Development of an Ethanol Flexible Fueled, High Efficiency Trail Snowmobile for the SAE Clean Snowmobile Challenge

Andrew Palardy, Madeleine Moir, Alex Rath, Zach Fulcher Mihir Mistry
Kettering University

Abstract

Clean snowmobile technology has been developed and 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 increasing vehicle dynamic performance with an increase in peak power over the original equipment version. Further, for maximum rider convenience, this snowmobile can operate using any blend of gasoline, ethanol, and isobutanol fuel. All goals were achieved while keeping the cost affordable. Snowmobiling is a recreational sport; thus the snowmobile must remain fun to drive and cost effective to produce.

The details of this design effort including performance data are discussed in this paper. Specifically, the effort to improve the dynamic performance, fuel efficiency, and emissions of a commercially available two cylinder, four-stroke snowmobile is described. Engine thermal efficiency has been increased through Late Intake Valve Closure (LIVC) valve timing modification for Atkinson/Miller cycle operation, while high load power was increased through the implementation of a turbocharger and variable electronic boost control. A new full-authority engine management system was implemented, featuring electronic throttle control. Additionally, a new exhaust system featuring a Lean NOx trap and catalytic converter and a simple, lightweight muffler utilizing a passive acoustic valve has been developed to reduce chemical and noise emissions. This snowmobile was modified to run the full range of ethanol blended fuels using student-developed engine controls. Excellent fuel efficiency has been achieved with the lean-burn Miller cycle powertrain in addition to an exhaust emissions improvement of 13 percent from the original equipment version

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, they 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 fulltime 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 has 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.

To meet this challenge, Kettering University has chosen to use four-stroke engine technology, reasoning that this technology offers the best long-term potential to meet increasingly stringent exhaust and noise emissions levels.

Design Objectives

The design objectives included reducing exhaust emissions to levels which are below the BAT standard and increasing the snowmobile's dynamic performance. Minimizing the cost and performance compromises were also major considerations. Snowmobiling is, after all, a recreational sport; thus the snowmobile must remain fun to drive and cost effective.

Competition requirements outline that the snowmobile must be able to run a range of 0-85% ethanol blended in gasoline. As Table 1 shows, Ethanol is a very favorable fuel for spark ignition engines, due to it's high Octane Number and Vaporization Enthalpy, both of which are utilized to maximize efficiency and power of Kettering's snowmobile when running on high ethanol blends. Kettering has developed a complete engine management system which can optimize the engine performance at all times, under a wide range of ethanol blends, resulting in optimal performance and efficiency at all times.

In order to meet these objectives, a commercially available 2014 Ski-Doo MXZ Sport 600 ACE was modified for the 2016 CSC competition.

The base snowmobile was chosen because it is equipped with a four-stroke engine, meets 2012 NPS BAT requirements without modification, and is light-weight through the use of the Rev-XP chassis and a 120 inch track length. The team focused on reducing chemical and noise emissions, improving efficiency, and improving performance while maintaining the best-in-class comfort, safety and durability of the vehicle.

Table 1: Fuel Properties

	Gasoline	Ethanol
Density (g/cm^3)	0.72-0.77	0.79
Low Heat Value (MJ/kg)	~43	26.8
Octane Number (AKI)	~91	100
Oxygen Content (%)	-	35
Boiling Temperature (degC)	-	78
Vaporization Enthalpy (J/g)	~350	839

The 120" track length was chosen for its efficiency, handling characteristics, and low mass. A 137" track length was also tested, however it was found that the test riders preferred the handling of the 120" track better. Though the 137" track was slightly smoother over bumps and offered better traction in deep snow, on the trail the sled had a tendency to understeer in corners while the 120" track test snowmobile did not. The 120" snowmobile was found to be better for trail use due to its ability to navigate corners well and the traction and rough trail capability was not degraded enough compared to the 137" track to compensate for the handling differences. To increase traction, the use of a pre-studded track similar to the OE track was investigated. The development of custom powertrain controls including traction control, however, rendered the extra cost, rotational inertia, and weight of the aftermarket track unnecessary. The OE Camoplast Ripsaw 1" lug 1-ply track weighs only 32 lb, 4 lb lighter than the pre-studded track considered. This track also reduces noise emissions from the drivetrain of the vehicle compared to its pre-studded and studded counterparts.

Engine Selection

The Ski-Doo MXZ Sport comes factory-equipped with a Rotax 600 ACE (Advanced Combustion Efficiency) 600cm3 four-stroke, 56 horsepower (hp), naturally-aspirated two-cylinder engine. The specifications for this base engine are presented in Table 2 below.

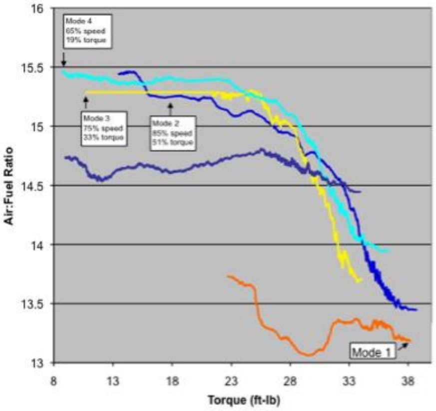
Table 2: Base Engine Specifications

Displacement	600cc
Configuration	Inline 180deg Two Cylinder
Block Material	Aluminum
Valve Actuation	Dual Overhead Cam, Type 1 (Direct Acting Follower)
Ignition	Coil On Plug
Valves Per Cylinder	Four
Compression Ratio	12:1
Bore x Stroke	74 x 69.7 mm
Intake Valve Open/Close	3 BTDC/37 ABDC
Exhaust Valve Open/Close	44 BBDC/6 ATDC
Engine Control System	Bosch Motronic ME17.8.5
Engine Weight	40 kg (88 lb)
Maximum Power	42 kw (56 hp)
Maximum Torque	55 Nm (42 ft*lbf)
Maximum Power Speed	7250 rpm

The SAE paper published by Rotax[3] for the development of the 600 ACE engine details several notable characteristics of the powerplant. Of great significance to the Kettering CSC team is the fact that the engine has been designed to run lambda 1.2 and leaner at part load for increased fuel economy. [6] Rotax credits the combustion stability made possible by a hemispherical combustion chamber for the engine's ability to run lean during much of its operation. Dynamometer testing was performed at Kettering with the unmodified snowmobile to characterize its calibration. The results of the calibration characterization can be seen in Figure 1. With knowledge of the speeds and loads at which the factory sled runs lean and rich of stoichiometric, calibration of the flex-fuel capable engine control unit can be completed more quickly and safely.

In addition to designing an efficient combustion chamber, Rotax utilized an advanced diamond-like carbon (DLC) coating on the valve tappets to reduce frictional losses in the engine. Other design criteria which decreased the 600 ACE FMEP include minimizing the amount of oil in the cylinder head and reducing pumping losses in the crankcase through the use of a dry sump oil system.

Figure 1: 600 ACE factory engine calibration



Detailed Modifications

Starting with the base four-stroke 600 ACE engine, the team worked on the following emissions reductions and fuel economy improvement strategies:

1. Full-Authority Engine Management System – The stock Bosch Motronic engine controller is unable to implement the required software features to support Ethanol flex-fuel, so the team developed a completely student-developed engine control system including a model-based engine control algorithm.

2. Electronic Throttle Control – The Rotax 600 ACE and 900 ACE family of engines are the only engines in the snowmobile industry to feature electronic throttle control, although it has been a standard in passenger cars for many years. As part of the Full-Authority Engine Management System, a new throttle control algorithm was developed which additionally considers the throttling effects of lean-burn operation, and incorporates a number of advanced fuel economy and efficiency improvements over the stock control system.

3. Fuel Utilization – Ethanol blended fuels have properties which greatly help to reduce emissions and the propensity for engine knock. Ethanol fuel contains oxygenates to decrease exhaust emissions and feature improved knock resistance and increased latent heat of vaporization to allow improved engine performance over OE. The engine was fully mapped by Kettering on an engine dynamometer to optimize performance and economy under any ethanol blend.

4. Exhaust Aftertreatment – A Lean NOx trap and catalytic converter was chosen to reduce emissions. Due to the unique makeup of lean gasoline engine emissions compared to normal powersports and automotive engines, a unique catalyst package was required. The team looked to Diesel catalyst designs for inspiration, and a Lean NOx trap system was designed an implemented, which is able to store NOx emissions during lean cruising periods for later conversion.

5. Lean Calibration – To further decrease emissions and improve the fuel efficiency of the snowmobile, an always-lean-burn engine calibration was utilized. Using increased amounts excess air as the charge diluent, engine pumping losses and pre-catalyst NOx emissions were decreased relative to the OE calibration.

6. Turbocharged Miller Cycle Operation – To reduce pumping losses, a late intake valve closing strategy with a custom intake camshaft lobe profile was implemented in combination with a turbocharger to increase engine power for the performance trail snowmobile, while simultaneously reducing fuel economy while cruising.

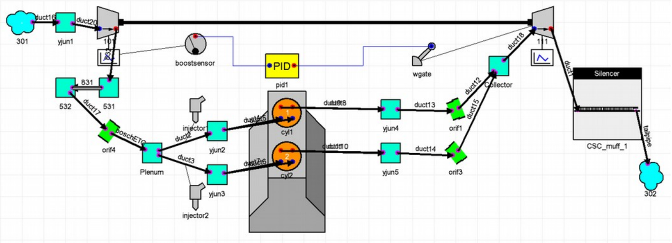
7. Minimize Weight – In order to improve fuel economy and reduce emissions, the team chose a lightweight snowmobile and made several efforts to maintain low weight with its modifications. Weight was considered in every modification, and many of the replaced parts are lighter than their OE equivalents.

Each of these strategies is described in detail below.

Engine Simulation and Design

Due to limited resources, not all design concepts could be physically tested for conformance to the team's objectives of improved emissions, fuel efficiency, and performance. A 1D engine simulation model, a view of which is seen in Figure 2, was constructed in Ricardo WAVE engine simulation software. The model was created from measurements of the Rotax 600 ACE engine, published specifications, dynamometer test data, and prior experience correlating models of small engines.

Figure 2: Ricardo WAVE engine model



In order to verify and correlate the model, baseline dynamometer testing was performed at Kettering using an unmodified snowmobile as well as several candidate engine concepts. A crankshaft water brake engine dynamometer with a servo-controlled load valve was used for all testing. Additionally, data regarding fuel mixture as a function of speed and load was also gathered to aid in calibration of the flex-fuel capable engine control unit.

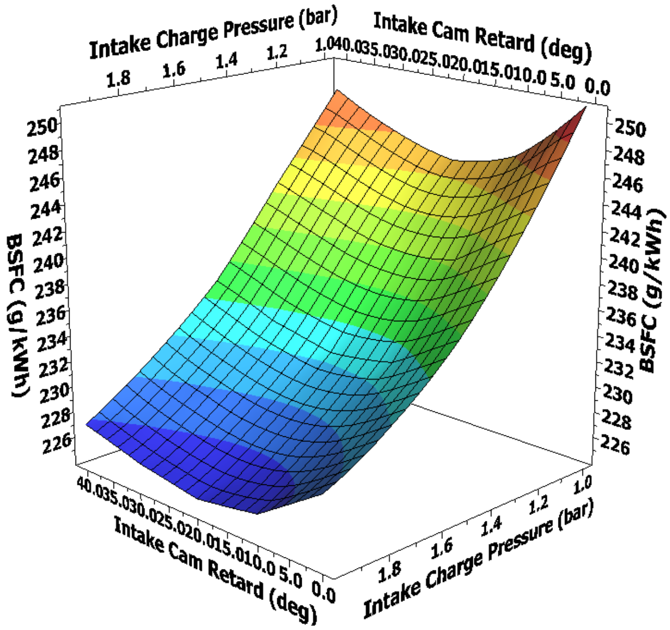
Through careful modeling of the engine, reasonable correlation to the OE 600 ACE performance was achieved with relatively few iterations of the model.

A design strategy that behaves symbiotically with boosting is LIVC in order to create Miller cycle conditions. Miller cycle operation improves pumping losses from throttling a spark-ignited (SI) engine at part load by decreasing the dynamic compression ratio and amount of retained charge; thus reducing engine output while minimizing the use of the throttle. Further, the relative increase in expansion ratio relative to the decreased compression ratio, allows more of the thermal energy to be captured during the expansion/power stroke of the engine, resulting in improved efficiency. The engine's decreased output can be mitigated through charge boosting to provide the benefits of LIVC at part-load and increased engine output over the original engine at peak load.

In order to estimate the effect of Intake valve timing on engine performance, a parametric sweep was conducted using the boosted model in WAVE. The results of this study with respect to Brake Specific Fuel Consumption (BSFC) can be seen in Figure 3. These results were then used to determine an appropriate amount of intake camshaft retard for a given intake charge boost pressure.

Based on the simulation results, it was decided that an intake charge boost pressure of 1.6 bar and intake cam timing retarded 20 degrees from the OE engine would provide the best performance to meet the team objectives. Charge air cooling through the use of an intercooler was deemed necessary to cope with a possible low blend fuel, but would not be required with a sufficient ethanol blend.

Figure 3: Modeled Brake Specific Fuel Consumption

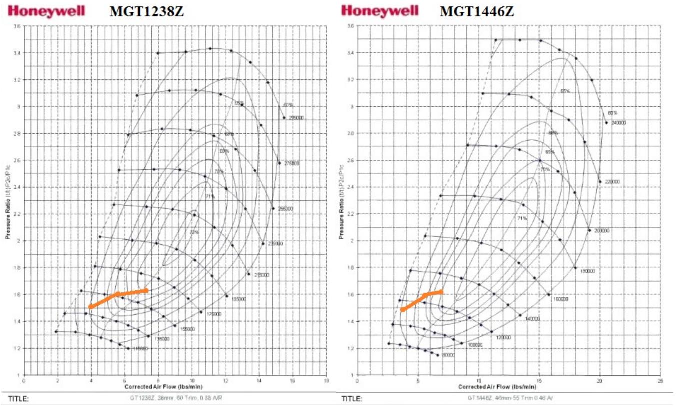


Turbocharger Matching

To increase charge air pressure, both supercharging and turbocharging were considered. Recreational and powersport engines such as the 600 ACE do not feature accessory belt drives; thus making it difficult to implement conventional belt-driven superchargers. Further, engine power would be lost in driving the compressor. Finally, a supercharger provides no attenuation of exhaust noise and often creates additional mid-high frequency noise that would not fit within the team objective of creating a quiet vehicle.

A turbocharger was selected for its ability to capture waste heat energy in the exhaust to drive a compressor. Further, the restriction of the turbocharger turbine housing provides significant attenuation of exhaust noise that helps simplify the design of the vehicle silencer. Three turbochargers were evaluated in a compressor matching exercise for use on the Miller cycle turbo 600 ACE—the Garrett MGT1238Z, MGT1446Z, and GT1541V. The 1446 and 1238 were initially selected because they operate in a more efficient region of the compressor map at peak boost level throughout the engine speed range used by the Continuously Variable Transmission (CVT)-equipped snowmobile. Figure 4 shows the maximum operating line for the engine on both the 1238 and 1446 compressors. The two turbochargers were tested back-to-back on an engine dyno. While the 1238 compressor map suggests that it is more closely matched than the 1446, the 1238 was found to have insufficient turbine matching and wastegate flow due to the very large exhaust pulses of an odd-firing twin cylinder engine. This resulted in excessive boost pressures even with a fully open wastegate. The 1446 turbine was very well matched to the 600 ACE engine, however the surge margin on the compressor was extremely low. As the 1446 turbine and 1238 compressor were desired, a hybrid turbo was constructed out of the two, using a 1238 compressor and center bearing housing and 1446 turbine. This '1246' hybrid turbocharger was tested and found to greatly improve boost creep and VE over the 1238, while reducing charge temperatures due to more efficient operation with the 1238 compressor.

Figure 4: Compressor Maps for MGT1238Z and MGT1446Z



Testing the Effect of LIVC and Turbocharging on the Engine Output

The 600 ACE engine was modified for Miller cycle operation with an intake camshaft retarded by 20 degrees from the OEM timing. Initially, the OEM intake cam was retarded 20 degrees. The LIVC valve lift compared to OEM is shown in Figure 5. After successful testing, the OEM intake cam was further retarded, but as expected, this did not result in improved efficiency. The solution was to increase the duration of the cam to allow later intake valve closing without resulting in a negative overlap. The Kettering CSC cam profile is shown in Figure 5.

To quantify the loss in engine performance attributable to LIVC alone, the baseline naturally aspirated engine was tested with the OEM intake valve timing. The engine was then adjusted to provide LIVC and tested.

A comparison of the results with the factory valve timing and Atkinson (un-boosted Miller) cycle valve timing was then made. The reduction in crank power can be seen in Figure 6 and the reduction in BMEP can be seen in Figure 7. Both tests were performed with the Kettering CSC engine controller and mapping while using an E15 ethanol blended fuel. As shown, the greatest reduction in BMEP due to LIVC cam timing occurs at low engine speed, decreasing slightly as the engine speed increases.

Figure 5: Valve Timing Diagram

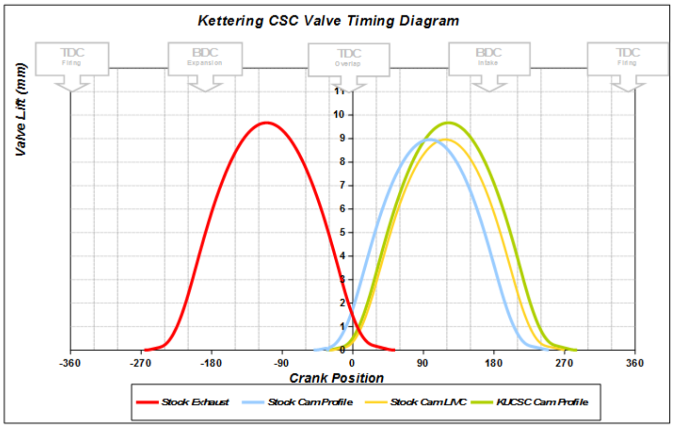


Figure 6: Crank Power

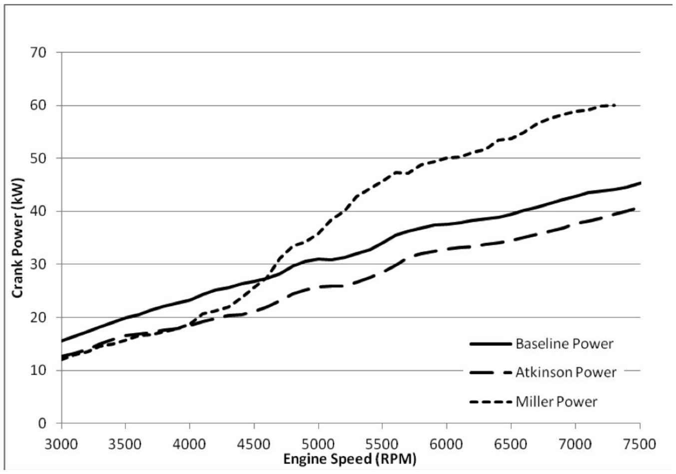
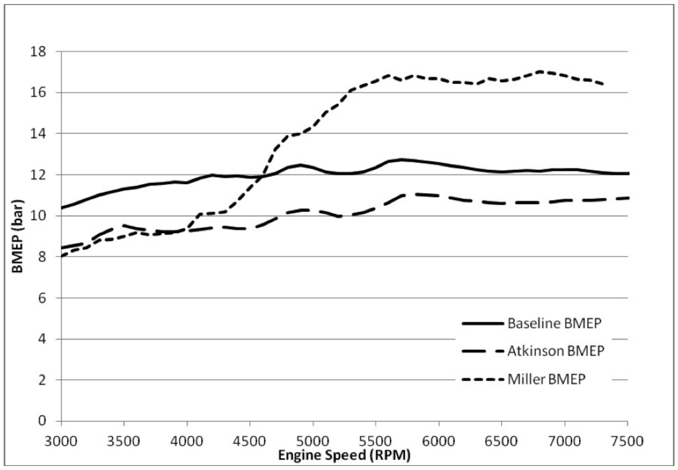


Figure 7: Brake Mean Effective Power (BMEP)



Aftertreatment Systems

In addition to the conversion to ethanol lended fuel and altering the engine management accordingly in an effort to decrease emissions, Kettering CSC has implemented a Lean NOx Trap catalyst.

Using an engine dynamometer and Horiba MEXA 5-gas analyzer, the engine emissions were measured during lean operation, both uncatalyzed and using a conventional Three-Way Catalyst (TWC). The engine was found to have better than stock engine-out emissions, without a catalyst. It was found that the TWC had approximately 70% conversion efficiency for carbon monoxide (CO) and total hydrocarbons (THC), but only conversion efficiency for oxides of nitrogen (NOx). This was due to a relatively high NOx due to lean operation, and extremely low gas temperature and hydrocarbon levels which do not support catalyst light-off. At all points tested, the catalyst substrate temperature did not exceed 385ºC, which is below the 400ºC required for a conventional TWC to reach full activation temperature.

It was clear that a new catalyst strategy was required. As the emissions makeup of a lean-burn spark ignition engine closely matches that of a Diesel engine, Diesel type catalysts were investigated. Diesel engines typically operate lean, which produces high NOx and low THC/CO emissions, similar to the makeup of the Kettering engine. In addition, the high compression ration of Diesel engines results in a lower exhaust gas temperature, in the range that the Kettering engine produces.

The aftertreatment options explored include Selective Catalytic Reduction (SCR) and Lean NOx Trap (LNT) systems [3][4]. SCR systems use a reductant, such as urea, which is dosed into the catalyst. Lean NOx trap systems use fuel as a reductant, but must be periodically regenerated using fuel-rich spikes.

A LNT was selected. LNT catalysts are able to store NOx emissions from the engine during extremely lean cruising periods. Periodically, the catalyst must be dosed with a reductant, which allows it to fully convert the NOx into harmless byproducts. The reductant used is gasoline or ethanol, and it is produced by cycling the engine to a rich mode of operation for a short period of time. A software model of the engine NOx production and catalyst loading allows fully automated NOx trap regeneration, in a way that is completely transparent to the rider. In addition, refined calibration for 2016 optimizes the engine-out emissions (especially NOx) to reduce the NOx storage requirements for the catalyst, and minimize the fuel economy impact of periodic regenerations.

Engine Controller Selection

The snowmobile was factory equipped by Ski-Doo with a Bosch Motronic ME17.8.5 engine control unit (ECU); however there was no way for the team to access and reprogram it. Furthermore, the original system did not support many required flex-fuel features.. A new ECU was required.

For the 2016 CSC competition, a Woodward MotoTron ECU is used. The 128-pin ECU contains a 32-bit Freescale MPC 565 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 8.

Custom engine control code was designed by the student for the MotoTron controller. The control code implements a model-based engine control algorithm, including a speed-density airflow estimation model and a full-authority engine torque control system. Extensive controls development was done to support variable fuel/air ratio targeting and efficiency optimization at all times, on all ethanol blends. Extra attention was also given to ignition energy for the ability to ignite the lean charges that the powertrain is designed to run. High-energy Mercury Marine ignition coils were chosen for their 103 mJ (rated) spark energy, and are operated to 120 mJ in extended lean burn operating regions.

Figure 8: Woodward ECM-0565-128-702C Engine Control Module

The MotoTron ECU replaces the original Bosch ECU rather than simply running in parallel with it. The stock wiring harness is modified to use the connector of the new ECU but otherwise unmodified. The ECU has a multitude of inputs and outputs which enable improved engine performance through the ability to control both the fuel injection and ignition timing.

The engine controls feature an electronic throttle control system. The throttle angle of the engine is not directly coupled to the thumb-throttle input from the driver, and is varied as a function of speed, load, ambient conditions (e.g. air temperature and altitude), fuel/air ratio target for efficiency, ethanol blend, NOx catalyst control strategies, and engine/catalyst protection strategies. The system uses a single path torque-based control system.

The rider's requested percent of maximum torque is determined based on the thumb throttle and CVT ratio. The current engine operating conditions are considered, including air temperature, engine temperature, and altitude to determine the lean stability limit of the engine. The required throttle opening to achieve the desired torque is calculated, considering the reduction in torque due to lean operation.

When the rider is not requesting torque, the engine may remove fuel on one or both cylinders, depending on the current vehicle speed. This feature, known as 'Deceleration Fuel Shut-Off', is common in the automotive industry but not in snowmobiling. This saves fuel when engine power is not needed. To further improve fuel economy and reduce undesirable effect of significant engine braking, Kettering has extended this concept with Intelligent DFSO (I-DFSO). In I-DFSO, the throttle may be opened with fuel shut off. The engine pumping torque/PMEP is significantly reduced, resulting in a 30% reduction in engine braking torque. These transitions are smoothly blended by the torque controller and are fully transparent to the rider, who only feels great coasting similar to a 2-stroke engine.

When the vehicle is not moving fast enough for I-DFSO, the engine returns to a controlled idle mode. In idle mode, a fully warm engine may not require power from both cylinders. Under these conditions, the engine management system will shut off one cylinder, leaving only one cylinder firing. This reduces FMEP due to the reduction of friction due to gas pressure in the unfired cylinder, and the required increase in throttle angle to achieve a stable idle reduces PMEP as well. The torque-based control system is able to smoothly blend both the throttle and spark advance during this transition so it is totally transparent to the rider. As an added bonus, this mode is extremely quiet, allowing easy conversation near a parked but running sled.

The engine is also able to protect itself and critical emissions components. The engine restricts the operator to safe boost levels, which vary depending on ethanol content. At high ethanol blends, the boost and power limits are significantly increased, due to the reduction in spark knock with the higher octane fuel. The engine will reduce power to self-protect in a number of damaging conditions, including extended operation at high knock areas, high air temperature, or high coolant temperature.

To regenerate the LNT, the control system must produce an excess of hydrocarbons in the exhaust. This is done by cycling the engine rich for a short period of time. Due to the torque-based control architecture, the desired fuel/air ratio is changed to a rich value, and the appropriate throttle is calculated to achieve the same torque with an increase in fuel. This results in the throttle automatically closing during LNT regenerations, and the control system smoothly blends this in a way that the rider will not feel.

Weight Minimization

Chassis modifications were kept to a minimum because the base MXZ Sport utilizes the REV-XP chassis which incorporates an aluminum frame. This makes it a relatively light trail snowmobile with a dry weight of only 206 kg (454 lb).

The 2011 Skidoo Renegade 600 ACE that was previously used had a dry weight of 213 kg (470 lb). When compared to the 2014 MXZ sport, the total weight reduction equates to 7 kg (16 lb).

Cold Start Modifications

One of the trade-offs of using higher blend ethanol fuels is poorer cold startability. Of course, this is of paramount importance for a snowmobile; therefore modifications must be made to allow for cold starting ability. The reason for poorer cold startability is shown in Table 1, specifically the high latent heat of vaporization for ethanol compared to gasoline. Below 11°C, Cold startability becomes a significant issue as ethanol will not vaporize for combustion.

In order to compensate for this, the team programmed the ECU to adapt for the cold at startup using fuel enrichment. This is done by injecting a greater volume of fuel into the cylinder during a cold start in order to allow enough gasoline into the cylinder to vaporize and initiate combustion. The cold start enrichment levels were determined through testing, and vary based on the ethanol content of the fuel in the tank.

To ignite rich charges while cranking and lean charges during snowmobile cruising, the ignition coils receive high dwell times resulting in high spark energy. The ignition coils are fired in wasted-spark, once per crank rotation, scheme during cranking and light-off for fast crank-to start times and decreased emissions. During the catalyst light-off period after starting, the idle control is calibrated to intentionally retard the ignition angle and increase fuel/air ratio for increased exhaust temperatures, until the catalyst has reached the light-off temperature, to reduce the emissions during the critical cold-start phase.

Mechanical Noise Reductions

To isolate the sources of mechanical noise, the snowmobile was placed on a stationary warm-up stand and run at different speeds. Sound readings were taken from different points around the snowmobile. The greatest noise levels contributed by mechanical systems were found to be coming from the engine compartment and the track tunnel.

In an effort to reduce mechanical noise, water and heat resistant foam insulation was installed under the hood and body panels, and the body panel seams were treated with rubber sealing strip to reduce noise caused by vibrations between panels.

The track noise is reduced through the use of a sound deadening mat on the inside of the track tunnel. This will result in lower noise levels experienced by bystanders or in pass-by testing.

Rider Safety

As with any recreational vehicle there are safety hazards to consider. As per competition rules, the unmodified clutch was enclosed with the stock guard made of aluminum and plastic. The rear suspension mid shock has been replaced in order to increase handling responsiveness to allow the rider to be better prepared for obstacle avoidance situations and more stable over rough terrain. A leak proof gel cell battery was placed in plastic enclosure to prevent any potential hazards. The stock DESS tether retains its functionality.

Cost Effectiveness

The original Ski-Doo MXZ has a base Manufacturer's Suggested Retail Price (MSRP) of $8,549. However, added technology and performance enhancements drove this number up. After various fuel system improvements, a more advanced ECU, sound deadening treatment, and exhaust aftertreatment had been added to the snowmobile, the snowmobile cost increased to an estimated base MSRP of just under $10,400. With the average base MSRP of a new snowmobile sold in North America in 2009 being $8800, this MSRP is very attractive considering the added value and advanced technology passed on to the customer. The cost of several components, can be expected to decrease with proper sizing for snowmobiles and volume production.

Conclusions

The members of the 2016 Kettering University Clean Snowmobile Challenge team have produced a well-rounded snowmobile which is both clean and still fun to drive. The team has been able to deliver a quieter, cleaner, more efficient snowmobile without compromising the cost, durability, rider safety or performance. Through the use of ethanol and isobutanol blended fuels and add-on technology, the snowmobile has demonstrated much lower emissions than those required in the 2012 Federal regulations.

Contact

Dr. Gregory W. Davis, P.E.
Faculty Advisor
gdavis@kettering.edu

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