Exhaust Gas Recirculation Implementation and Displacement Increase for Improvements on a Rotax ACE Engine

Saager Paliwal, Kyle Karnick, Thomas Steffel, Jennifer Bartaszewicz
Ethan K. Brodsky, Glenn R. Bower
University of Wisconsin-Madison

ABSTRACT

The University of Wisconsin-Madison Snowmobile Team has designed and constructed a clean, quiet, high performance snowmobile for entry in the 2016 SAE International Clean Snowmobile Challenge. Built on a 2013 Ski-doo MXZ chassis, the design features a Rotax ACE port fuel-injected four-stroke engine bored and stroked to 674 cc that is equipped to operate efficiently on gasoline and alcohol fuel blends. The engine has been customized with a Woodward control system, which allows for full engine optimization with complete flex-fuel ethanol capabilities. An electronic throttle body and mass airflow sensor are used in conjunction with a wideband oxygen sensor to enable closed-loop fuel control. A dedicated external intercooled exhaust gas recirculation system has been implemented reducing oxides of nitrogen emissions. Utilizing a 3-way catalyst designed by Continental Emitec GmbH and Heraeus GmbH, oxides of nitrogen, unburned hydrocarbons, and carbon monoxide are reduced up to 96%. With all of the modifications, the clean Rotax ACE is capable of a power output of 40 kW and utilizes a combination of a muffler in addition to sound dampening material to reduce sound levels to 65.8 dB using SAE test procedure J1161. The lightweight combination of the MXZ chassis and improved ACE engine results in a rider-friendly package that meets the criteria to succeed at the Clean Snowmobile Challenge while also being desirable to snowmobile consumers.

INTRODUCTION

The Society of Automotive Engineers (SAE) developed the "Clean Snowmobile Challenge" (CSC) in 2000 when snowmobiles were banned from National Parks. It is an engineering design competition among colleges and universities that demonstrates clean, quiet, and practical alternatives to the conventional two-stroke snowmobile. Competition entries are redesigned versions of Original Equipment Manufacturer (OEM) snowmobiles and are expected to significantly reduce unburned hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_X), and noise emissions while maintaining a consumer acceptable level of performance. Successful CSC entries must also demonstrate reliability, efficiency, and cost effectiveness. The 2016 CSC will be held in Michigan's Keweenaw Peninsula from March 7^{th}-12^{th}.

This paper discusses how the University of Wisconsin – Madison team has engineered the Wisconsin/Rotax Advanced Combustion Efficiency 674 (WRACE 674) for the 2016 CSC improving upon the industry's best available emissions and sound technology, while maintaining exceptional riding characteristics. The sections of the paper address the following:

1. Engine selection process and optimization in a 1-D computation fluid dynamics solver.
2. Engine modifications including boring and stroking the engine.
3. Implementation of exhaust gas recirculation and emissions control technologies.
4. Design enhancements for noise reduction and flex fuel capabilities.
5. Summary of costs compared to a production snowmobile.

MARKET SURVEY

An important aspect of the Clean Snowmobile Challenge is being able to maintain certain characteristics that consumers expect from modern snowmobiles. To market a product to current snowmobile consumers, the team surveyed 25 snowmobile clubs in Wisconsin to determine which attributes are most valued.

The survey asked riders to rank several characteristics they considered when investing in a new snowmobile. The characteristics surveyed were acceleration, handling, price, fuel economy, emissions, and sound output. Handling, along with price and fuel economy, were the top three characteristics while sound was the least considered when purchasing a snowmobile as shown in Table 1.

Table 1. Characteristics Valued Most by Consumers

Characteristic	Rank	% Valued
Handling	1	100%
Price	2	94.9%
Fuel Economy	3	86.6%
Acceleration	4	86.0%
Emissions	5	73.2%
Sound	6	65.5%

The results of the survey are in line with the Wisconsin team's goals of designing a cost effective snowmobile with good handling and fuel economy while also being environmentally friendly.

ENGINE OPTION EVALUATION

Taking into account the results of the market survey with consumers valuing handling, price, and fuel economy, the team looked for engines with good fuel efficiency at a low cost. Also considered by the team were engine sound and engine out emissions in order to successfully match the design objectives of the Clean Snowmobile Challenge. The team considered the following engine options:

- Two-stroke snowmobile engines
- Four-stroke snowmobile engines
- Turbo-charged four-stroke snowmobile engines
- Direct injection (DI) two-stroke snowmobile engines
- Compression ignition (CI) engines

It is well known that two strokes have significantly higher power-to-weight ratios than current four-stroke models. A snowmobile emissions study conducted in 2002 by Southwest Research Institute (SwRI) states that commercially available four–strokes "…emit 98-95 percent less HC, 85 percent less CO, and 90-96 percent less PM" than conventional two-stroke snowmobile engines [1]. To the teams knowledge no head to head studies have been funded since to examine the emissions of DI two stroke snowmobiles compared to 4 strokes but 2 strokes tend to have more noise emissions and none are currently Best Available Technology (BAT) compliant [1]. In addition, aside from the three pollutants measured for competition scoring, direct inject two-stroke spark ignition engines are known emitters of benzene, 1,3-butadiene, and gas/particle-phase polycyclic aromatic hydrocarbons, all of which are classified as known or probable carcinogens by the U.S. Environmental Protection Agency (EPA) [2].

In past years the team evaluated compression ignition (CI) engines recognizing their excellent HC and CO emissions. In the 2015 Clean Snowmobile Challenge the Diesel Utility Class (DUC) was introduced, a separate category from traditional gasoline powered snowmobile within the Internal Combustion (IC) Class. As most consumer snowmobiles are gas powered, as well as acknowledging the poor power-to-weight ratio of diesel engines, difficulty of implementation, and costly modifications needed, the Wisconsin team decided to design based off of a spark ignited engine.

To aid in engine selection, the survey conducted also had volunteers choose the powertrain option they would most likely buy between a direct-injection two-stroke and a fuel-injected four-stroke given equal price and performance. The results conclude that just over 60 percent of the voters would choose a four-stroke engine to power their snowmobile. Currently rules restrict peak horsepower to 130 horsepower, and at these power levels, four-stroke engines designed for snowmobiles offer far easier implementations and improvement.

FINAL ENGINE SELECTION

With the focus of the Clean Snowmobile Challenge on emissions, the team compared three of the leading snowmobile engines for low emissions as shown in Table 2. Taking into consideration the results of the market survey, the team also valued the fuel consumption of each engine as well as the power and weight of each engine. The Rotax Advanced Combustion Efficiency (ACE) 600, which is available through BRP's Ski-doo snowmobile line, advertises 42 kW (56 hp) and is BAT compliant from the factory. Another model in the same product line is the ACE 900, which develops 67 kW (90hp) and is also BAT compliant. Other options considered included the Ski-doo 4-TEC, which is capable of higher power outputs than either of the ACE engines.

Table 2. Engine Comparison of Leading 4-Stroke Snowmobiles.

Base Snowmobile	Power (kW)	Weight (kg)	Fuel Economy (km/L)	Emissions g/kW-hr		
				HC	CO	NO_x
Ski Doo ACE 600	42*	40	12.3	8	90	N/A
Ski Doo ACE 900	67**	55	10***	8	90	N/A
Ski Doo 1200 4-TEC	97	64	7.2	6.2	79.9	N/A

OEM Reported Power
*****Sport mode operation***
******Eco mode operation.***

It can be seen in Table 2 that all engines have comparable HC and CO emissions and when coupled with an optimized catalyst, CSC E-Scores of over 205 could be reached.

While all engine options fulfill current EPA emissions requirements, both the stock ACE 600 and 900 engines "set new standards in efficiency" giving them an advantage as fuel economy plays a fairly large role in the CSC [3,4]. The ACE design also allows for integrated engine lubricant and cooling systems, which minimizes weight, complexity, and external plumbing, making it easier for modification and implementing Wisconsin's designs. Table 3 below shows the similar specifications of the two ACE engines.

Table 3. Specifications of the Rotax ACE 600 and 900 engines.

Engine	ACE 600	ACE 900
Engine Type	Four-Stroke	Four-Stroke
Cooling	Liquid	Liquid
Cylinders	2	3
Displacement	600 cc	900 cc
Bore x Stroke (mm)	74 x 69.7	74 x 69.7
Ignition	Bosch	Bosch
Exhaust	2 into 2	3 into 1
Fueling	Electronic PFI	Electronic PFI
Compression Ratio	12:1	12:1

More importantly the ACE 600 is the lightest 4-stroke engine the Wisconsin team considered. Both the stock ACE 600 and ACE 900 feature the use of an electronic throttle body (ETB), a device used by the Wisconsin team since 2009. Several drawbacks of the ACE 900 are its increased weight, fuel consumption, and higher cost. The combination of these drawbacks made the ACE 600 the power plant of choice for the Wisconsin team.

ENGINE SIMULATION AND OPTIMIZATION

For the 2016 competition the team used a 1-D model to evaluate multiple options for increasing the power of the ACE 600. The three main ways to increase the indicated power of an engine include operating the engine at higher speeds, increasing engine size, and raising cylinder pressure [5]. Many systems exist to increase the cylinder pressure for power improvement including turbochargers and superchargers. The drawback to many of the these systems are the added weight, complexity of plumbing, added overall cost, and in some cases reduced overall efficiency. Increasing the engine speed would also result in a decrease in engine efficiency by increased friction losses, moving away from peak engine torque, and would require redesigning the clutching and transmission system. For these reasons the team elected to increase the displacement in order to improve the performance of the stock ACE 600 engine. Increasing the displacement of the ACE 600 would increase the power and torque output while maintaining the lightweight, fuel efficient package compared to the larger ACE 900.

In order to optimize the increase in engine displacement and allow quick evaluation of different designs to the ACE engine, a 1-D model of the engine was developed using Ricardo Wave. Starting with the stock bore and stroke of 74 mm and 69.7 mm respectively, the team evaluated several designs changing the bore and stroke dimensions taking into consideration the geometric constraints of the engine block and crankcase.

When optimizing the stroke of the engine, the team avoided modifying the stock crankcase to remain within the physical constrains of the engine package. Sweeps were conducted from 69.7 mm to 75.7 mm representing the values of the stock stroke to the maximum physical stroke respectively. The bore was also swept from the stock value of 74 mm to 76 mm. It was found that increasing the stroke by 6.0 mm to 75.7 mm total, in combination with the new bore of 75 mm, increased the power by 8.2% to 32.5 kW at 5000 RPM range and increased peak torque by 7.3% when compared to the stock ACE 600 as shown in Figure 1. The model also predicts a 5% lower power output than stated by Ski-Doo for the stock ACE 600.

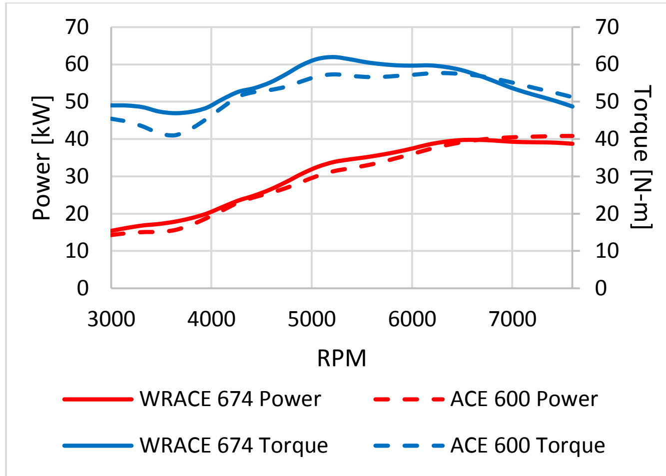

Figure 1. Torque and power curves for the stock ACE 600 and optimized WRACE 674 engines.

With changes to the bore and stroke the team evaluated changes in intake and exhaust camshaft timings to allow the maximum airflow into the engine. Intake timing was swept 5 by degrees both advanced and retarded from the stock timing. Results showed minimal change in the respective torques across timings leading to the team implementing the stock intake and exhaust camshafts.

Dynamometer testing of the 2015 Wisconsin entry showed high exhaust backpressure as one of the efficiency losses incurred. Backpressure from the catalyst was 40.4 kPa resulting in a pumping loss of 2.42 kW of power, 7.8% of the engine's power at 6000 RPM during the 2015 CSC. Different exhaust and catalyst designs were considered in order to reduce the backpressure and pumping losses resulting in increased power output. An optimized exhaust coupled with a 400 cpsi metal honeycomb catalyst were implemented for a backpressure reading of 13.5 kPa recovering 1.61 kW of power for the 2016 competition sled.

POWERTRAIN ENHANCEMENT

The stock Rotax ACE 600 shown in Figure 2 did not leave much room for improvement, already being a highly efficient engine. The engine features diamond like carbon coatings on the surface of the tappets to reduce friction losses and a magnesium valve cover on top of the cylinder head sealed by rubber gasket to reduce any radiated noise [4]. Even with the advanced features of the ACE engine, the Wisconsin team found aspects of the efficiency, power, and fuel economy to improve.

Figure 2. The stock Rotax ACE 600, showing the integrated oil cooler.

Boring and Stroking

The team first specified the change in the crankshaft stroke, which was limited by the clearance in the stock block, which included an integrated windage tray in the casting; increasing the crank throw by 3 mm would leave a 0.5 mm of clearance in the windage tray. With the stroke now set at 75.7 mm, the analysis moved to the piston size – analysis indicated that a 'square' (stroke = bore) engine provides excellent low-end torque and fuel efficiency where the snowmobile will be operating during most trail riding conditions.

The next stage of the engine design was to determine whether Wisconsin had to specify custom pistons or whether some current aftermarket pistons could be modified to suit our design. Wiseco is one of the world's largest aftermarket piston manufacturers and generally sells forged pistons which have better mechanical properties than cast pistons (the stock ACE pistons are cast). To meet the Wisconsin piston specifications, the candidate piston would need to have a higher wrist pin location and a shorter skirt so that the piston would be confined to the original bore of the engine.

Wisconsin determined that Wiseco had candidate pistons with 75 mm and 76 mm diameters. Upon consultation with Nigel Foxhall, Director of Advanced Engineering at BRP-Powertrain GmbH & Co KG, Wisconsin was provided the original piston liner details – the BRP information indicated that boring the engine block for 76 mm piston would 'thin' the original cast iron sleeves beyond common engineering practices. Wisconsin reviewed the limited Wiseco information available on the internet for 75 mm pistons; after identifying the 3 best candidate pistons, Wisconsin ordered them and analyzed them when they arrived. It was determined that a 75 mm piston designed for a Honda CBR954RR met almost all of Wisconsin's criteria in addition to allowing the team to utilize the stock connecting rod.

The V-shaped high compression ratio dome on the stock Honda CBR954RR piston needed to be modified to ensure proper valve clearance and combustion chamber geometry. The piston was decked and then machined to create a two-tiered bowl design mimicked from the stock ACE piston. Figure 3 shows a comparison of the Rotax stock piston versus the Honda piston that was chosen after all modifications had been made. The original valve cut-outs in the Wiseco piston aligned perfectly with the valves in the stock ACE cylinder head. The only modification that was performed was machining 0.5 mm off the face of the intake valves so they were flush with the cylinder head surface. The final values for the modified piston compared to the stock piston are shown in Table 4.

Figure 3. From left to right: stock Rotax piston, unmodified Honda piston, and machined Honda piston with two tier piston bowl design to improve mixing in combustion chamber.

Table 4. Table comparing the stock Rotax ACE piston to the modified Honda Piston from Wiseco.

	Rotax Stock	Honda Modified
Diameter [mm]	74	75
Wrist Pin Diameter [mm]	17	17
Wrist Pin Location [mm] (relative to compression ring)	28	25.5
Compression Ring to Deck Height [mm]	5.5	5.12
Mass* [grams]	254.5	219.36
Bowl Size (cc)	5	5.15
Skirt Length from bottom of Wrist Pin [mm]	9.6	6.4

Mass includes piston, rings, wrist pins, and clips.

To achieve the appropriate bore diameter an Advanced Engine Technologist bored and plateau honed the cylinder walls to achieve a desired bore diameter for 75.3 mm; providing a 'medium' clearance using the stock 600 engine manual criteria. A plateau hone technique was used with a multi-level hone to ensure that the cylinder surface was smooth while also ensuring that the cylinder wall cross hatching was deep enough to achieve efficient oil cling producing sufficient ring seal and longevity of the engine.

With the piston, valves, bore and crankshaft all finalized, Wisconsin calculated the theoretical compression ratio using a stock ACE 600 head gasket; it was determined that the compression ratio was 13.8:1. Wisconsin contacted Cometic gaskets which was able to supply a copper head gasket to Wisconsin specifications. The custom copper gasket was 1.092 mm thick and was sandwiched between the two halves of the original head gasket with an appropriate adhesive: the WRACE 674 final compression ratio is 11.82:1. This design allows Wisconsin the ability to increase or decrease the compression ratio of the engine by simply installing a different thickness copper head gasket spacer.

Ported Head

In order to continue to increase power output, the stock intake and exhaust ports were hand-ported in order to increase flow and consequently power and torque. Porting the head removes the material at the bottom of the ports where the most dense and highest velocity air flows during the intake and exhaust processes allowing more air to enter the combustion chamber. A SuperFlow calibrated flow bench was used to measure the flow into the intake and exhaust ports as valve lift was changed. The largest improvement was seen on the exhaust valves as shown in Figure 4; a consistent improvement of 5-7% was observed over the entire exhaust valve lift. This lead to the implementation of a ported exhaust head on the WRACE 674.

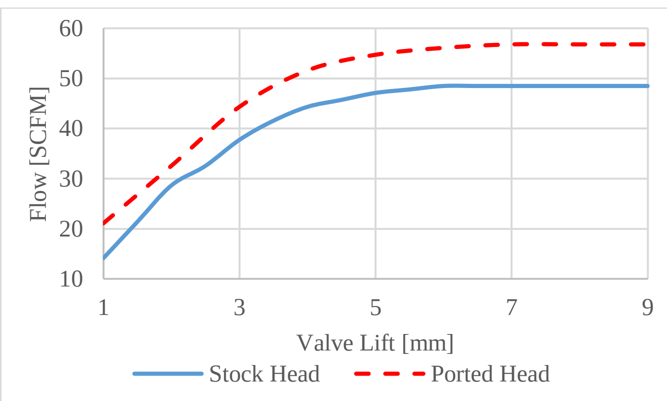

Figure 4. The exhaust ports of the ported head compared to the stock head. The ported head shows flow improvement across the valve lift profile.

Calibration and Control

Several major components were installed to allow the optimization and control of the WRACE 674. The team makes use of the stock Electronic Throttle Body (ETB) for idle control and electronic starting. Utilizing the ETB also reduces complications of calibration, improves cold start ability, and reduced part load throttle losses by operating at the optimal angle for airflow. The ETB also compensates the amount of flow required when adding exhaust gas to achieve the desired equivalence ratio. In addition to using the ETB was the implementation of a mass airflow (MAF) sensor reading intake mass airflow and temperature as well as a manifold absolute pressure (MAP) sensor both relaying directly to the Motorola Engine Control Unit (ECU). To be able to real-time monitor engine NO_X output as well as implement a closed loop fueling algorithm based on exhaust oxygen content the team has also installed a heated Continental Smart NO_X sensor in the exhaust stream which measures both exhaust NO_X and oxygen content during calibration.

The combination of the ETB, MAF sensor, MAP sensors and dual NO_X/O_2 sensor was used to calibrate and control fuel injection and develop a fuel control strategy. Part of the control strategy is used during large transients when the closed loop system is unable to maintain the air-fuel ratio (A/F ratio) within one percent of the desired value. In this situation, predefined default fueling tables determine fuel injection control.

Typically, when calibrating an engine, the main goals are to minimize Brake Specific Fuel Consumption (BSFC) under part-throttle operation and to maximize torque at Wide Open Throttle (WOT) while staying within specified constraints. Typical constraints consist of emissions levels, running quality, exhaust gas temperature limits, knock limits, and engine speed [1]. These constraints define a window, shown in Figure 5, that the engine must be calibrated to operate within.

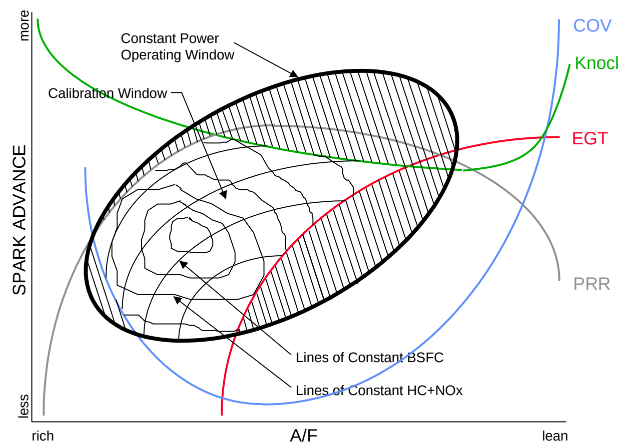

Figure 5. Graph of typical calibration window [6].

Calibration of the 2016 engine shown in Figure 6 was performed using a water-brake dynamometer, wideband oxygen sensors, and exhaust thermocouple probes. By monitoring torque, exhaust temperatures, and A/F ratio values, spark timing and fueling could be properly calibrated.

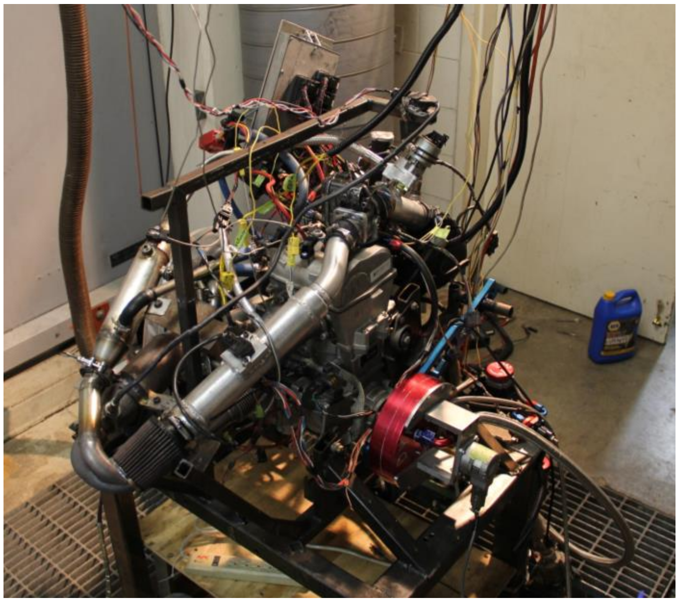

Figure 6. Dynamometer testing stand used for all calibrations.

Another improvement made to the powertrain to enhance efficiency was the addition of belt drive instead of the stock chain driven system. This eliminated the need for chain case oil, which can be very viscous at lower temperatures. Like most drive shafts found on modern snowmobiles, the stock drive shaft has plastic molded drive paddles that were un-machined. The molding process of these drive paddles does not create a very uniform shape, which can cause a snowmobile's track to change tension while moving. This effect of relaxing and tensioning of the track can make the snowmobile less efficient as well as increase snowmobile noise and wear. To reduce these effects, the driveshaft was machined on a lathe so that both drive paddles were concentric circles.

EXHAUST GAS RECIRCULATION IMPLEMENTATION

Several successful emission control technologies have been implement in both the automotive and off-highway industries in order to meet stricter EPA regulations. The Wisconsin team chose to implement an exhaust gas recirculation (EGR) system to further reduce engine out oxides of nitrogen.

EGR is primarily used for the reduction of NO_X emissions by recirculating a fraction of the exhaust gas through control valve from the exhaust to the intake system. NO_X is formed at high combustion temperatures by the disassociation of oxygen and nitrogen found in the air inducted into the cylinder. The recirculated exhaust gas is mixed with fresh air and acts as a diluent reducing the peak burned gas temperatures and NO_X formation respectively [5]. Studies have shown that cooling the exhaust gas before introduction into the intake can further reduce emissions and improve fuel economy in high speed applications as well as reduce the production of in-cylinder CO [7, 8]. For these reasons the team also designed a custom EGR cooler for further emissions reduction.

Valve Selection

In order to properly control the amount of EGR flowing into the intake system, the Wisconsin team examined several types of valves available for automotive applications. Though vacuum operated valves and differential pressure feedback systems were considered, the team elected to use an electronically controlled valve to be able to optimize the EGR flow across the RPM range. Several factors went into selecting the optimal valve including cost, ease of implementation, integration into existing hardware, and maximum flow rate. With highest priority placed on the valve flow rate, a Delphi EG10176 EGR valve, shown in Figure 7, was selected with a flow rate of 16.1 kg/h measured by the team on a SuperFlow flow bench. The valve is controlled through a low-side driver driven by the PCM and used to populate EGR rate tables.

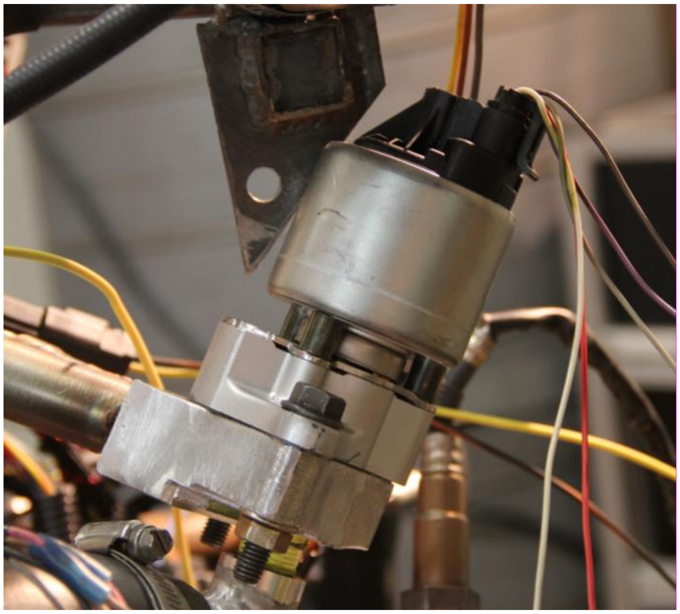

Figure 7. The Delphi EG 10176 EGR valve used to reduce oxides of nitrogen emissions by lowering peak combustion temperatures.

Cooler Implementation

Once it was decided to utilize an EGR cooler, Wisconsin created the following EGR cooler criteria:

1. Maximum diameter of 64 mm
2. Maximum length of 204 mm
3. Cooling capacity of 3 kW
4. Utilize engine coolant

Due to the limited number of engines less than 1 liter running EGR there were no widely available air to water coolers that would meet the team's requirements. The ones available were designed for turbocharger applications with significantly higher cooling capacity than required by the team. Therefore, the team opted to design a custom EGR cooler.

The design strategy stated by collecting engine exhaust and coolant temperatures. Using the NTU effectiveness heat exchanger sizing method, the system was modeled in Engineering Equation Solver (EES). It was found that the heat transfer from the exhaust to the tubes of the shell and tube heat exchanger was the limiting factor. To engineer a balance between back pressure and convective heat transfer rates, Wisconsin utilized enhanced surface tubes as shown in Figure 8. The 'rough' surface increases the contact area and creates turbulent flow which significantly increases the heat transfer rates.

Figure 8. The enhanced surface of the tubes manufactured by Vipertex. The increased roughness of the walls disrupts the boundary layer creating turbulent flow, which increases the amount of heat transfer from the recirculated exhaust gas to the engine coolant.

Since the amount of space the cooler would take up was one the set design criteria, the team analyzed the effect of the number tubes that would be most effective while also being able to fit into the small foot print required. The effectiveness of the cooler versus the number of tubes was considered as shown in Figure 9; it can be seen that there is minimal change after 15 tubes as effectiveness approaches 100%.

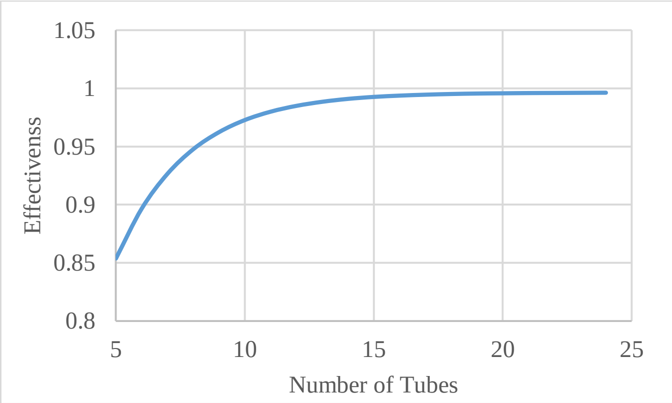

Figure 9. The effectiveness of the cooler reaches within 5% of its max effectiveness by approximately 8 tubes.

Due to under-hood space constraints 15 tubes of 9.53 mm (0.375 in) would not fit in the design area. The final design, shown in Figure 10, uses 9 tubes fitting into a 64 mm diameter by 204 mm length tube with an effectiveness of 96%.

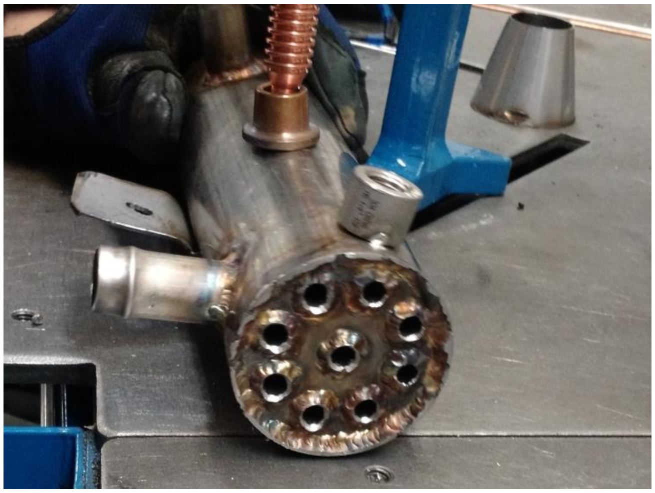

Figure 10. The 9 tubes of the cooler were spaced to maximize the amount of turbulence in the cooler resulting in the highest amount of heat transfer out to the engine coolant.

NO_X Reduction

In addition to modeling the WRACE 674 engine for power and performance improvements, NO_X emissions were evaluated with various volumetric percentages of EGR compared to engine air intake. Ricardo Wave incorporates a built in EGR percentage function to add to the air going into the engine. The team evaluated EGR rates of 0%, 6%, and 12% of the intake air across the RPM range as shown in Figure 11.

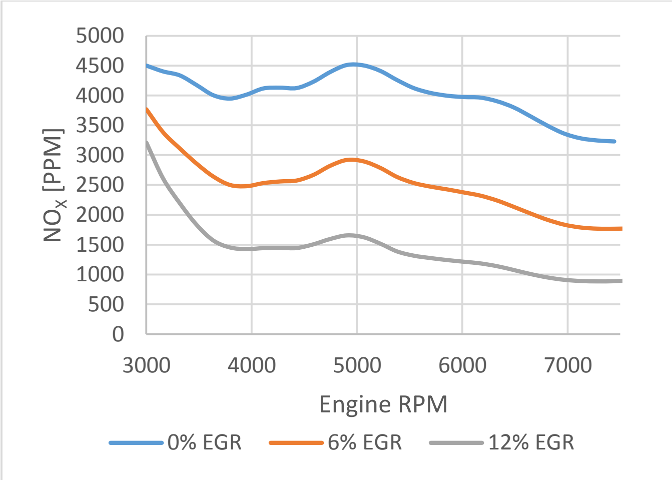

Figure 11. Simulated engine out NO_X of the WRACE 674 using volumetric percentages 0%, 6%, and 12% EGR.

In order to validate both the computer model predictions and the effectiveness of the valve and cooler system the team used the dual NO_X/O_2 sensor during calibrations to collect data at several rates of EGR across the RPM range. It can be seen in the simulation results in Figure 11 that at high rates of EGR NO_X is reduced by nearly 67% at 5000 RPM.

CONTROL HARDWARE

In order to have a flexible engine controller, a Motorola PCM565 ECU embedded system specifically designed for automotive applications was implemented. The ECU uses an operating system designed by Woodward Inc. and is hermetically sealed making it ideal for a range of under-hood conditions. The module can withstand temperatures from -40°C to 105°C, vibrations up to 18G, and submersion in water up to a depth of 3m; all conditions a snowmobile might experience. It also has 34 analog inputs, 8 digital inputs, 24 low side driver power outputs, 16 logic level outputs and a dual CAN 2.0B interface. The Motohawk software provided by Woodward auto-generates code from the Wisconsin Simulink model.

The base Simulink control model underwent numerous modifications to incorporate ignition and fueling tables that are load, speed, and manifold pressure dependent. To create a more robust and marketable control strategy the model adapts to atmospheric conditions and cold start conditions, as well as engine protection features for excessive coolant temperatures and/or low oil pressures. The model calculates optimized fueling rates in real time based on inputs from the wideband oxygen sensor and mass airflow sensor.

FUEL SYSTEM MODIFICATIONS

In order to run alcohol-based fuels without adversely effecting performance and emissions, modifications to the fuel delivery system were necessary. The fuel injectors needed to be changed to accommodate the higher fuel flow rates needed for alcohol fuels due to their lower heating values. The replacement injector specifications are given in Table 5.

Table 5. Fuel injector specifications.

	Stock Injector	WRACE Injector
Manufacturer	Continental	Bosch
60 Sec Flow	160 g	237 g
Spray Angle	20º	20º
Rail Pressure	400 kPa	300 kPa

Another consequence of increased fuel flow is that a larger fuel filter and fuel pump are needed. The team decided to use an in-line 40 micron stainless steel fuel filter capable of delivering fuel at over 2 gal/min. This reusable filter ensures adequate fuel flow to the pressure regulator, injectors, and flex fuel sensor.

To accommodate a range of fuels containing 0% to 85% ethanol, the team installed and calibrated an inline Continental Flex-Fuel sensor. It uses a dielectric measuring principle to detect the amount of alcohol in the fuel. The sensor also reports fuel conductivity and temperature [7]. Since air-fuel ratios are calculated on a gravimetric basis and fuel injectors are measured on a volumetric basis, the fuel temperature is measured to allow for density compensation.

These fuel properties, along with the MAF sensor measurements are supplied to the Mototron controller. The engine management system is based on the physical models of the induction and combustion process instead of simply using correction tables for deviations from the base calibration. Wisconsin's calibration provides a prescribed global A/F ratio, which is used to calculate the correct fuel injection amount based on the intake mass airflow rate, the fuel density, and the desired A/F ratio.

EMISSIONS

For the 2016 Clean Snowmobile Challenge, the Wisconsin team worked with Continental Emitec GmbH and W.C. Heraeus GmbH to reduce emissions on the WRACE 674 to automotive standards. With a focus on HC, CO and NO_X, emissions a three-way catalyst was implemented before the muffler to effectively reduce the targeted species.

To fully optimize the precious metal washcoat, exhaust gas was collected before the muffle for testing. Using a vacuum chamber case, exhaust gases flowed into sampling bags for each of the 5 modes of the CSC laboratory dynamometer test. While sampling, fuel flow, mass airflow, equivalence ratio, and exhaust gas temperatures were also recorded. The collected exhaust gases were then analyzed with a ThermoNicolet Nexus 674 FTIR spectrometer, which reported emission concentrations using the Omnic 8.3 software.

Working with Heraeus, a platinum/palladium/rhodium-based washcoat was applied to Emitec's metal honeycomb substrate. The loading characteristics as well as substrate description are shown in Table 6. The high loading of palladium is used to effectively oxidize the CO and HC without the unwanted reactions that can occur with high platinum loading.

Table 6. Catalyst substrate and washcoat data.

Manufacturer	W. C, Heraeus GmbH
Diameter	92 mm
Length	168 mm
Foil thickness	0.03 mm
Substrate	Emitec Metal Honeycomb
Density	400 cpsi
Loading	Platinum 11.1 g/ft^3
	Palladium 55.6 g/ft^3
	Rhodium 8.3 g/ft^3

To optimize the reduction of CO, HC and NO_X, the exhaust gases entering the three-way catalyst must alternate between slightly rich and slightly lean. As seen in Figure 12 the catalytic reduction efficiency for NO_X at a stoichiometric air-fuel ratio is slightly under 80%, while HC and CO are reduced at almost 90% efficiency. When a lean exhaust mixture passes through the catalytic converter, excess NO_X is absorbed on the surface of the substrate while the CO and HC are reduced to H_2O and CO_2 in the presence of excess oxygen. In contrast, when a fuel-rich exhaust mixture goes through the catalyst, the NO_X is released from the substrate and immediately reacts with the HC and CO to form N_2 and CO_2 and/or H_2O [Heywood].

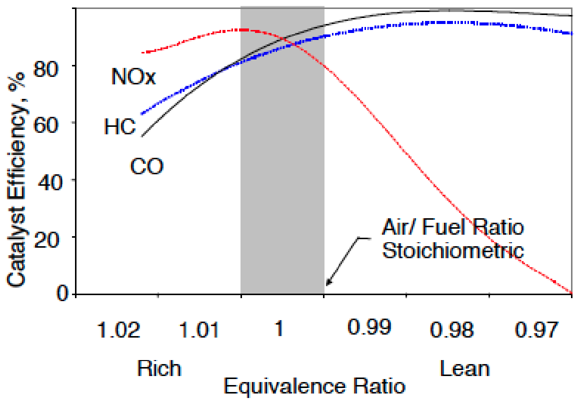

Figure 12. Shows the NO_X, CO, and HC conversion efficiency for a three-way catalytic converter as a function of exhaust gas air/fuel ratio operating on gasoline (Adapted from [5]).

This lean-to-rich oscillation of the engine is controlled using the team's closed-loop fuel trim algorithm, maximizing emissions reduction. These fluctuations in the oxygen sensor output in addition to the fueling multiplier are show below in Figure 13. In this area of engine operation, the base calibration is slightly rich, probably due to atmospheric conditions, and so the emissions control algorithm has adjusted the fuel multiplier to oscillate around an air-fuel equivalence ratio of 0.96.

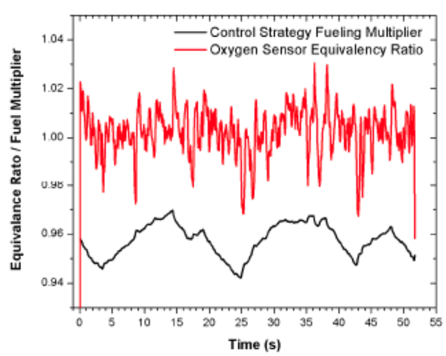

Figure 13. Engine equivalence ratio oscillating near stoichiometric as a result of closed-loop control.

The engine's speed density and target A/F ratio tables are populated with the engine loaded by the dynamometer to within 0.2% of the target exhaust oxygen content. From here the closed loop fuel trim algorithm, which utilizes the heated wideband oxygen sensor, is activated and is responsible for fine tuning the air-fuel ratio to a stoichiometric level. The computing power of the Mototron controller is used to continually optimize the correct fuel injection amount using the intake mass air flow rate, the fuel density, and the desired fuel air ratio, shown in Figure 14.

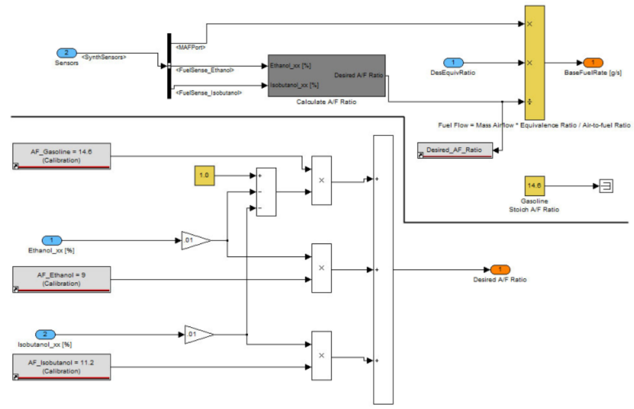

Figure 14. Simulink block diagram for flex-fuel and iso-butanol engine control strategy.

The combination of the optimized washcoat and the closed loop fuel algorithm with the wideband oxygen sensor provides an ultraclean snowmobile. The projected E-score for Wisconsin's 2016 CSC entry is calculated to be 206.9. Table 7 shows projected 2016 weighted 5-mode lab emissions results against stock ACE 600 emission results.

Table 7. Emissions of the stock ACE 600 and WRACE 674.

	WRACE 674	ACE 600 [3]
CO (g/kW-hr)	11.40	90
HC (g/kW-hr)	0.382	8
NO_x (g/kW-hr)	0.041	N/A
E-Score	206.9	190

MECHANICAL NOISE REDUCTION

The team used a stock 2015 Ski-Doo MXZ 600 ACE to identify sources of mechanical noise emitted from the snowmobile. Testing consisted of a drive-by at a speed of 35 mph and WOT acceleration with two microphones, one on each side of the snowmobile at a distance of 15 m away from the line of travel. The Extech 407736 microphones were set to a low range, fast response, with an A weighting technique as described by SAE test procedure J1161. Using this method stock ACE 600 sound levels were measure to be 68.2 dB.

With the stock ACE 600 the clutch engagement occurs at 4200 RPM resulting in a crankshaft frequency of 70 Hz and a piston frequency of 140 Hz. The WRACE 674 has a higher torque curve in the lower RPM range allowing for clutch engagement at 3200 RPM. Engaging the clutch at 3200 RPM reduces 1st and 2nd order by 20% to 56 Hz and 112 Hz for the crankshaft and piston respectively. The lower frequencies of WRACE 674 result in a lower relative decibel sound response due to the percentages of the A weighting scale.

The application of LizardSkin® Sound Control coating to the underside of the tunnel, shown in Figure 15, was applied to reduce noise resonating from the drive paddles and rear suspension. The Lizard Skin is designed to dampen rattles, vibrations, and road noise all of which are helpful in ensuring a quiet experience for bystanders and the rider.

Figure 15. View of tunnel underside lined with Lizard Skin material.

To help reduce driveline noise, the common chain final drive was replaced with a quieter, more efficient belt drive from C3 Powersports. By reducing the amount of metal on metal contact in the drive system, the sled's driveline noise became noticeably lower. The 2016 WRACE 674 also makes use of a Camoplast Ripsaw II track which reduced track noise from previous competition entries.

In its stock form, Ski-doo MXZ Sport ACE 600 is already relatively quiet. The addition of the catalyst has improved this by reducing the low frequency engine exhaust noise levels as the exhaust pulses are lessened. Higher frequency noise is emitted from mechanical systems such as the intake, clutches, final drive, and suspension. To reduce the effects of these higher frequencies, a rubber sound attenuation material was used to coat the clutch cover and air box. Further reduction of engine noise was accomplished with the addition of foam material with a silver heat reflective lining in the under-hood area.

Taking into consideration the lower frequency of clutch engagement and sound dampening material the WRACE 674 is expected to have a sound output of 65.8 dB, 2.4 dB lower than the stock ACE 600.

COST ESTIMATES

Every component of the WRACE 674 is designed for manufacturability. Many of the technologies are currently in use in other transportation applications such as the three-way catalyst, exhaust gas recirculation valve, and mass air flow sensor. By using available parts to find a compromise between performance and improved emissions/fuel economy, the team was able to concentrate on fine tuning the sled in places such as engine calibration and sound reduction. While these modifications add value to the sled, they would not significantly increase the price to the end user. The retail price of many of the components that replaced stock parts was less expensive. This is not reflected in the MSRP as competition rules require a 50% premium be added to any component which increases perceived customer value compared to the stock snowmobile. With an attractive MSRP of $11,516.11 the 2016 WRACE 674 has a comparable price to other commercially available 4-stroke sleds with similar power-to-weight ratios, such as the Yamaha Phazer and Artic Cat ZR5000 LXR. If key components of the WRACE 674 such as the catalyst and exhaust gas recirculation became standard parts within the snowmobile industry, the base price would only be approximately $1500 greater than today's stock MXZ Sport ACE 600 configuration.

CONCLUSIONS

The 2015 University of Wisconsin-Madison Clean Snowmobile Challenge Entry improves upon the Best Available Technology in performance and emission standards for over-snow recreational vehicles. Taking into consideration consumer performance requirements as well as CSC competition guidelines, the team bored and stroked the stock ACE 600 engine for power improvements while also implementing an exhaust gas recirculation system for emission reduction. The WRACE 674's flex fuel capability gives customers the ability to use a variety of renewable fuels such as E30 and E85. The redesigned exhaust after treatment system as well as many of the other implement designs ensure that Wisconsin's sled is both consumer and environmentally friendly. Designed for manufacturability with an aesthetically pleasing package, the WRACE 674 is a cost effective solution for performance oriented riders seeking a cleaner, quieter snowmobile.

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DEFINITIONS/ABBREVIATIONS

A/F	Air/Fuel
ACE	Advanced Combustion Efficiency
BAT	Best Available Technology
BSFC	Brake Specific Fuel Consumption
CAN	Controller Area Network
CI	Compression Ignition
CO	Carbon Monoxides
cpsi	cells per square inch
CSC	Clean Snowmobile Challenge
DI	Direct Injection
DUC	Diesel Utility Class
ECU	Electronic Control Modular
EES	Engineering Equation Solver
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
ETB	Electronic Throttle Body
FTIR	Fourier Transform Infrared Spectroscopy
HC	Hydrocarbons
IC	Internal combustion
MAF	Mass Air Flow
MAP	Mass Air Pressure
MSRP	Manufacture Suggested Retail Price
NO_X	Nitric Oxides
OEM	Original Equipment Manufacture
RPM	Revolutions per Minute
SAE	Society of Automotive Engineers
SwRI	Southwest Research Institute
WOT	Wide Open Throttle
WRACE	Wisconsin Rotax Advanced Combustion Efficiency