Clean snowmobile technology, in the form of a three cylinder, four stroke diesel engine, has been developed and applied to a commercially available snowmobile. The goals of this effort included reducing exhaust emissions to meet Tier 4 off-road limits for compression ignition engines, much lower than levels set by U.S National Parks Service in their BAT standard. Dynamic performance of the snowmobile was improved with a better overall torque output relative to the original equipment version, making the snowmobile more fun to drive. Total vehicle cost was maintained to original manufacturer's price of a comparable gasoline powered snowmobile. In addition, fuel economy in excess of 30mpg riding at speeds of 35mph make the snowmobile very cost effective. These are important targets for snowmobiles used as utility vehicles.

The details of the design effort including the specifics on powertrain performance are discussed in this paper. Specifically, the effort to improve the dynamic performance, fuel efficiency and emissions of a commercially available snowmobile is described. With the use of a light aluminum block diesel engine featuring modern clean diesel technology, the torque output was improved and fuel economy reduced compared to the original gasoline engine. Furthermore, the common rail direct injection system offers improved electronic control, which is fully utilized to reduce exhaust and noise emissions. Exhaust emissions are also controlled with the help of an aftertreatment system that uses Exhaust Gas Recirculation (EGR), an oxidation catalyst, and a particulate filter. Due to the cold weather application of a snowmobile, careful attention has been paid to cold startability, including cold engine calibration and glow plug usage.

Introduction

Snowmobiles were first introduced into the commercial market emergency and utility usage. The first snowmobile, developed in 1935, was capable of carrying 12 people. The introduction of the snowmobile meant that emergency medical personnel could get to those in need of care even during heavy snowfall. Other early uses included farming and ranching. It was not until the late-1950s that snowmobiles began being used for recreation. However, once recreational snowmobiling began, it grew rapidly. For example, within a decade, dozens of manufacturers were producing snowmobiles. Today, only four primary manufacturers remain with global industry sales of approximately 164,000 snowmobiles annually [1].

Due to the rising environmental concern pertaining to the noise and exhaust emissions of recreational snowmobiling, snowmobiles have come under increased scrutiny by the federal government. As snowmobiles are used in the winter season, the environmental impacts are greater due to the cold dense air. The cold, dense ambient air will not disperse the exhaust emissions rapidly; this tends to trap the concentrated exhaust leading to locally high concentrations of pollutants. These hazards are especially of concern to ecologically sensitive areas such as Yellowstone national park as well as other national parks where recreational snowmobiling is popular.

Snowmobiling is important to the local and national economy. According to the International Snowmobile Manufacturers Association (ISMA), snowmobiling generates over 29 billion US dollars (USD) of economic activity annually in the world economy. New snowmobile sales directly account for about 1.2 billion USD, while the remainder is accounted for by apparel and accessories, registrations, permits, tourism and spare parts. The snowmobiling industry accounts for over 90,000 full time jobs and nearly 2,200 dealerships.

Considering the economic impact of this market, a blanket ban on snowmobiling is not a feasible option. Currently, U. S. national parks are operating under a temporary winter use plan which restricts the number of snowmobiles entering the parks per day. All snowmobiles are required to be Best Available Technology (BAT), which are the cleanest and quietest commercially available snowmobiles. Further, the EPA issued a three-phase reduction on snowmobile emissions. The regulations include a 30% reduction in overall emissions by 2006, a 50% reduction overall by 2010, and a 70% reduction overall by 2012.

This legislation has forced a rapid change upon manufacturers; and they have responded by further developing two-stroke technology and shifting to four-stroke engines in place of the typical two-stroke engines. While the two-stroke engine offers advantages in light weight and peak power output compared to four-stroke engines, the disadvantage is that it emits much higher levels of exhaust pollutants. The four-stroke engine is also quieter, and more fuel efficient when compared with an equivalent two-stroke engine. Nonetheless, the four-stroke engine size and weight disadvantage is a substantial challenge to overcome in a lightweight vehicle.

The Clean Snowmobile Challenge (CSC), which is part of the Collegiate Design Series of the Society of Automotive Engineers (SAE), was created to challenge students to reduce the environmental impact of snowmobiles while retaining the essential performance and cost limitations required to ensure a successful recreational market. Eventually, the CSC expanded, incorporating additional classes for different powertrain designs, now including spark ignition, compression ignition, and electric classes. No manufactures currently produce a compression ignition or electric snowmobile, leaving a large potential market hole for innovation in this area.

To meet this challenge, Kettering University has entered in the Diesel Utility Class. While two stroke spark ignition engines dominate the high power, low weight performance snowmobile segment, there is also a large demand for utility and workhorse type snowmobiles. The Diesel engine is a very capable utility engine, so Kettering has chosen a common-rail direct injection engine, with the potential for lowest emissions and fuel consumption of a hydrocarbon-fueled snowmobile.

Design Objectives

The competition requires improvements to the snowmobile to implement an operational Diesel powertrain, reduce emissions to below NPS BAT levels, and maintain a minimum dynamic performance. Kettering has gone beyond the competition minimums and set the following design goals:

* Functional Diesel powertrain using modern clean Diesel technology

* Emissions level meeting or exceeding EPA Tier 4 off-road limits for compression ignition engines, which are significantly more stringent than current snowmobile standards

* Fuel economy exceeding 30 miles per gallon during trail riding at 35mph

* Maintain dynamic performance appropriate for a utility snowmobile, including towing and load capability

* Maintain MSRP cost equivalent to the base sled, including the removal and exchange of the original gasoline engine for the clean Diesel engine

To implement these design goals, a 2016 Ski-Doo Tundra SE Sport Utility sled and Mercedes-Benz OM660 engine were chosen by the Kettering team for 2017.

Base Snowmobile Chassis Selection

Several snowmobiles from produced by the four major snowmobile manufacturers as defined in the rules were considered when choosing which sled to use for the diesel engine. Due to the team's familiarity with the SkiDoo 600 ACE series of sleds and future plans to potentially continue using the 600 ACE motor in the future, it was decided to give special consideration to that snowmobile type. One of the other major criteria that was considered is track length. Generally, snowmobiles in the "Utility" class of sleds have very long tracks that are advantageous for carrying large loads through ungroomed trials, however longer tracks result in significantly more track noise and drivetrain losses. Given that the Clean Snowmobile Challenge very heavily weighs noise and fuel economy it was decided to look for a sled with a short track. The Ski Doo Tundra SE uses a 600 ACE powertrain and has a track of length 137", which was the shortest track length sled available in the utility sled class. Longer tracks have been proved to provide better traction depending on snow conditions, but results in higher rolling resistance and higher track noise. Due to the fuel economy and noise benefits of a short track, the 137" track length was chosen.

Engine Selection

The Kettering CSC Team chose a common-rail direct diesel injection engine for the 2017 Challenge. Diesel engines show significant benefits compared to gasoline engines in the utility market segments, where their high torque, towing capacity, fuel efficiency, and reliability overcome their weight and high end power disadvantages. This is a perfect fit for a utility snowmobile, optimized for low speed riding with high loads.

The Diesel engine is also more efficient in practice than an Otto or Miller cycle gasoline engine due to operation with high compression ratio. Since Diesel engines do not inject fuel until combustion is desired, there is no chance of pre-ignition, allowing an increase in compression, resulting in higher thermal efficiency. In fact, the high combustion pressures and temperatures which result in pre-ignition and knock in gasoline engines are desired, as they are the only source of ignition in a Diesel engine. This, combined with the lack of a throttle valve and the associated pumping losses at part load, greatly improves the fuel economy of Diesel engines. In addition, diesel engines are estimated to have 15% lower emissions of greenhouse gases compared to their gasoline counterparts [2].

The Mercedes-Benz OM660 diesel engine used in the model 450 Smart car was chosen primarily because this engine has a common rail direct injection system and aluminum block and cylinder head. The main advantage of an aluminum engine is primarily the lighter weight compared to a cast iron engine. The weight of a cast iron block engine in the sled would severely impact the maneuverability of the snowmobile and hinder the team's dynamic performance in the competition. Since the OM660 has an aluminum block, the total weight is less than 100lbs over the previous 600 ACE gasoline engine in the Tundra SE Sport. Additionally, this engine has much better low engine speed torque. The combination of the small weight addition and torque advantage reduces the impact on dynamic performance.

Figure 1. Mercedes-Benz OM660 Engine

The second advantage of the engine over other small Diesel engines is its usage of a common rail direct injection system. Unlike most utility focused small Diesel engines, which rely on distributor style or inline injection pumps and separate injection nozzles, a common rail system provides significant flexibility in electronic management of the engine, and enabling much more precise control over the combustion process. The common rail injection system employed by this engine is a Bosch design, and supports up to 1400 bar injection pressure and 3 injections per cycle for each cylinder. By comparison, distributor style injection pumps are capable of a maximum of approximately 600 bar at the injector, and a single injection. Using higher injection pressure enables the fuel to be injected through smaller diameter nozzles faster, which leads to significant reductions in the total particular matter (PM) produced. Electronic control in turn allows multiple injections to be precisely controlled and spaced adequately apart. Multiple controlled injections may be used to shape the start of combustion burn rate, and pressure rise rate, drastically reducing the noise and emissions output of the engine, and reducing the characteristic Diesel clatter sound.

While not an advantage exclusive to common rail fuel systems, the fuel system is electronically controlled. The majority of inline or distributor type injection pumps are mechanically controlled, and are only able to account for the fueling requirements of the engine at design conditions. With the use of heavily boosted diesel engines, many of these pumps are not able to correctly fuel during tip-in transients as boost builds, and this results in excessive soot. The use of electronically controlled fuel quantity and timing allows the injection parameters to be tailored to the specific environmental conditions, including ambient air density and boost pressure, resulting in optimal power, soot, and emissions at all times.

The specifications of the Mercedes OM660 engine are presented in Table 1 below.

Table 1. Smart Diesel Engine Specifications

Model	OM660
Displaced volume	799cc
Stroke	79mm
Bore	65.5mm
Compression ratio	18.0:1
Number of cylinders	3 in-line
Dry weight	190lb.
Combustion chamber	Direct injected
Valve mechanism	Chain-driven OHV
Rated Power	33kW @3800rpm
Rated Torque	110Nm @2000rpm
Fuel System	Common Rail
Maximum Fuel Pressure	1300 Bar
Fuel System Supplier	Bosch

Detailed Modifications

Turbocharger Matching

The OM660 engine was originally equipped with a turbocharger, however the specifications of that turbocharger were not known. Further, the original turbo was not provided with the engine. A new turbocharger was matched to the engine. Several turbochargers were compared to the expected OM660 power curve, including the Garrett MGT1238Z, GT1541V, and GT0632. The GT15V was the preferred choice due to the variable vane design (the other two are waste gate type turbochargers), however the compressor was poorly matched to the engine. The GT0632 was selected as it meshed well with the expected engine operating parameters, was extremely small, and was available to the team. This turbocharger was used for all engine testing. Due to the even firing order of the inline 3 engine, exhaust pulsations do not significantly affect the turbine operation, so the turbine did not need to be oversized compared to the steady-state match.

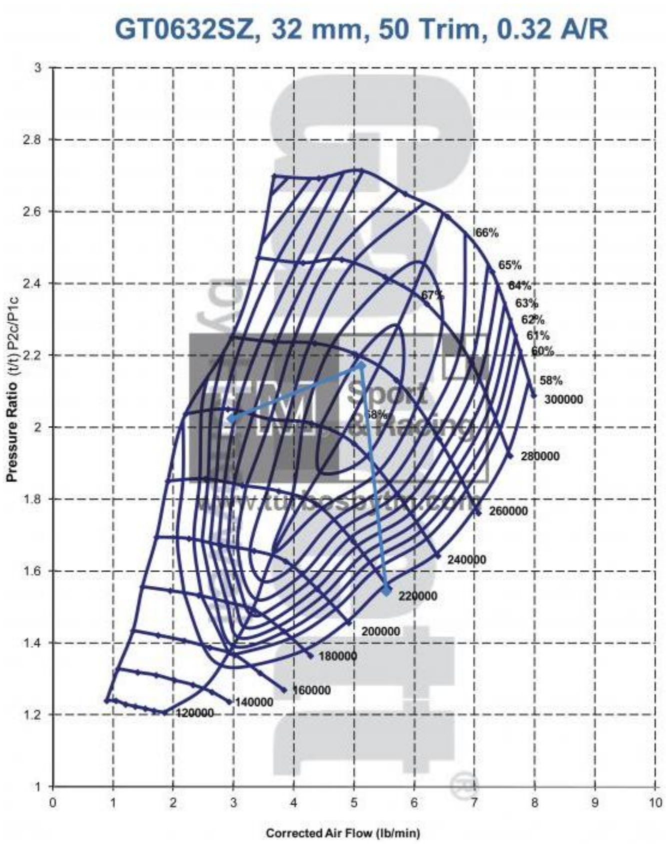

Figure 2. Turbocharger map

Aftertreatment and Emissions Strategy

The engine emissions are handled in three ways, using a mix of precise injection and combustion calibration, exhaust gas recirculation (EGR), and a catalyst and particulate filter. All three work together to optimize the tailpipe emissions of the vehicle.

The first method of reducing emissions consists of careful combustion calibration of the engine. During engine dynamometer testing, the combustion parameters are mapped to attempt to reduce NOx production and brake specific fuel consumption to minimum levels at all engine speeds and power settings. The combustion strategy uses a small pilot and large main injection in most cases, with the quantity and advance of both mapped to produce the required torque, ideal combustion phasing, and pressure rise rate. All of the key combustion parameters - common rail pressure, pilot quantity, and injection advance for both pilot and main - are mapped together in a centralized combustion manager within the software. This method of improving emissions using pilot injections and adjustable rail pressure is a unique feature of common rail direct injection systems.

In addition to carefully mapping the combustion parameters for the entire engine map, an additional calibration stage is used to limit soot. The soot limit is calculated from the modeled airflow and a maximum fuel/air ratio (phi) is chosen which is used to determine the maximum torque which may be requested instantaneously. Since the soot limit is always based on modeled airflow at current charge conditions, it will change roughly linearly with changes in the boost pressure to control soot even during transients. The soot limit phi is also calibrated with respect to engine speed and temperature, allowing a more conservative soot limit during warm-up.

For conditions when engine out emissions cannot be reduced through calibration alone, exhaust gas recirculation (EGR) is used to further reduce nitrous oxide (NOx) formation in the engine. The EGR system used is a ‘high pressure loop’ type, with gases taken from prior to the turbocharger and introduced into the intake after the compressor and intercooler. The exhaust gas is cooled using an air to water heat exchanger, cooled with engine coolant. The EGR system used is not original to the OM660 engine, but instead features a much larger cooler and proportional EGR valve with feedback control. EGR is primarily utilized at light loads to reduce NOx formation without increasing soot production.

As the Diesel engine operates with a stratified and lean combustion cycle, the hydrocarbon emissions and carbon monoxide emissions are very low in proportion to the NOx. This is significantly different from a homogenous charge gasoline engine, and requires a different after treatment approach. The approach chosen is to incorporate a Diesel Oxidation Catalyst (DOC), and Diesel Particulate Filter (DPF). The DOC catalyst is able to oxidize any unburnt hydrocarbons and carbon monoxide in the presence of excess NOx and oxygen, leaving only NOx and soot in high levels. The soot passes through to the DPF, which captures the soot between periodic regenerations. Regeneration requires that the engine is operated to to significantly increase its exhaust gas temperature, causing the soot stored in the DPF to burn off and clear the catalyst so that the catalyst can then trap more soot during normal operation. Due to the short period of the Clean Snowmobile Challenge, regenerations are not performed for the duration of the competition.

Engine Controller Selection

The OM660 was factory equipped by Smart with a Bosch engine control unit (ECU); however the original ECU was designed for a production road vehicle and would be difficult to modify for this application.

The base snowmobile was also equipped with an ECU, which managed the original gasoline port fuel injection system, as well as several other functions on the sled (including the main power system and relay controls for the head lamps and heated grips). Although the original gasoline engine was removed, there were several ECU functions which still remained and would need to be replicated by a new ECU.

For the 2017 CSC competition, a Woodward MotoTron SECM-70 ECU is used. The 70-pin automotive style ECU contains a 32-bit PowerPC processor, and has the ability to operate in ambient temperatures between -40°C and 105°C. Sealed connectors allow the ECU to remain operable when submerged in up to 10 ft. of water, among other various tough environmental conditions. The controller is shown in Figure 3. Custom engine control code was designed in Simulink by students for the MotoTron controller.

Figure 3. Woodward SECM-70

The new ECU completely replaces the stock ECUs of both the snowmobile and the smart car rather than running parallel with one or both of them, controlling all functions on the snowmobile. The new ECU is not able to drive the high voltage injectors directly, so a separate injector driver box was built to manage the high voltage, peak and hold waveform required. The driver box utilizes a NXP MC33816 Precision Solenoid Driver IC and operates along with the ECU, controlling the injectors with the required current control.

Control System

The Woodward MotoHawk rapid prototyping control system utilized to develop all of the engine control algorithm software. MotoHawk provides a Simulink environment and access to ECU input and output hardware, but leaves the developer to implement all relevant algorithm code, including sensor scaling, fault detection and handling, and engine management. Using MotoHawk, a complete full-authority engine management system was developed. A foundation was developed, including support for all of the required inputs and outputs, sensor circuit fault detection and accommodation, and engine position synchronization from crank and camp position signals. Then, a model-based engine control control algorithm was implemented, including a full-authority engine torque control system, multimode combustion management, and a speed-density airflow estimation model.

The heart of the engine torque control system is a torque-based engine request arbiter, which selects the appropriate requestor to control the engine. Requestors include the driver's pedal, idle control, overspeed control, soot and emissions limitations, and modifiers for fast warmup and powertrain protection. The pedal mapping is designed to be very flexible, incorporating speed and CVT ratio sensitive modifiers tuned to provide good feel for the rider under all conditions.

The output of the engine torque arbiter is used to command the engine torque request using an integrated combustion manager. The combustion manager determines all of the required combustion parameters to optimize brake specific fuel consumption and emissions, including support for up to three injections per cycle with control of the advance and quantity of each. The combustion manager outputs are used to schedule injection events, using injector data determined experimentally on a common rail hydraulic test bench.

To further optimize emissions, the engine torque arbiter considers the current soot and emissions derived fueling limits, which are used to impose steady state and transient limits on the injection quantity. The soot limit is derived from the modeled airflow and a calibrated equivalence ratio maximum, and will accurately track airflow through boost pressure and atmospheric condition changes.

To fine-tune the control software, the engine was mapped on an AC dynamometer to determine the required combustion and airflow parameters under all operating conditions.

Cold Start Modifications

The OM660 engine comes equipped with glow plugs, which are controlled by the Bosch ECU. This functionality is retained in the snowmobile. The glow plugs are automatically turned on during cold starts when the safety tether is connected, and are energized by the ECU for several seconds after the engine is started to ensure combustion is stable while the engine is warming up. The glow plug control is completely automatic and requires no user input. It is suggested that the user wait a few seconds before cranking, to allow the glow plugs to heat up.

Cost Effectiveness

Efforts were made to make the snowmobile as affordable as possible, and the cost of components was strongly considered with designing the snowmobile. The Woodward ECU was an ideal fit as it costs roughly $400 from the manufacturer which is significantly cheaper than other aftermarket Diesel ECUs such as a Bosch or Motec unit which can cost anywhere from $5,000-$12,000. Using the OM660 also fit into the cost effectiveness philosophy of the sled as engines can be purchased for $1,600.

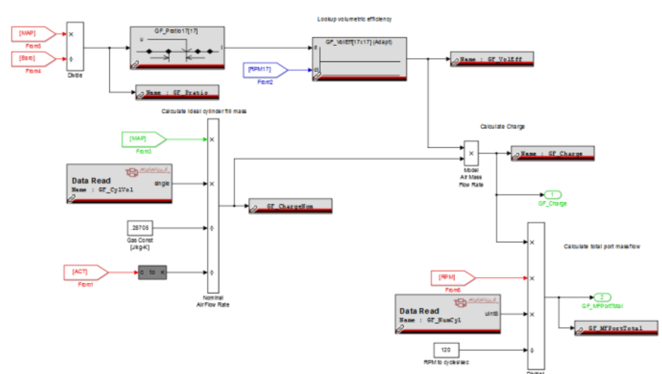

Figure 4. Subset of Airflow Estimation Model in Simulink

Conclusions

Clean diesel technology, in the form of a three cylinder, four stroke diesel engine, has been utilized to improve the emissions and utility characteristics of a snowmobile for the Clean Snowmobile Challenge. The engine was able to meet Tier 4 off-road limits for compression ignition engines, much lower than levels set by U.S National Parks Service Best Available Technology standard, and lower than any production snowmobile. Dynamic performance of the snowmobile was improved with a better low end torque output, improving the utility of the snowmobile. Total vehicle cost was maintained to original manufacturer's price of a comparable gasoline powered snowmobile. In addition, fuel economy was improved during trail riding, making the snowmobile very cost effective to own.

The design utilizes a Mercedes-Benz OM660 Clean Diesel engine, featuring a common rail direct injection fuel system. Electronic control of the common rail fuel system is utilized to optimize exhaust emissions, dynamic performance, and fuel consumption under all regions of operation. Tailpipe emissions are further reduced with the use of Exhaust Gas Recirculation, a Diesel Oxidation Catalyst, and a Diesel Particulate Filter.

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