Design and Development of an Economical Eco-Friendly Snowmobile

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Abstract

Common automotive industry technology has been applied to a commercially available two cylinder, four-stroke snowmobile. The goals of this effort included reducing exhaust and noise emissions to levels below the U.S National Parks Service (NPS) Best Available Technology (BAT) standard while maintaining vehicle dynamic performance compared to the original equipment version. For maximum rider convenience, the snowmobile may operate on any blend of gasoline and ethanol, up to 85%. All goals were achieve using cost effective technologies. Snowmobiling is a recreational sport, thus the snowmobile must remain fun to drive and cost effective to produce.

Innovation

While Kettering University did not compete in the 2017 Spark Ignition class, the chassis used for Kettering's previous SI entry was used to reduce costs to the team. For the 2018 season, Kettering has decided to depart from the previous SI emissions strategies of the team, with a stronger focus on improved emissions and engine control accuracy using low cost technologies proven in the automotive industry.

Overall, Kettering has chosen to use the Rotax 600 ACE (Advanced Combustion Efficiency) for its combustion and fuel economy performance. The ACE engine has been extended through the use of a completely custom model based engine control system to allow full calibration of the chosen emissions strategy, and full support of all ethanol blends available at fuel stations. The control software was developed from the ground up to incorporate physical-based models to reduce the calibration effort and improve the accuracy of the engine control. The control model is full-authority including electronic throttle control, allowing the model to cohesively control airflow, fueling, and spark parameters to meet the rider's demand while balancing emissions and fuel economy at a given operating point. For the 2018 season, the spark ignition control model was developed from the 2017/18 Diesel model, and shares no code with the previous spark ignition control models.

Figure 1: Rotax 600 ACE

To improve the snowmobile emissions while maintaining excellent reliability, a strictly stoichiometric calibration approach was selected along with a three-way catalyst. This technology has been used in automotive applications for decades but has never been applied to a production snowmobile. However, the technology is mature and inexpensive to implement. To fully utilize the three-way catalyst capabilities, closed loop oxygen sensors are used both before and after the catalyst to hold a stoichiometric fuel to air ratio, targeting the perfect exhaust makeup for ideal catalyst efficiency. Downstream oxygen sensing is used to monitor the catalyst performance and modify the upstream fuel to air ratio slightly to account for oxygen storage within the catalyst. Long-term airflow adaption is used to reduce transient deviance from stoichiometric, improving emissions in real world conditions. Stoichiometric engine operation is ideal for operation with a three-way catalyst, as well as the use of closed-loop control through oxygen sensors, and these have not been done by Kettering in recent years.

Strong attention has been paid to both engine and vehicle noise emissions. A dual chamber muffler, including a passive acoustic valve, is used, integrating the three-way catalyst. Additional noise enhancements have been added, with a strong focus on reducing radiated noise through chassis and body panels.

Team Organization and Management

One of the key requirements for successful completion of all of the SAE Collegiate Design Series (CDS) is effective project management and team organization.

Team Organization

In a traditional company or organization there is a very structured approach to project management. Every employee has a job title and a specific set of job requirements. Timelines are set and processes are well defined for how a product should move from a set of requirements to a finished product.

While that approach has many potential advantages it was decided that that would not be the best approach for the Kettering Snowmobile team. Unlike a job at a corporation participation on the team is purely voluntary. Additionally, there are relatively few opportunities for gaining course credit or academic achievements, unlike some schools where their CDS programs are a formal part of their capstone courses. As such it is very difficult to have a ”traditional” team organization structure as students who are involved with the team do not have many tangible short term incentives to be very active on the team. Instead of the more traditional approach, we decided to operate using a ”Scrum” project management approach that is an application of agile project management principles.

In the Scrum approach the team management comes up with high level objectives for the team. Individuals on the team are given the high level objectives and then people who are interested in working on the project split up into a smaller subgroup to work on that project. That way they have a wide breadth of freedom to complete the objective in whatever manner they choose. Projects that are chosen are generally designed to be modular in nature, that way if a particular group is unable to complete the task they are working on, the sled is still functional or able to be reverted back to a previous design. This allows new and innovative solutions to problems be implemented quickly.

This type of team organization works well in teams that have several very dedicated members that are driven, self starters, and have good problem solving skills.

Recruitment and Team Building

Recruitment of new team members is essential to keeping a team running and long term success. The Kettering team focuses on two main avenues of recruitment, the first is bringing in freshmen and new transfer students that are starting at Kettering. The second avenue is recruiting among students that are already a part of other SAE CDS competitions, such as Formula SAE and Baja SAE. Recruitment of students that are new to college has some benefits and challenges. There is generally a very steep learning curve for students that start early in their college career, however, getting students started early on allows time to for them to develop their skills and become very strong team members by the time they become upperclassmen. Recruiting from other SAE teams allows us to tap into the knowledge base, skills, and experiences that are gained from other competitions.

Specifications

The specifications for the 2018 Kettering University entry to the Spark Ignition class are presented below.

Table 1. Snowmobile Specifications.

Snowmobile Model	Ski-Doo MXZ Sport
Model Year	2014
Track	Camso Ripsaw
Engine Model	Rotax 600 ACE
Cylinder Configuration	2 In-Line
Fuel	Gasoline/Ethanol
Displacement	599cc
Compression Ratio	12:1
Peak Power	42 kW @ 7250 rpm
Peak Torque	55 Nm @ 6000 rpm
Fuel System Type	Returnless Port Fuel Injection
Fuel System Pressure	400 kPa
Engine Control Module	Woodward MotoTron SECM-70
Engine Control Model	Student Developed
Silencer	Dual Chamber with passive acoustic valve
Aftertreatment - TWC	Heraeus Pt/Pd/Rh 1/0/1 33g/cu ft loading Emitec 600cpi substrate

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 2018:

1. Emissions level meeting or exceeding EPA Tier 4 Off-Road limits, which are significantly more stringent than the NPS BAT and EPA Snowmobile limits. The exact limits are discussed in 'Emissions Test Procedure'.

2. Fuel economy exceeding 24 miles per gallon when traveling at 45 miles per hour

3. Sound pressure level exceeding NPS BAT requirements, and pleasant sound quality during sporty operation

4. Maintain dynamic performance of the original snowmobile

5. Maintain MSRP cost comparable to original snowmobile

To achieve these goals, a 2014 Ski-Doo MXZ Sport sled and Rotax 600 ACE engine were chosen by the Kettering team for 2018

Snowmobile Selection

When choosing the base snowmobile for the SI entry, the primary consideration was the engine. The Rotax ACE family of engines represent the pinnacle of design for fuel economy and emissions among four-stroke snowmobiles. After the engine, the snowmobile's original acoustic properties were considered. It is known that the track length of a snowmobile has a large effect on the track noise, which represents a large portion of non-exhaust noise on a snowmobile [1]. For this reason, the shortest track length available was chosen. The combination of the 600 ACE and 120" track resulted in the selection of the Ski-Doo MXZ Sport.

Engine Selection

The Rotax 600 ACE engine was selected as it a modern four-stroke engine designed from the ground up with strong consideration for fuel economy and emissions. Rotax discusses many of the detailed design choices made in the development of the engine in the SAE paper [8]. Dynamometer testing of the unmodified 2014 MXZ Sport showed that the emissions are well below the National Parks Service (NPS) Best Available Technology (BAT) requirements.

Engine Modifications

While the 600 ACE engine is well designed to meet the required regulatory emissions and noise limits, many modifications were required to further improve the emissions, noise, and fuel economy of the engine while maintaining the same dynamic performance. Most notably, the control system was completely replaced to provide superior flex-fuel support and easier calibration, the exhaust system was completely replaced to integrate a three-way catalyst and provide superior noise attenuation.

Exhaust and Aftertreatment

To improve the snowmobile emissions while maintaining excellent reliability, a strictly stoichiometric calibration approach was selected along with a three-way catalyst. This technology has been used in automotive applications for decades but has never been applied to a production snowmobile. However, the technology is mature and inexpensive to implement. The three-way catalyst was integrated into a dual chamber catalytic silencer, resulting in a compact but effective exhaust system.

Three Way Catalyst

When a SI engine is operated at stoichiometric conditions, the exhaust makeup has roughly equal parts of HC (hydrocarbons), CO (carbon monoxide), and NOx (nitric oxides) in an oxygen poor environment. This mixture is very well suited to a Three-Way catalyst.

A Three-Way (Oxidation-Reduction) type catalyst contains platinum and rhodium, and promotes both oxidation reactions of HC/CO and reduction reactions of NOx. The oxidation reactions require the presence of oxygen, but the reduction reactions favor a lack of oxygen. To balance the oxidation and reduction reactions, the catalyst substrate is designed to store oxygen. The engine is then cycled slightly rich (low NOx and oxygen) and slightly lean (low HC and CO) to provide the minimal oxygen required to complete reduction of NOx and oxidation of HC and CO. To control this balance, oxygen sensors are used to control the engine output and lean/rich perturbations.

The feedback control system implemented uses two narrow-range heated oxygen sensors, located upstream and downstream of the catalyst. The upstream oxygen sensor is used to trim engine fueling in real time to maintain stoichiometric conditions, and to control lean/rich perturbations. The downstream oxygen sensor monitors the oxygen slip out of the catalyst and maintains the correct oxygen level within the catalyst, by adjusting the upstream oxygen sensor control voltage.

Silencer

To reduce exhaust noise, a two chamber silencer was designed, and the three-way catalyst was integrated into the silencer assembly. The first chamber is an open resonator designed to attenuate low frequency exhaust content. The second chamber uses a fiberglass packed absorptive design, with 130g/l fill. Between the two chambers is a passively activated valve. The valve spring is set to open at high engine speed and load to avoid engine restriction at high power, while closing to attenuate exhaust noise when cruising.

Figure 2: Passive Noise Reduction Valve

Control System

The base snowmobile was equipped with an engine control unit, which functions to control both the 600 ACE engine and additional vehicle features such as the main power relay and grip heaters. Due to the limitations of the original Ski-Doo ECU, a new control system was developed. The control system is based on the Woodward MotoHawk rapid prototype control system hardware, along with student developed control models in Simulink.

Controller Hardware Selection

The MotoHawk system was chosen due to the selection of rugged and powerful control modules, and strong support for a Simulink development environment. The module chosen for 2018 is the SECM-70 variant 1562. The module features a fully sealed automotive style connector, and is designed to operate in tough automotive and powered industrial equipment. It also features 32-bit PowerPC processor with sufficient memory and processing bandwidth for real-time engine control systems, as well as improved angular timing accuracy compared to previous models. The new ECU completely replaces the features of the original Ski-Doo engine ECU, rather than running in parallel with it.

Figure 3: Woodward SECM70 ECU

Control Model Overview

The control software for the MotoHawk ECU is implemented in Simulink using a model-based design process. The use of a model-based design process for control software allows Kettering to greatly reduce the work required to implement and iterate control algorithms. As seen in Figure 4, the traditional V-model for software design contains 8 steps, but using a model-based design process and auto-generating the executable code allows us to perform only four steps. Requirements for the control model flow down from vehicle level requirements, and are defined specifically for the control model. The model itself is implemented in Simulink, where it may be tested for correctness through co-simulation with a plant model. The model is validated through engine dynamometer testing, and finally on-vehicle testing.

While Kettering has been developing custom control models since the 2013 season, the control model used for the 2018 Spark Ignited entry is derived from the 2017/18 Diesel control model, and the model has been restructured to incorporate lessons learned through Diesel development without carrying over legacy code.

The control model is structured into a number of sub-models for control functionality, along with ancillary modules for sensor and actuator processing, fault detection and accommodation, and communications. The key modules will be described in detail below.

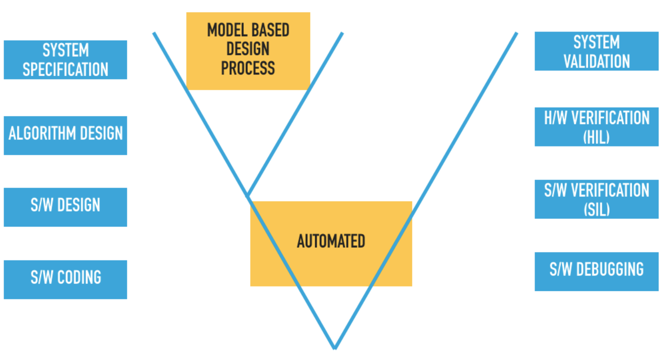

Figure 4: Model-Based V-Model for Control Software Development

Torque Management

The core of the gasoline engine torque control model is a multi-source torque request arbiter. Multiple control modes for the throttle include power-on mode (responding to the pedal), idle control mode, power-off mode, and deceleration fuel shut off. The appropriate control mode is selected based on engine operating conditions. The chosen control mode calculate the required throttle position, spark map, and if the throttle and fuel should be enabled. Fuel to air ratio is not used to control torque, as the fuel to air ratio must be kept at stoichiometric for proper emissions.

Gas Flows

The calculation of gas flows through the engine is critical to many of the other control models. The Gas Flows model is responsible for modeling the flow of charge air into the engine, and controlling the air induction system to achieve the desired charge air.

The charge air model is based on the ideal gas law, which can be solved at measured intake manifold pressure and temperature to estimate the fresh air mass in the cylinder. This mass is corrected by an empirical volumetric efficiency map, to account for non-ideal intake and dynamic conditions.

In addition to calculating the mapped airflow, the Gas Flows system is responsible for correcting engine airflow using narrow range oxygen sensor feedback. Two sensors are used, one upstream and one downstream of the catalyst. All error due to oxygen sensor correction is attributed to an error in airflow estimation, rather than the fuel system, leading the oxygen sensor feedback to adapt the calculated charge.

The upstream oxygen sensor is used to control the engine exhaust fuel to air ratio around the switching point. When operating in closed loop, the controller will continually oscillate around the switching point, resulting in ideal engine-out emission makeup for the three way catalyst. The downstream oxygen sensor is used to control the tailpipe exhaust fuel to air ratio, adjusting the switching point of the upstream sensor to maintain the correct ratio of lean to rich cycling for the three way catalyst.

Flex-Fuel

To account for the fuel characteristics of gasoline and ethanol, a flexible fuel system has been developed. The system relies on a Continental alcohol content sensor, which is low cost and used in production automotive applications. The sensor outputs a variable frequency signal corresponding to the percent of alcohol in the fuel. The alcohol is assumed to be ethanol, and the fueling is calculated appropriately. The stoichiometric fuel to air ratio of the given fuel is calculated from the ethanol percent, and this is used directly when calculating the required fuel quantity. Additionally, many of the engine calibration tables are mapped for both gasoline and ethanol, and the resulting tables are blended based on the ethanol percent. Some of the duplicated tables include thermal fuel enrichment, spark advance, start fuel, and warmup fuel vaporization fraction.

Vehicle Modifications

Track Selection and Noise Dampening

One of the sources of noise in a snowmobile is the track. Noise from the track is generated due to wind noise from the lugs, as well as mechanical noise from interactions between the track, drive cogs, and suspension. Attenuating track noise required a two-pronged approach, in reducing the noise generated from the track through track selection, and attenuating the noise radiated through the metal tunnel.

To minimize noise generated from the track, the track length and lug length were considered. In both cases, a shorter track and shorter lug tend to reduce noise generated by the track[7]. As the snowmobile is designed to operate on packed trails, where a short length track is desired from a handling standpoint, the shortest track length available (121”) was selected. The track selected is a Camso Ripsaw. Studs are not desired and have not been selected, as they significantly increase noise when on icy surfaces.

Once the appropriate track was selected for minimum noise, the noise which is produced is attenuated through careful sound dampening of the track tunnel. A layer of Dynamat Xtreme, a sheet material consisting of butyl rubber bonded to aluminum, was used to coat the interior of the tunnel. Any areas of the tunnel and foot rests which are too small to cover are coated in spray-on rubber sound deadening material.

Underhood Noise, Vibration, and Harshness

Many underhood components produce noise, and not all may be readily silenced. To attenuate noise produced underhood, a number of materials have been selected and applied. First, to reduce noise radiation through the sheet metal chassis, all chassis surfaces and body panels were coated in Dynamat Xtreme. Seams between body panels were also filled with Dynamat Xtreme, to reduce noise generated due to vibrations between panels. Where space permits, Dynamat Hoodliner was used to protect the sound dampening materials from high engine temperatures while improving noise attenuation itself. Near particularly hot components such as the exhaust system, foil mylar was used to protect the sound dampening materials from high temperatures.

Ethanol Compatibility

To support high ethanol content fuel, minor changes were required to the vehicle. As most fuel sold in the United States contains up to 10% ethanol, vehicle manufacturers already consider the effects of ethanol on fuel system components. The original Ski-Doo fuel system components were verified to be ethanol safe by soaking samples of hose and o-rings in a jar of ethanol for two weeks. Another change with ethanol fuel is the increased stoichiometric fuel to air ratio due to the presence of oxygen in the fuel, along with the decrease in lower heating value of the fuel. Both of these considerations require approximately 50% more fuel flow with high blend ethanol compared to gasoline. This required new fuel injectors to be selected and tested. The Bosch EV14 Compact was chosen as it is mechanically compatible with the Rotax intake manifold and provided the required flow rate increase. The fuel pump was tested using a flow meter and was confirmed to be capable of providing the required flow rate increase, requiring no modifications.

Design Validation

Cost Effectiveness

An emphasis was placed on not increasing the cost of the snowmobile unreasonably to meet the environmental goals of the Challenge. The cost of Kettering's 600 ACE MXZ is $8,752.67, a 16% increase from the stock MXZ. The majority of the added cost is from the noise attenuation system and performance suspension upgrades for increased driver satisfaction.

Emissions Test Procedure

Emissions and Fuel Consumption (brake specific) are evaluated using a Land and Sea water brake dynamometer along with a Horiba MEXA-7100 series gas analyzer and fuel flow meter. The same dynamometer configuration is used for engine mapping and calibration. Emissions testing was completed using the Snwomobile 5-mode emissions cycle defined in 40 CFR part 1051 [3].

Summary

Common automotive industry technology has been applied to a commercially available two cylinder, four-stroke snowmobile. The goals of this effort included reducing exhaust and noise emissions to levels below the U.S National Parks Service (NPS) Best Available Technology (BAT) standard while maintaining vehicle dynamic performance compared to the original equipment version. For maximum rider convenience, the snowmobile may operate on any blend of gasoline and ethanol, up to 85%.

The Rotax 600 ACE was chosen for its exceptional OEM emissions and fuel economy, compared to the snowmobile industry. A custom full authority control system was developed, allowing new control features to be developed. A three-way catalyst was selected and applied to reduce the engine emissions, using closed-loop upstream and downstream oxygen sensor control. Noise emissions were reduced by addressing exhaust noise through a silencer, and mechanical noise through careful application of sound dampening materials throughout the vehicle.

All goals were achieve using cost effective technologies. Snowmobiling is a recreational sport, thus the snowmobile must remain fun to drive and cost effective to produce.

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