Optimization of an Increased Displacement Rotax ACE With Exhaust Gas Recirculation

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Abstract

The University of Wisconsin – Madison Clean Snowmobile Team has designed and constructed a clean, quiet, high performance snowmobile for entry in the 2017 SAE International Clean Snowmobile Challenge. The Wisconsin design features a Rotax Advanced Combustion Efficiency (ACE) port fuel-injected four-stroke engine, bored and stroked to 674 cc, powering a 2015 Ski-doo MXZ Sport chassis. The engine is equipped to operate efficiently on gasoline and alcohol fuel blends, and is customized with a Woodward control system allowing for full engine optimization, complete with 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. Implementation of an external intercooled exhaust gas recirculation system targets oxides of nitrogen emissions. Utilization of a three-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 Wisconsin Rotax ACE 674 is capable of a power output of 35 kW. The utilization of a Rotax muffler, combined with additional sound dampening materials, sound levels are lowered to 65.8 dB, in accordance with SAE test procedure J1161. The lightweight combination of the MXZ Sport 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 2017 CSC will be held in Michigan's Keweenaw Peninsula from March 6th-11th.

This paper discusses how the University of Wisconsin – Madison team has engineered the Wisconsin/Rotax Advanced Combustion Efficiency 674 (WRACE 674) for the 2017 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 having the ability to maintain desired characteristics 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 was the highest ranked characteristic, followed by price and fuel economy. Sound was considered least 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 helped formulate the Wisconsin team's goal of designing a cost effective snowmobile with good handling and fuel economy while also being environmentally friendly.

Engine Selection

Taking into account the results of the market survey, with high value on handling, price, and fuel economy, the team searched for engines with good fuel efficiency at a low cost. The team also considered engine sound and engine out emissions to successfully fulfill the design objectives of the Clean Snowmobile Challenge. The team considered the following engine options:

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

Engine Option Evaluation

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 team's knowledge, no head to head studies have been funded 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 [2]. Outside of the three pollutants measured for competition scoring, direct injection two-stroke spark ignition engines are known emitters of benzene, 1,3-butadiene, and gas/particle-phase polycyclic aromatic hydrocarbons; all are classified as known or probable carcinogens by the U.S. Environmental Protection Agency (EPA) [3].

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, and also 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 select the powertrain option they would rather 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.

Final Selection

Due to the Clean Snowmobiles Challenge's emphasis on emissions, the team compared three of the leading snowmobile engines for low emissions as shown in Table 2. Using the data collected from the market survey, the team focused on the fuel consumption, 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. The third option considered was 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. When coupled with an optimized catalytic converter, high CSC E-Scores can be achieved.

While all engine options fulfill current EPA emissions requirements, the stock ACE 600 and 900 engines "set new standards in efficiency" providing an advantage as fuel economy plays a fairly large role in the CSC [4,5]. 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 implementation of 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. The stock ACE 600 and ACE 900 both feature the use of an electronic throttle body (ETB), a device used by the Wisconsin team since 2009. Directly comparing these two engines, the team found several drawbacks to the ACE 900 including, increased weight, fuel consumption, and cost. The combination of these drawbacks made the ACE 600 the power plant of choice for the Wisconsin team.

Engine Simulation and Optimization

Prior to the 2016 competition, the team used a 1-D model to evaluate options for increasing the power output of the ACE 600. Three main techniques to increase the indicated power of an engine include: operating at higher engine speeds, increasing engine size, and raising cylinder pressure [6]. Many systems exist to increase the cylinder pressure for power improvement such as turbochargers and superchargers. The additional weight, plumbing complexity, cost, and potential for decreased efficiency create drawbacks for these systems. Increasing engine speed would result in degraded engine efficiency due to increased friction loss, moving away from peak engine torque. Also, greater engine speeds would require the team to redesign the clutching and transmission system. For these reasons, the team elected to increase the engine displacement to attain performance improvements from the ACE 600. Altering the displacement of the ACE 600 would increase the power and torque output while maintaining the ideal lightweight, fuel efficient package in comparison to the larger ACE 900.

The team utilized Ricardo Wave to develop a 1-Dimensional model of the ACE engine. This allowed for quick evaluation of various designs along with optimization of the engine displacement increase. The stock bore and stroke of the ACE 600 is 74 mm by 69.7 mm. The team evaluated several designs which modified 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 constraints 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.

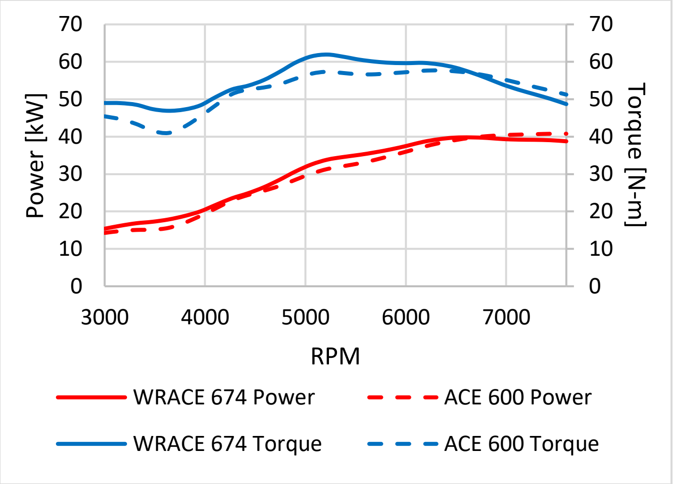

Figure 1. Torque and power curves for the stock ACE 600 and optimized WRACE 674 engines simulated with a Ricardo Wave model.

The team preformed dynamometer testing to validate the simulation results. Figure 2 compares experimental results of the stock ACE 600 torque and power curves to the WRACE 674. The data confirms the Ricardo Wave model results as the team recorded 35kW peak power and 55 Nm peak torque.

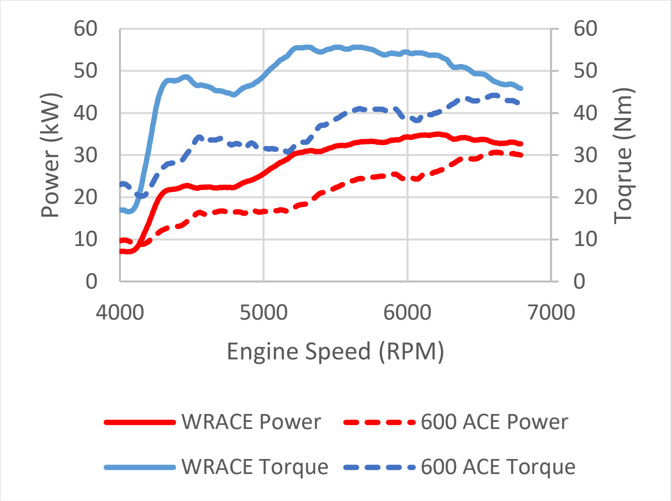

Figure 2. Experimental dynamometer torque and power curves for the stock ACE 600 and optimized WRACE 674 engines.

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's implementation of the stock intake and exhaust camshafts.

Dynamometer testing of the 2015 turbocharged ACE 600 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, 7.8% of the engine's power, at 6000 RPM during the 2015 CSC. By eliminating the turbocharger, different exhaust and catalyst designs were considered 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 2017 competition sled.

Powertrain Enhancement

The stock Rotax ACE 600, shown in Figure 3, is a highly efficient engine featuring diamond like carbon coatings on the surface of the tappets and a magnesium valve cover, sealed by rubber gasket to reduce friction losses and radiated noise, respectively [5]. While this did not leave much room for improvement, the Wisconsin team still found aspects of efficiency, power, and fuel economy to improve.

Figure 3. The stock Rotax ACE 600, showing the integrated oil cooler.

Boring and Stroking

The team specified the change in the crankshaft stroke, which was limited by the clearance in the stock block, including an integrated windage tray in the casting. Increasing the crank throw by 3 mm would leave a 0.5 mm clearance in the windage tray. With the new stroke set at 75.7 mm, analysis moved toward bore dimensions. The analysis indicated a 'square' (stroke=bore) engine provides excellent low-end torque and fuel efficiency in operation conditions typical for snowmobile trail riding.

The next stage of the engine design was to determine whether available aftermarket pistons could be modified to suit the design, or if the team would have to request custom pistons. Wiseco is one of the world's largest aftermarket piston manufacturers and sells forged pistons. Forged pistons have better mechanical properties than cast pistons (the stock ACE pistons are cast). Specifications required for the piston to fit Wisconsin's new bored and stroked engine included: a higher wrist pin location and a shorter skirt to ensure the piston would be confined to the original bore of the engine.

Wisconsin determined that Wiseco had two piston diameters, 75mm and 76mm, that were candidates for the ACE 600 modifications. Upon consultation with Nigel Foxhall, Director of Advanced Engineering at BRP-Powertrain GmbH & Co KG, the team was provided the original piston liner details – indicating that boring the engine block for 76 mm piston would 'thin' the original cast iron sleeves beyond common engineering practices. The Wisconsin team reviewed the available Wiseco information for 75 mm pistons. After identifying the 3 best potential pistons, Wisconsin placed an order for further analysis in house. It was determined a 75 mm piston designed for a Honda CBR954RR met almost all of Wisconsin's criteria while allowing the utilization of stock connecting rods.

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 mimicking the stock ACE piston. Figure 4 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 dimensions for the modified piston compared to the stock piston are shown in Table 4.

Figure 4. 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 the desired bore diameter of 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.

Inspecting the 2016 WRACE 674 after competition it was found the wrist pin offset for the selected pistons were install in the opposite direction required to balance out the inertial forces. This was due to the selected CBR pistons having intake valve relief pockets 180 degrees off from the stock ACE pistons. For the 2017 WRACE 674 the exhaust valve pockets were machined to make room for the intake valves correcting for the wrist pin offset.

After finalizing the piston, valves, bore, and crankshaft, the team calculated the theoretical compression ratio using a stock ACE 600 head gasket. It was determined that the compression ratio was 13.8:1, higher than desired. The team contacted Cometic gaskets to acquire a copper head gasket to desired specifications. The custom copper gasket was 1.27 mm (0.050 in) thick and installed with appropriate adhesive, resulting in a new WRACE 674 final compression ratio of 12.05:1. This design provides Wisconsin the ability to readily modify the engine compression ratio by 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 airflow 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 5. 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.

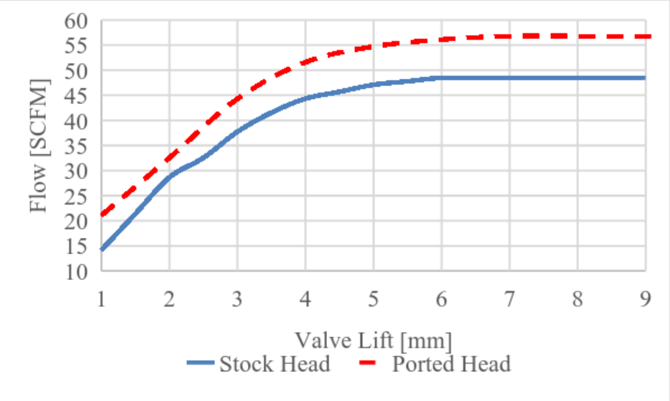

Figure 5. The exhaust ports of the ported head compared to the stock head. The ported head shows flow improvement across the valve lift profile.

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 reduces part load throttle losses by operating at the optimal airflow angle. Also, the ETB compensates the amount of flow required when adding exhaust gas to achieve desired equivalence ratio.

In addition to using the ETB, the team implemented a mass airflow (MAF) sensor, manifold absolute pressure (MAP) sensor, and dual NO_x/O_2 sensor, relayed directly to the Motorola Engine Control Unit (ECU). The combination of sensors enabled the team 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. In order to monitor real-time engine NO_x emissions, and implementation of a closed loop fueling algorithm based on exhaust oxygen content, the team installed a heated Continental Smart NO_x sensor. The sensor measures NO_x and oxygen content from the engine's exhaust stream, allowing for engine tuning and calibration.

During the initial calibration process, Bosch LSU 4.9 wideband oxygen sensors were installed into each exhaust header to monitor individual cylinder A/F ratio, with an additional oxygen sensor placed later in the exhaust stream to control the global fueling. During the calibration process, it was discovered that a global fuel command was not sufficient for individual cylinder A/F ratios. Cylinder 1 A/F ratio would often run rich while cylinder 2 A/F ratio often lean. After simulation, the team discovered an imbalance in the air flow in cylinder 1 versus cylinder 2 due to the odd-fire dictated by the opposed piston crankshaft balancing choice. It was also found there was a significant pressure difference between each cylinder, shown in Figure 6.

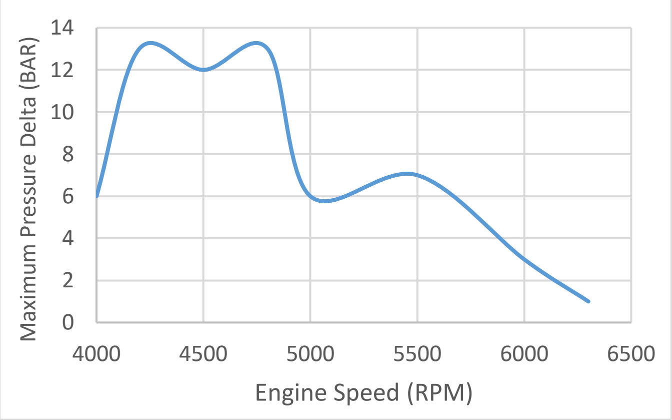

Figure 6. Simulated cylinder to cylinder pressure difference.

It was determined that each cylinder would require an individual fueling command to ensure a stoichiometric A/F ratio. With the improved fueling, lower tailpipe emissions and increase efficiency could be achieved. The dual oxygen sensor strategy allows cylinder 2 fuel command to vary ± 0.1 phi of the cylinder 1 fuel command in order to achieve an A/F ratio of 1. This strategy also allows for either oxygen sensor to be the exhaust feedback for the fueling command. If either oxygen sensor becomes invalid, or is reading out of the acceptable value range, the controller will automatically select the oxygen sensor reading correctly to execute the global fuel command. The dual oxygen sensors decrease tailpipe emissions while also adding redundancy.

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 7, that the engine must be calibrated to operate within.

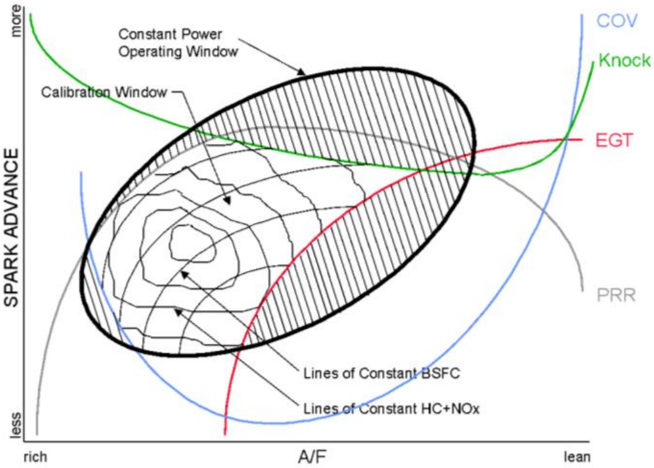

Figure 7. Graph of typical calibration window [6].

Calibration of the 2017 engine shown in Figure 8 was performed using a water-brake dynamometer, wideband oxygen sensors, and exhaust thermocouple probes in conjunction with Optrand spark plug pressure transducers and ¼ degree resolution shaft encoder. By monitoring torque, exhaust temperatures, peak cylinder pressure, fuel flow, and A/F ratio values, spark timing and fueling were properly calibrated. Utilizing a pressure trace, as shown below in Figure 9, in conjunction with fuel flow measuements, spark advance was prcisely calibrated to ensure low BSFC, high heat release rate, Maximum Break Torque (MBT), and low tailpipe emissions

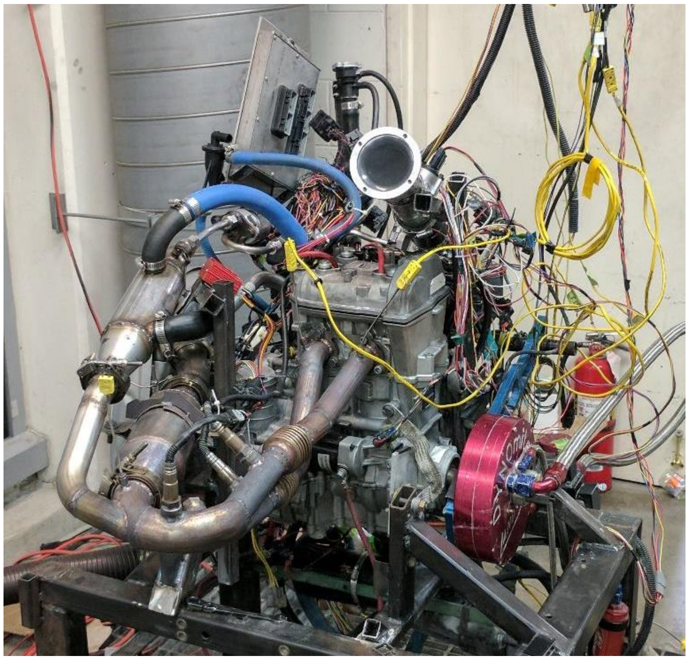

Figure 8. Dynamometer testing stand used for all calibrations.

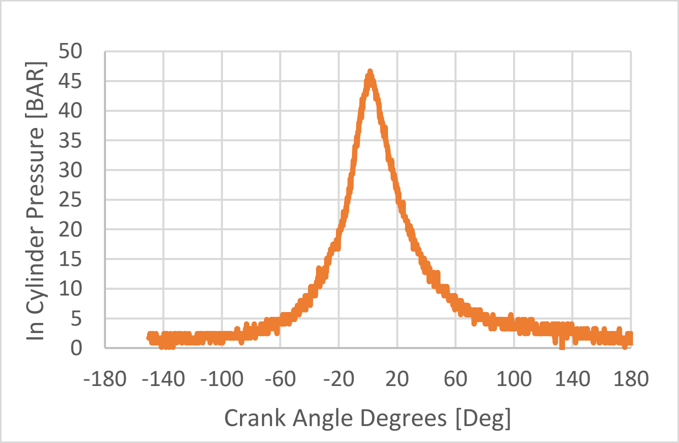

Figure 9. Average in cylinder pressure at Emissions Mode 3.

Exhaust Gas Recirculation

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

EGR is primarily used for the reduction of NO_X emissions by recirculating a fraction of the exhaust gas through a 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 [6]. 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 [8, 9]. For these reasons, the team also designed an optimized EGR cooler for further emission reduction.

EGR 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 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. Highest priority was placed on the valve flow rate, a Delphi EG10176 EGR valve, shown in Figure 10, was selected. A flow rate of 16.1 kg/h was 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.

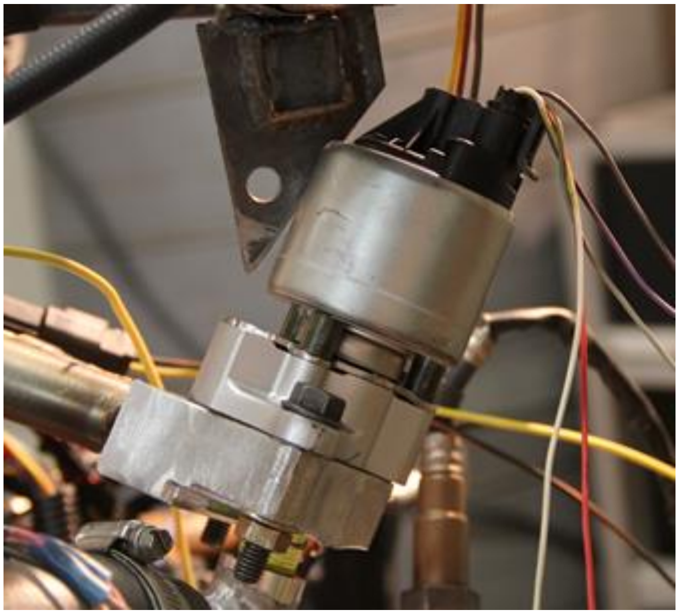

Figure 10. The Delphi EG 10176 EGR valve used to reduce oxides of nitrogen emissions by lowering peak combustion temperatures.

EGR Cooler Design

Once it was decided to utilize an EGR cooler, the team developed the following EGR cooler criteria:

1. Maximum diameter of 76 mm
2. Maximum length of 178 mm
3. Cooling capacity of 3 kW
4. Utilize engine coolant

Due to the limited number of engines smaller than 1 liter running EGR, there were no widely available air to water coolers that met the team's requirements. The options 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 started 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 11. The 'rough' surface increases the contact area and creates turbulent flow, significantly increasing heat transfer rates.

Figure 11. 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.

In order to optimize the cooling capacity in the available space, the team analyzed the correlation between internal tube quantity and effectiveness. The effectiveness of the cooler versus the number of tubes was considered as shown in Figure 12; it can be seen that there is minimal change after 15 tubes as effectiveness approaches 100%.

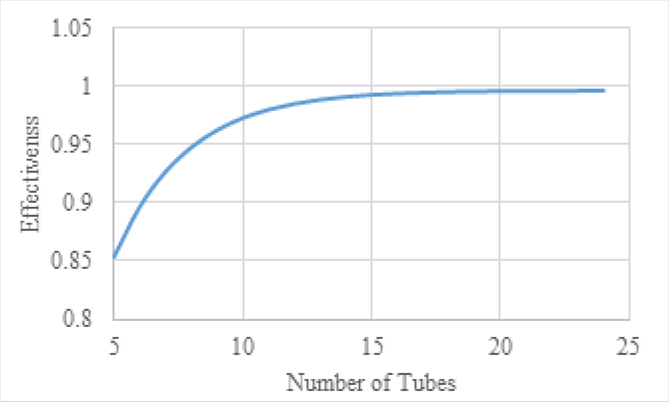

Figure 12. The effectiveness of the cooler reaches within 5% of its maximum effectiveness by approximately 8 tubes.

With the 2015 MXZ Sport chassis and new designs, the team acquired enough space under the hood to implement an optimized EGR cooler utilizing 16, 9.53 mm (0.375in) diameter tubes. The final design, shown in Figure 13, shows the 16 tube layout in the newly optimized EGR cooler before it was welded into its shell. The cooler fits into a 76 mm diameter by 178 mm length tube and attains up to 99% effectiveness. This design resulted in consistent EGR temperatures of 60 degrees Celsius and below.

Figure 13. The 16 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.

NOx 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 intake air ingested by the engine. The team evaluated EGR rates of 0%, 6%, and 12% of the intake air across the RPM range as shown in Figure 14.

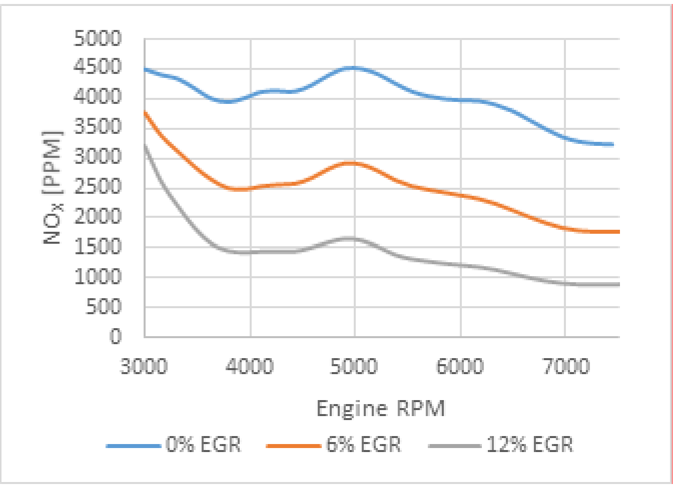

Figure 14. Simulated engine out NO_X of the WRACE 674 using volumetric percentages 0%, 6%, and 12% EGR.

In order to validate both the computer model predictions and the effectiveness of the valve and cooler system, the team used a Continental Smart NO_x sensor during calibrations to collect data at theoretical competition emission mode points. At each mode point, the EGR valve duty cycle was adjusted to determine the correlated NO_x emission change. Figure 15 displays the effect of EGR from the team's dynamometer testing.

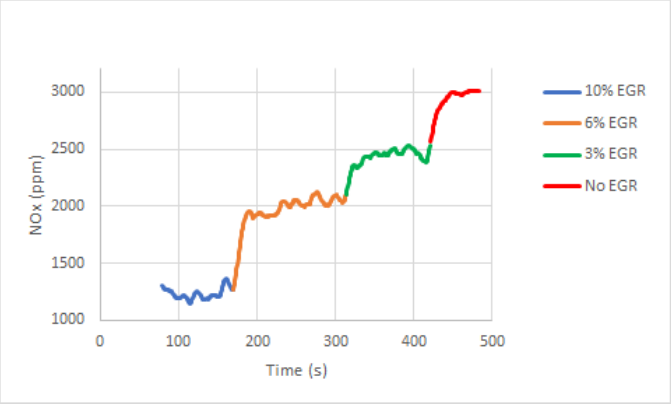

Figure 15. Recorded NO_x emissions at the team's estimated mode 2 at various EGR percentages. Data was recorded while running non-oxygenated 91 octane fuel.

The team used the NO_x emission data collected during calibration to select appropriate EGR valve duty cycles to run. During calibration, the team monitored NO_x emissions and torque the WRACE 674 produced based on the applied duty cycle. The team's goal was to attain peak NO_x reduction while negligibly effecting torque output. Taking the results into consideration, the team decided to run no greater than 0% EGR for mode 1, 10% at modes 2 and 5, and 15% at modes 3 and 4.

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 may 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, cold start conditions, and provides 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 affecting performance and emissions, modifications to the fuel delivery system were necessary. The fuel injectors were 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

A consequence of increased fuel flow is the requirement of a larger fuel filter and fuel pump. 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 [8]. 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 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 2017 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. Focusing on HC, CO, and NO_x emissions, a three-way catalyst was implemented before the muffler to effectively reduce targeted species.

To fully optimize the precious metal washcoat, exhaust gas was collected before the muffler 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 24.7 g/ft^3
	Palladium 45.2 g/ft^3
	Rhodium 4.1 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 16 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].

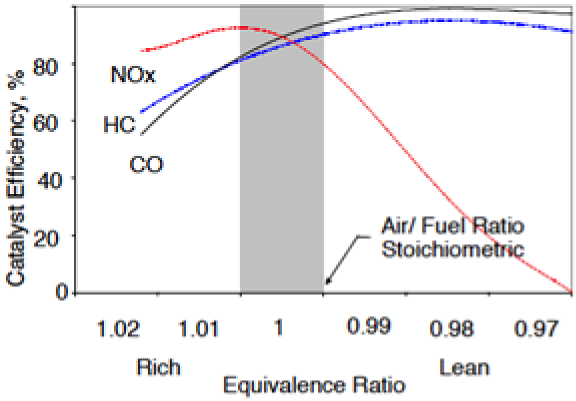

Figure 16. Shows the NO_X, CO, and HC conversion efficiency for a three-way catalytic converter as a function of exhaust gas air/fuel ratio operating on gasoline (Adapted from [6]).

This lean-to-rich oscillation of the engine is controlled using the team's closed-loop fuel trim algorithm, maximizing emission reduction. The fluctuations in the oxygen sensor output, in addition to the fueling multiplier are shown below in Figure 16. In this area of engine operation, the base calibration is slightly rich, probably due to atmospheric conditions, so the emissions control algorithm has adjusted the fuel multiplier to oscillate around a fuel- air equivalence ratio of 0.96.

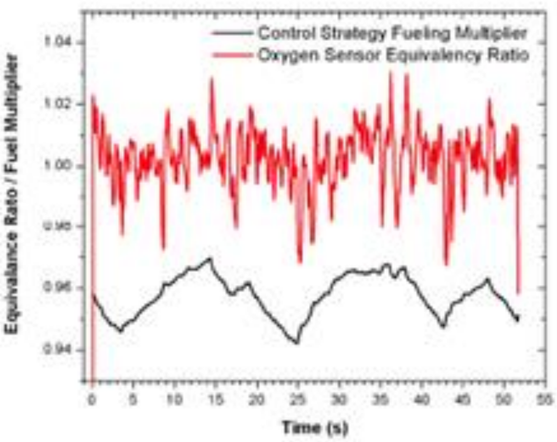

Figure 16. Engine equivalence ratio oscillating near stoichiometric as a result of closed-loop control.

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 target exhaust oxygen content. From there, the closed loop fuel trim algorithm, which utilizes the heated wideband oxygen sensor, is activated and 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 17.

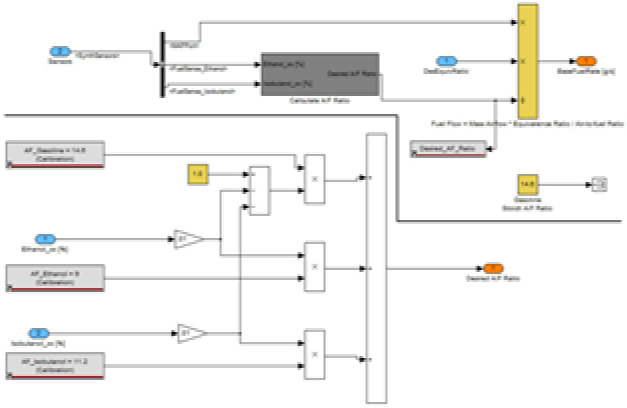

Figure 17. Simulink block diagram for flex-fuel and iso-butanol engine control strategy.

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 2017 CSC entry is experimentally estimated to be 205.4. Table 7 shows projected 2017 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)	12.6	90
HC (g/kW-hr)	0.228	8
NOx (g/kW-hr)	1.961	N/A
E-Score	205.4	190

Sound Reduction

The Ski-doo MXZ Sport ACE 600 is marketed as being considerably quieter than most snowmobiles. This was taken into consideration when Wisconsin team started looking into muffler designs. After weighing the benefits of designing a custom muffler versus modifying Ski-doo's already quiet muffler it was decided to make modifications to the stock muffler. The inlet tubes were modified to allow for a v-band connection to the catalytic converter while maintaining the stock visual appeal with minimal manufacturing requirements.

The team also tested the natural frequency of the tunnel and compared the values to the engine's operating speed when the sled is rode at a steady 35 mph, mimicking the competition sound testing procedure. It was found the tunnel frequencies were orders of magnitude higher than that of the engine, removing the need for tunnel dampeners used in previous iterations of the Wisconsin entry in the CSC. The sled sound output was also measured using the competition procedure and found to be a quiet 66.2 dB.

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 components that replaced stock parts were 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 $11,145.63 the 2017 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 be only approximately $1500 greater than today's stock MXZ Sport ACE 600 configuration.

Conclusions

The 2017 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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Acknowledgments

The team also thanks its many sponsors, especially the Wisconsin Corn Promotion Board, the United Wisconsin Grain Producers and Ford Motor Company for their extensive support. Additional thanks go out to National Instruments, Mototron Control Solutions, Continental Emitec GmbH, W.C. Heraeus GmbH, 3M, Camoplast, Continental ContiTech, Polaris Industries, Bombardier, Rotax, Castle Racing, Snap-On, Milwaukee Tool, C3 Powersports, Mirco-Track Systems, Ecklund's Motorsports, Cometic Gaskets and Wiseco for supporting the team with the best available products. The team also wishes to thank the students and instructors at the Madison Area Technical College for the graphics and Jonco Industries for sponsor logos. Recognition is also due to Tom Wirth for his assistance and expertise on engine modifications and Eric Gore for his expertise on porting heads.

The team would also like to thank their advisors Ethan K. Brodsky and Glenn R. Bower. When it comes down to crunch time, their assistance is often overlooked but without their expertise, commitment of time, enthusiasm, and willingness to teach, this project would not have been possible.

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
MBT	Maximum Brake Torque
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