Starting Reliability, Run Quality Improvements and Sound Reduction of the WRACE 674

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Abstract

For 2018 the University of Wisconsin's Clean Snowmobile team improved upon the cleanest entry to the 2017 competition: the WRACE 674. With a 2015 Ski-Doo MXZ Sport chassis containing a Rotax ACE four-stroke engine bored and stroked to 674cc, the core design appears similar. Despite this, the 2018 entry is anything but the same, with a dampened tunnel that lowers its natural frequency amplitude by 50%, a fundamentally improved EGR cooler and a plethora of improved control and calibration tactics. The 2018 design features a power output of over 35 kW coupled with improved emissions, a quieter ride, more reliable starting and the most affordable MSRP Wisconsin has provided in years, with a cost of only $10,717.69. The result is a snowmobile which satisfies all aspects of the SAE Clean Snowmobile Challenge while still appealing to consumers.

Innovations

Analyzing the results from the 2017 SAE Clean Snowmobile Challenge, it was clear the University of Wisconsin clean snowmobile team had room for improvement. The team focused on four principal areas for improvement in the 2018 competition entry:

- Sound
- Cold Starting Reliability
- Engine Cooling
- Emissions

Research, development and testing in these areas led to innovation both in components and controls/calibration. The innovation section of this paper is divided into two primary sections: components and controls.

Components

Tunnel Noise Reduction

The two main sources of sound from a snowmobile are engine noise and track/chassis noise. To reduce track and chassis noise, the Wisconsin team looked to attenuate the resonating frequencies by investigating the benefits of LizardSkin® Sound Control. LizardSkin® Sound Control is a spray on coating which claims to dampen noise by reducing the vibration off of the coated surface. The team tested and analyzed the resonance frequency and amplitude of the uncoated stock 2015 MXZ Sport tunnel. To isolate the tunnel, the snowmobile was suspended in the air with the track, suspension and engine removed. Vibrations were induced by applying a consistent strike to the outside of the tunnel. Vibrational data from an accelerometer attached to the tunnel was captured in the time domain on an oscilloscope. Using Matlab, a Fast Fourier Transform (FFT) was applied to convert the time-based data to frequency based allowing for analysis of the amplitude of the tunnel in the frequency domain.

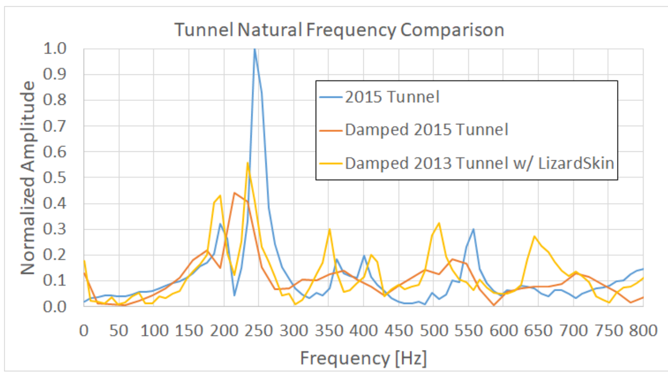

Figure 1: Normalized tunnel frequency amplitude comparison of damped and undamped 2015 chassis and dampened 2013 chassis

This test was then repeated with the team's 2013 MXZ Sport chassis, a year in which the team tried reducing the noise from the tunnel by adding

LizardSkin®. The amplitude of the natural frequency of the 2013 chassis was half of the undamped 2015 chassis. Next, the team added temporary dampening to the inside of the 2015 tunnel similar in thickness to the LizardSkin® on the 2013 chassis. The analysis of the three natural frequencies is shown in Figure 1. The addition of dampening to the 2015 chassis reduced the amplitude to roughly the value of the 2013 chassis and shifted the fundamental frequency from 244 Hz to 214 Hz. Dampening the resonance reduces the amplitude of the tunnel, which sits roughly three times higher than the engine frequency. Once the team confirmed the 2015 chassis reacted similarly to the 2013 chassis, the decision was made to apply LizardSkin® to the tunnel as shown in Figure 2. Clearly it was a mistake for the Wisconsin team to forego applying LizardSkin® to the tunnel in 2017 when the chassis change first occurred.

Figure 2: View of tunnel underside lined with Lizard Skin material

EGR Cooler

Since the Wisconsin team designed and fabricated an EGR Cooler for the 2016 CSC the snowmobile had experienced engine cooling issues. The student-fabricated cooler was initially designed as a countercurrent heat exchanger, which is a theoretically more efficient design [1].

However, in implementing this heat exchanger configuration, the team did not consider the possibility of coolant boiling due to the extremely high temperature of the incoming exhaust gas. While the bulk flow of the coolant within the cooler is turbulent, there is still a laminar film of coolant around each tube of the heat exchanger caused by viscous forces. Within the laminar sub region, the velocity of the fluid is slowed significantly. This slow flow combined with the large temperature difference was postulated to have caused film boiling. In turn, rapid expansion of coolant occurred and caused an overflow from the coolant reservoir. As a result, the theoretical efficiency from the counterflow design was lost.

After looking into industry cooler designs, the team realized parallel flow coolers were being used for the reasons stated above. This design allowed for the largest temperature difference at the inlet of the engine exhaust gas. While the laminar region near the heat exchanger tubes is unavoidable, the parallel flow heat exchanger allowed for the largest delta temperature preventing the coolant from boiling. This modification to the EGR cooler provided a stable, reliable cooling system for the Wisconsin team.

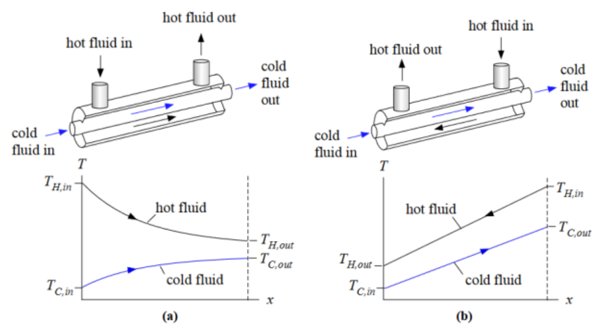

Figure 3: Operational characteristics of counterflow and parallel flow heat exchangers [1]

Controls

Cold Starting

The focus for 2018 control and calibration improvement was starting reliability. Last year's entry to the competition failed the cold start event and failed to start in time to make it to the acceleration event, causing an estimated loss of up to 80 points in the competition. This concern was addressed through repeated cold start testing starting the first week of January when ambient temperature dipped below -10°C. CAN data on parameters such as spark advance, fueling and many others were recorded and analyzed, which eventually led to calibration changes to improve cold start. More specifically, a new ethanol percentage based fueling modifier table was added to the software allowing additional fuel to be provided during cranking to compensate for ethanol's lower air-fuel ratio (AFR) for optimal combustion relative to gasoline [2]. This new code branch is pictured below in Figure 4.

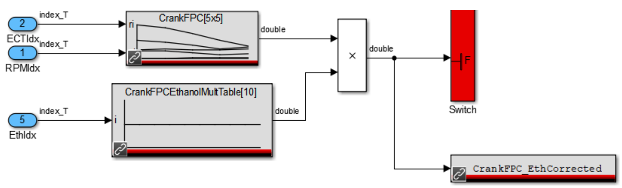

Figure 4: Ethanol based crank fueling multiplier code block

Idle RPM Control

During the process of improving crank fueling for a more reliable cold start, a few problems with the calibration were noticed and subsequently corrected. Most notably, the idle RPM governor, which is an electronic control strategy that adjusts spark advance to stabilize engine idle RPM at a desired setpoint of 2000 RPM, was not operating as expected. As shown in Figure 5, the idle RPM was somewhat unstable, as it varied by a value of ±200 RPM.

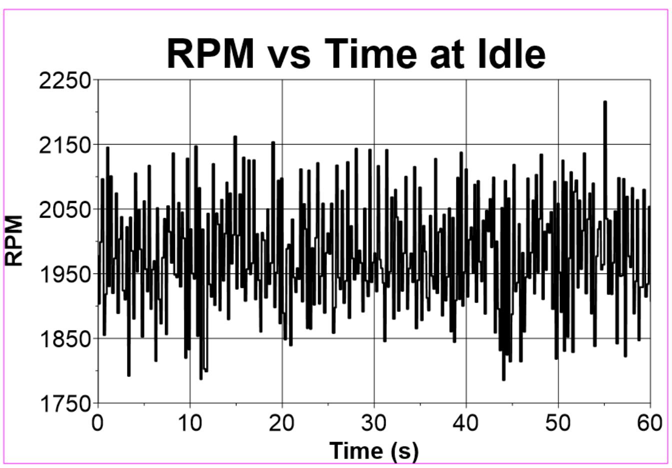

Figure 5: Engine Speed (RPM) at idle over 60 s run time

Upon further investigation, it was observed the cause of this RPM surge was the idle spark advance proportional and derivative (PD) controller. More specifically, the P and D gains were set so high that the system became unstable, and spark timing was rapidly oscillating between its limits of +10 degrees before top dead center (BTDC) and -12.5 degrees BTDC, which can be seen below in Figure 6.

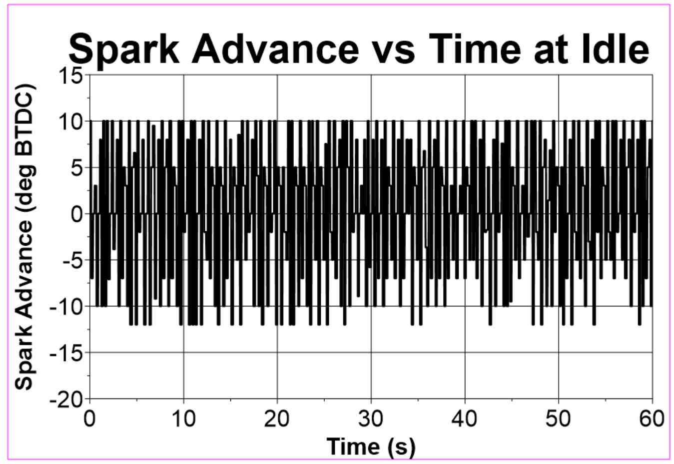

Figure 6: Spark Advance (degrees BTDC) at idle over 60 s run time

To alleviate this issue, these gain values were re-calibrated to provide a stabilized system which could still respond to disturbances in engine speed. Once adjusted, the new idle varied by only +/- 50 RPM at idle, as picture in Figure 7.

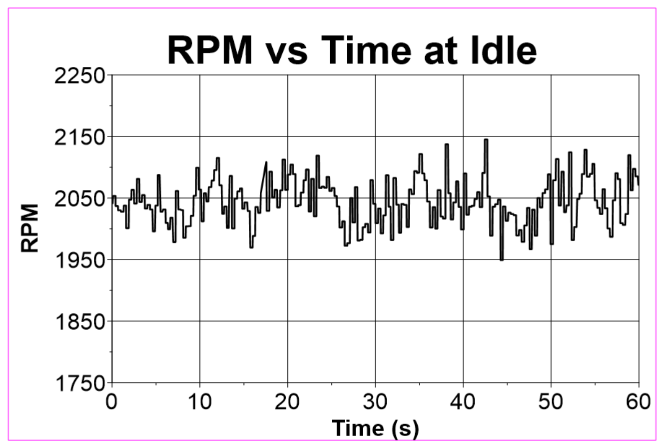

Figure 7: New spark PD controlled idle engine speed in RPM over 60 s run time

To test the responsiveness of the system, various tests were run, including rapidly opening and closing the EGR valve and observing the controller response. Figure 8 shows the spark controller still has enough authority to compensate for these disturbances and keep engine RPM from wandering too far from the desired setpoint. At roughly 25 seconds, the EGR Valve was rapidly opened, causing a sudden drop in RPM. The idle controller increases the spark to increase engine speed and bring the RPM back to its setpoint. Once the setpoint is reached, the spark advance returns to a normal level.

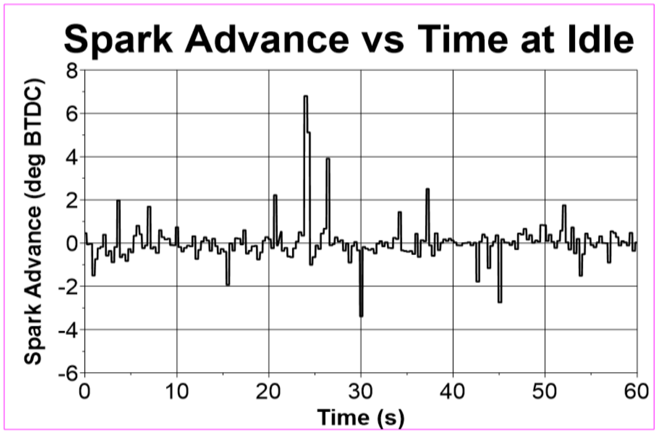

Figure 8: Spark Advance response to rapid EGR Valve Movement over 60s run time

EGR Startup Delay

Data logs from cold starts also presented another interesting issue with the snowmobile. Occasionally after sitting outside overnight and then cold starting, the engine speed would drop by almost 800 RPM while idling. This phenomenon happened roughly 100 seconds after starting, and after analyzing multiple data logs, the root cause of the issue was found. The EGR valve was set to a 10 second delay on startup, but after this time passed and EGR was enabled, the valve would not open to its desired idle setpoint. After the engine coolant temperature (ECT) reached a certain level, usually around 30°C to 40°C, the valve position would then overshoot its setpoint by over 160% before settling back in, as can be seen in Figure 9.

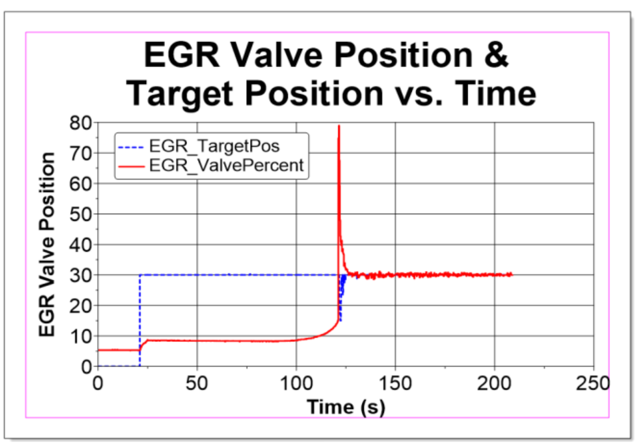

Figure 9: EGR Valve Position and Target Position while idling after a cold start

Using data analysis and engineering judgment, it was deduced that condensation in the exhaust was freezing the valve in place overnight, and the EGR Valve PID controller was reaching its maximum output to drive the valve to its desired setpoint. More specifically, this phenomenon was a case of I-term windup caused by a mismatch between the idealized model and the non-ideal behavior of the system after being kept outside overnight. Once the engine reached a high enough temperature for the valve to break free, the controller drove the valve to overshoot before bringing it back to the setpoint. To eliminate this issue, an ECT based EGR valve delay was created in the engine code as shown below in Figure 10. This delay was then calibrated to a desired ECT allowing the valve to thaw before attempting to open it.

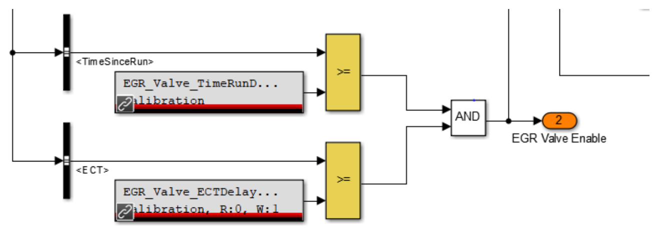

Figure 10: New branch of Simulink engine code containing ECT based EGR valve delay

Team Organization and Time Management

The University of Wisconsin-Madison joined SAE in 1939. The Clean Snowmobile Team formed in spring of 2001 and competed for the first time in Yellowstone in 2002 under the advisory and mentorship of Glenn R. Bower and eventually Ethan K. Brodsky, who started as a fellow student and participant at the competition. The team has competed in the Internal Combustion class at the Clean Snowmobile Challenge since its formation and the Zero Emission class from 2008-2011. The Wisconsin team is led by James Gerdes and Andrew Wild, who double as the electrical and calibration leads, respectively. Underneath the team leaders, Matthew Massman led mechanical and emissions projects. Some major projects and their timelines are shown in the Gantt chart in the Appendix.

Outside of working on the snowmobile, the University of Wisconsin team organizes and participates in many fundraising, team building and community events. Every year the University of Wisconsin SAE organization participates in the SAE

Milwaukee Chapter meetings to present their designs and accomplishments. The team is also awarded donations from the SAE during the event. Furthermore, the team annually presents the previous year's results to a major team sponsor the United Wisconsin Grain Producers. The team also gave tours to other major sponsors, like Magna, Milwaukee Tool, Snap-On Tool, Mercury Marine, Chrysler, and Ford Motor Company.

In a community outreach event before a Wisconsin Badgers' football game, where the team encouraged and educated the use of biofuels to the public. The team interacted with the student body and community through various University of Wisconsin wide and College of Engineering specific events. At the beginning of the fall semester, new members are recruited through Engineering Bash, the College of Engineering's organization fair. Also, the Engineering Expo is held on campus, where the snowmobile is displayed to the public. It is a great opportunity for children to learn about snowmobiles and internal combustion engines. Other public events that the entire SAE organization on campus displays the vehicles are at the Homecoming Parade and Badger Bash. Finally, various team events are organized outside of the shop to give opportunities for team bonding.

Current Snowmobile Build

- Chassis: BRP, Ski-doo MXZ Sport, 2015
- Engine: Rotax ACE 600 (Bored and Stroked to 674 cc) 4-stroke, gasoline, 47.4 hp (experimentally recorded on water brake Dynamometer)
- Track: Camso Ripsaw II
- Muffler: Manufacturer
- Catalytic Converter: Emitec Continental
- Skis: Stock
- Exhaust Gas Recirculation Valve: Delphi EG10176
- Exhaust Gas Recirculation Cooler: Custom Fabricated
- Injectors: Bosch EV-14-KT
- Battery: Renegade RG20L-BS
- Electronic Control Unit: Motorola PCM565 using Woodward Operating System

Engine Selection

Heavy consideration was put into engine sound and engine emissions to successfully fulfill the design objectives of the Clean Snowmobile Challenge. The team considered currently available two-stroke and four-stroke snowmobile engines.

Engine Option Evaluation

It is well known that two-strokes have higher power-to-weight ratios than current four-stroke models. However, two-stroke engines also produce greater amounts of HC and CO emissions. On average, two-strokes emit ten times as much HC, and two times as much CO as their four-stroke counterparts [3]. 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) [4].

Final Selection

After comparing two-stroke engines to four-stroke it became apparent that a four-stroke engine better suits the goals of the Wisconsin team. From there the team chose to refine the search to only four-stroke engines. Table 2 shows the three four-stroke engines the team seriously considered for their final selection and compares them to one of the lowest emitting two-strokes. The team focused on fuel consumption, power, and weight of each engine when making the final decision.

Table 2: Engine Comparison of Leading 4-Stroke Snowmobiles [3]

Base Engine	Power (kW)	Weight (kg)	Fuel Economy (km/L)	Emissions (g/kW-hr)		
				HC	CO	NO_x
Ski Doo ACE 600	42[1]	41.1	12.5	6	90	N/A
Ski Doo ACE 900	64.5 [2]	51.8	10[3]	6	75	N/A
Ski Doo 1200 4-TEC	92	60	8.85	8	130	N/A
[4]Polaris 600 Cleanfire	97	35	5.3	60	175	N/A

[1]OEM Reported Power
[2]Sport mode operation
[3]Eco mode operation
[4]Two-Stroke for comparison

While all the engines fulfill current EPA emission requirements, the stock ACE options outperformed their competitors in emissions and fuel economy [3]. The ACE design also allows for integrated engine lubricant and cooling systems, which minimizes weight, complexity, and external plumbing. These innovations made it easier for modification and installation 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

	ACE 600	ACE 900
Engine Type	Four-Stroke	Four-Stroke
Cooling	Liquid	Liquid
Cylinders	2	3
Displacement (cc)	600	900
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

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

The team used a Ricardo Wave 1-Dimensional model to evaluate options for increasing the power output and drivability 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 [2]. 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 when compared to the ACE 900.

Using Ricardo Wave, the team was able to create 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 assessed several designs which modified the bore and stroke dimensions, taking into consideration the geometric constraints of the engine block and crankcase.

The team was able to optimize the stroke of the engine without changing its physical limits, which allowed for the use of the stock crankcase. Sweeps were conducted from 69.7 mm to 75.7 mm, representing the values of the stock stroke to the maximum physical stroke limit. The bore was also swept from the stock value of 74 mm to 76 mm. Combining a bore of 75 mm, while increasing the stroke to 75.7 mm, power and peak torque grew 8.2% and 7.3%, respectively. These changes resulted in a simulated power output of 32.5 kW at 5000 RPM range, as shown in Figure 11.

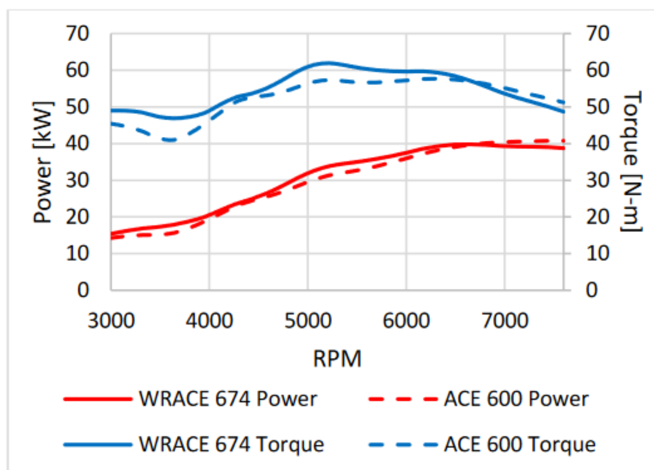

Figure 11: Torque and power curves for the stock ACE 600 and optimized WRACE 674 engines simulated with a Ricardo Wave model

The team ran power sweeps with the final 2018 engine setup and calibration on a water brake dynamometer. Figure 12 displays the results of these tests. The data once again confirms the Ricardo Wave model results as the team recorded 35.3 kW peak power and 53.1 Nm peak torque.

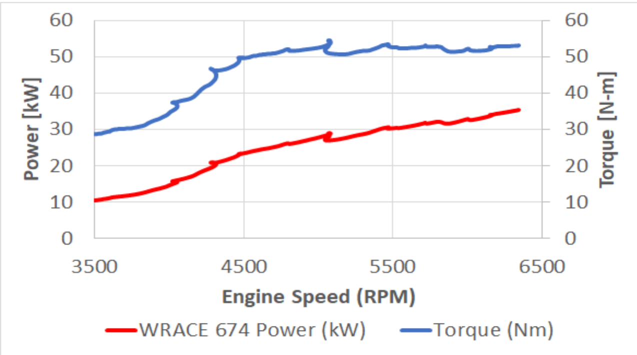

Figure 12: Experimental dynamometer torque and power curves for the optimized WRACE 674 engine

Due to changing the bore and stroke of the engine, the team investigated whether adjustments needed to be made to intake and exhaust camshaft timing. Intake timing was swept by 5 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.

Powertrain Enhancement

The stock Rotax ACE 600 is a highly efficient engine featuring diamond-like carbon coatings on the surface of the tappets and a magnesium valve cover [6]. While the engine was exceptionally designed, areas of improvement were still found. The Wisconsin team sought out to improve efficiency, power and fuel economy.

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. 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 Wisconsin team opted for forged pistons because of their superior mechanical properties over cast pistons. 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. It was determined a 75mm piston designed for a Honda CBR954RR motorcycle and made by Wiseco, met almost all of Wisconsin's criteria while allowing for 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. Additionally, the wrist pin offset was in the wrong direction for the ACE engine, so the exhaust reliefs were machined to fit the intake valves and the pistons were reversed. The Wisconsin team machined the pistons in house to create a two-tiered bowl design shown in figure 13 mimicking the stock ACE piston. The final dimensions of the modified piston compared to the stock piston are shown in Table 4.

Figure 13: Pictured 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

To achieve the appropriate bore diameter, the Wisconsin team provided a calculated bore diameter specification of 75.3 mm, which provided a 'medium' clearance using the stock 600 engine manual criteria, to an advanced engine machinist who then bored the cylinder walls.

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* (g)	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.*

After finalizing the piston, valves, bore, and crankshaft, the team calculated the new theoretical compression ratio using a stock ACE 600 head gasket. It was determined the compression ratio was 13.72:1, which was higher than desired. The team contacted Cometic Gaskets to acquire a new head gasket to reach the desired stock ratio of 12:1 [6]. In 2017, the Wisconsin team used a custom 1.27 mm (0.050 in) thick copper gasket achieving 12.05:1. However, upon going through the engine after the 2017 Clean Snowmobile Challenge, the team found the head gasket had failed. After Cometic informed the team that all copper gaskets will fail sooner or later and very thin clearance between the two cylinders is problematic for copper, the decision was made to switch to a composite fiber gasket with a fire ring to reduce the chances of another failure. Figure 14 compares the stock head gasket with the copper and composite fiber. Unlike the copper gasket, which is known to leak over time, the composite fiber gasket has a natural spring to it. Cometic told us to account for roughly 10% compression when torqued, so the new custom composite fiber gasket was 1.50 mm (0.059 in) before installation. After installation. the new gasket thickness was 1.35 mm (0.053 in), resulting in a new WRACE 674 final compression ratio of 11.97:1.

Figure 14: Pictured from left to right: stock Rotax head gasket, copper head gasket, and composite fiber head gasket with fire ring

Ported Head

To increase airflow, and consequently torque and power output, the stock intake and exhaust ports were hand-ported. 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 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 15. A consistent improvement of 5% to 7% was observed over the entire exhaust valve lift. This led to the decision to use a ported exhaust head on the WRACE 674.

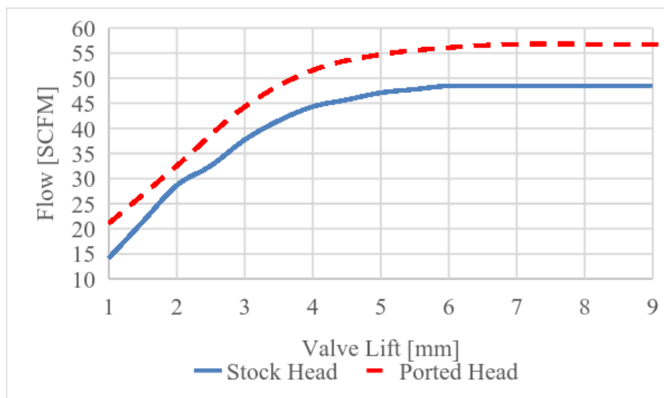

Figure 15: The exhaust ports of the ported head compared to the stock head. The ported head shows flow improvement across the valve lift profile

Calibration and Control

The WRACE 674 currently uses the stock 600 ACE Electronic Throttle Body (ETB) in combination with a mass airflow (MAF) sensor, manifold absolute pressure (MAP) sensor, and dual NO_x/O_2 sensors, relayed directly to the Motorola Engine Control Unit (ECU). These sensors combined with various actuators enable the team to calibrate and control fuel injection and develop a fuel control strategy. Many hours were spent by team members both in past years and in 2017-2018 calibrating the control system and ETB PID controller to optimize it for idle, startup and drive.

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 [7]. These constraints define a window, shown in Figure 16, that the engine must be calibrated to operate within.

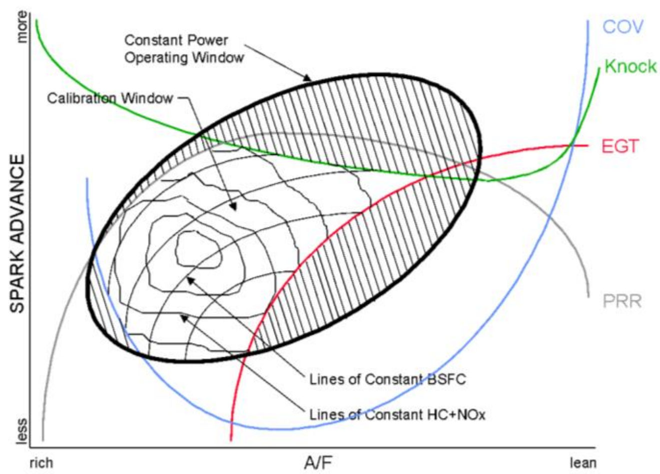

Figure 16: Graph of typical calibration window [2]

Calibration of the 2018 engine shown in Figure 17 was performed using a Land & Sea 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 AFR values, spark timing and fueling were properly calibrated. Utilizing a pressure trace, as shown below in Figure 18, in conjunction with fuel flow measurements, spark advance was precisely calibrated to ensure low BSFC, high heat release rate, Maximum Brake Torque (MBT), and low tailpipe emissions.

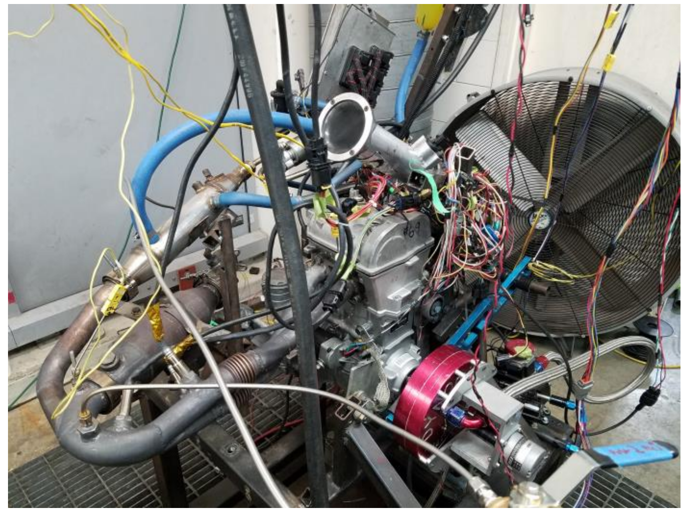
Figure 17: Dynamometer testing stand used for calibrations

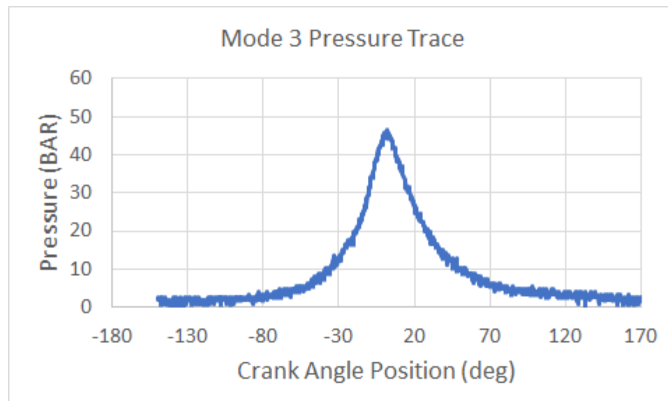

Figure 18: In-cylinder pressure at emissions mode 3

Exhaust Gas Recirculation

The Wisconsin team chose to implement an exhaust gas recirculation (EGR) system to further minimize nitrogen oxides (NO_X), by returning a fraction of the exhaust gas back into the intake system. NO_X is formed at high combustion temperatures by the dissociation 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 [2]. Studies have shown 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

16 “rough” surface inner-tube EGR cooler for further emission reduction, shown in figure 19. The cooler was paired with a Delphi EG10176 EGR valve. Flow bench testing was done which showed the valve was capable of providing 16.1 kg/h of EGR. Under normal operating temperatures this system was able to provide exhaust gas at a consistent temperature of 55 °C.

Figure 19: The sixteen 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

The aforementioned Ricardo Wave model can also be used to model an EGR system. To obtain a benchmark idea of what the EGR system was capable of, the model was used across a range of EGR percentages and a range of RPM.

The team validated the computer model predictions and the valve/cooler system effectiveness, using a Continental Smart NO_x sensor during calibrations to collect data at CSC lab emission mode points. At each mode point, the EGR valve duty cycle was adjusted to determine the correlated NO_x emission change. Figure 20 displays the effect of EGR from the team’s dynamometer testing.

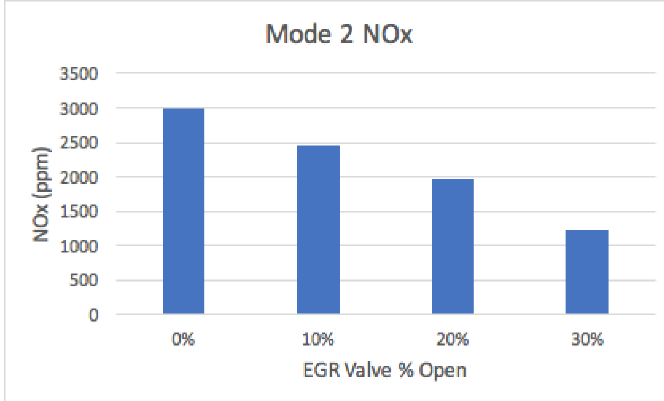

Figure 20: Recorded NO_x emissions in the team’s estimated Mode 2 at various EGR percentages, recorded while running non-oxygenated 91 octane fuel

The team used the NO_x emission data collected during calibration to select appropriate EGR valve duty cycles to test. During calibration, the team monitored NO_x emissions and torque being produced based on the applied duty cycle. The team’s goal was to attain peak NO_x reduction without a noticeable reduction in torque output. With these points in mind the team decided to use the valve position shown in Table 5. At the chosen EGR position from Table 5, the Mode 2 NO_X emissions were lowered by 1450 ppm, resulting in a potentially higher CSC E-score.

Table 5: Shows EGR valve position at CSC lab emission points, optimized to minimize NO_X while maintaining torque

Mode	1	2	3	4	5
EGR Valve Position	0%	25%	45%	50%	30%

Control Hardware

The Wisconsin team currently utilizes a Motorola PCM565 ECU embedded with a Simulink based Motohawk operating system designed by Woodward Inc. This controller has a total of 128 pins, including 34 analog inputs, 8 digital inputs, 24 low side driver power outputs, 16 logic level outputs and a dual CAN 2.0B interface. It is ideal for snowmobiles due to its durable nature, with the ability to withstand temperatures from -40°C to 105°C, vibrations up to 18G, and submersion in water up to a depth of 3 meters. In addition, the Motohawk software provided by Woodward auto-generates code from the Wisconsin Simulink model.

Fuel System Modifications

Modifications to the fuel delivery system were necessary to run ethanol-based fuels without adversely affecting performance and emissions. Fuel injectors capable of higher fuel flow rates were utilized to accommodate the lower heating value of ethanol. The replacement injector specifications are given in Table 6.

Table 6: Fuel injector specifications

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

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 capacity of 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 ethanol 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 AFR, which is used to calculate the correct fuel injection amount based on the intake mass airflow rate, the fuel density, and the desired AFR.

Emissions

For the 2018 Clean Snowmobile Challenge, the Wisconsin team worked with Continental Emitec GmbH and W.C. Heraeus GmbH to implement a three-way catalyst to reduce HC, CO and NO_X. Platinum and Palladium are the main oxidizers for HC and CO reactions, while Rhodium is used reduce NO_X.

To fully optimize the precious metal washcoat, exhaust gas was tested pre and post catalyst using a Snap-On five gas analyzer. This was done while recording fuel flow, mass airflow, equivalence ratio and exhaust gas temperatures. To quantify the catalyst data, catalytic efficiencies were calculated for the three major CSC emittents, shown in Table 7.

Table 7: Showing the catalytic efficiencies averaged across the 5 CSC mode points. See table 7 and 8 for catalyst technical specifications. Catalytic efficiency = (precatalyst emittent - postcatalyst emittent)/precatalyst emittent*100%

	HC	CO	NO_X
Catalyst 1 Efficiency	92.8%	86.8%	24.3%
Catalyst 2 Efficiency	99.9%	92.4%	34.2%

* Low NO_X efficiency is assumed to be occurring due to a low concentration of NO_X entering the catalyst. This is due to the EGR NO_X mitigation.

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 Tables 8 and 9. Catalyst 2 was chosen due to the higher palladium loading to effectively oxidize the CO and HC without the unwanted reaction that can occur with a high platinum loading. The higher rhodium loading was also a benefit of Catalyst 2 as it more effectively reduces NO_X, which is proved in Table 7.

Table 8: Catalyst 1 substrate and washcoat data

Manufacturer	W. C, Heraeus GmbH
Diameter (mm)	92
Length (mm)	168
Foil thickness (mm)	0.03
Substrate	Emitec Metal Honeycomb
Density (cpsi)	400
Loading (g/ft^3)	Platinum 24.7
	Palladium 45.2
	Rhodium 4.1

Table 9: Catalyst 2 substrate and washcoat data

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

To optimize the alleviation of CO, HC and NO_X, the exhaust gases entering the three-way catalyst must alternate between slightly rich and slightly lean [2]. 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 oxidized 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, CO_2 and H_2O [2].

The Wisconsin team utilizes a MAF-based fueling algorithm with a target equivalence table. 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 and lean-to-rich oscillation at 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 21.

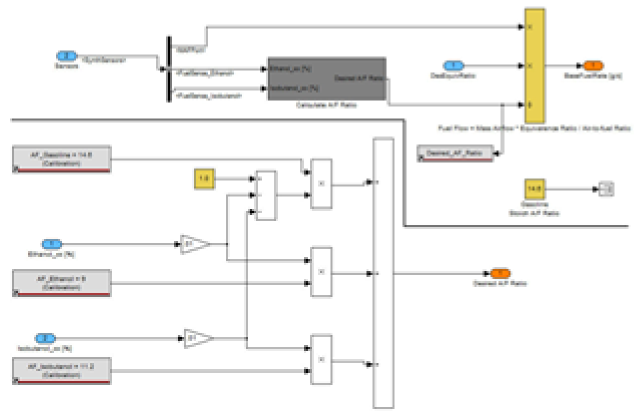

Figure 21: Simulink block diagram for flex-fuel and isobutanol engine control strategy

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 2018 CSC entry is experimentally estimated to be 205.9. Table 10 shows projected 2018 weighted 5-mode lab emissions results against stock ACE 600 emission results.

Table 10: Emissions of the stock ACE 600 and WRACE 674

	WRACE 674	**ACE 600 [5]**
CO (g/kW-hr)	12.3	90
HC (g/kW-hr)	0.216	8
NOx (g/kW-hr)	1.754	N/A
E-Score	205.9	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.

During the 2017 CSC the Wisconsin team was not pleased with its finish in the noise events. It was made a point throughout the year to improve upon the previous year's finish. Sound testing compared to a BAT compliant snowmobile, showed a potential decrease in 3 dB, compared to last year's entry. If the team had made the improvements prior to the 2017 event, it would've resulted in a 59.7 point increase.

Silent Drive

In an attempt to reduce track and chassis noise, the team researched Ski-Doo's Silent Drive System, which is an alternative driveshaft option found on Ski-Doo Grand Touring LE 900 ACE models since 2014. The Silent Drive relies on the ability of the drive gear to use the interior lugs to grab and turn the track. Figure 22 shows the Silent Drive has twice as many paddles on the sides and eliminates the paddles on top of the gear. This new style of gear is thought to be quieter than Ski-Doo's standard drive.

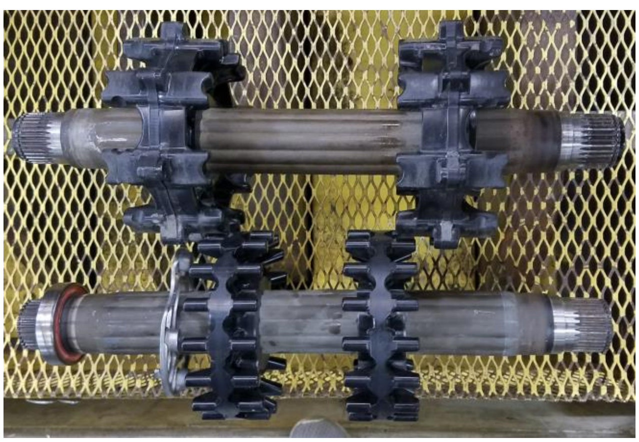

Figure 22: Ski Doo's standard drive is the top drive pictured above, with the Silent Drive below it

Unfortunately, the only track that is specifically made for the Silent Drive comes in a length of 137 in. The team's 2015 MXZ Sport chassis came with a 120 in track and could fit up to a 128 in track with minimal changes. However, the pursuit of the 137 in required permanent chassis changes to the tunnel and heat exchanger to utilize the Silent Drive. Alternatively, the team found the pitch of the interior lugs for the Silent Drive track was half the pitch of the standard drive Ski-Doo track. Armed with this knowledge, the team determined the Silent Drive would fit with the 120 in track.

When evaluating the two driveshafts, the team followed standard competition testing procedure J1161 for sound level metering. Ten runs were recorded on each drive with a ExTech 407736 Sound Level Meter set to A-weighted decibel metering. This testing was completed over two days in late January to allow time to swap out the driveshafts. To account for expected variation in conditions between the two days, a stock 600 E-TEC was used for baseline comparison. Table 11 shows that measured against the baseline E-TEC, the Silent Drive did not reduce the sound level compared to the standard drive. While the average sound level of the Silent Drive appeared to be 0.6 dB quieter, the E-TEC measurements taken on the same day were also 0.9 dB quieter. This shows the drop in sound was due to a difference in daily conditions.

Table 11: Mean of Experimental Sound Data in dBa from Silent Drive and Regular Drive

	Jan. 27, 2018	**Jan. 28, 2018**
Silent Drive	73.4	
Standard Drive		74.0
Stock 600 E-Tec	75.6	76.5

Along with not showing a noticeable decrease in sound, the Silent Drive and 120 in track combination produced noticeable ratcheting while at trail speeds due to not having the extra interior lugs and no paddles on the top of the drive gear. Additionally, each driveshaft was tested on a 40 mile endurance run using E-85 fuel. The Silent Drive achieved 16.9 miles per gallon vs the standard drive's 18.5 miles per gallon. Since everything was held constant besides the driveshafts, there were extra losses occurring between the connection of the Silent Drive and the track. From these test results, it became clear that the Silent Drive did not improve aspects of sound or fuel economy to justify using it.

Conclusion

The 2018 University of Wisconsin Clean Snowmobile Challenge Entry improves upon the Best Available Technology in sound performance and emission standards for over-snow recreational vehicles. Considering consumer performance requirements, as well as CSC guidelines, the 674 cc four-stroke engine has an improved power output of 35 kW. The 2018 entry features a dampened tunnel that lowers its natural frequency amplitude by 50%, a fundamentally improved EGR cooler and improved controls and calibrations. The WRACE 674 is flex fuel capable giving consumers the ability to run fuels ranging from E0 to E85. This highly reliable system comes packaged in an aesthetically pleasing arrangement. The WRACE 674 is a cleaner, quieter and performance-oriented option coming in at a marketable MSRP of $10,717.69.

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Definitions/Abbreviations

AFR	Air/Fuel Ratio
ACE	Advanced Combustion Efficiency
BAT	Best Available Technology
BSFC	Brake Specific Fuel Consumption
CAN	Controller Area Network
CO	Carbon Monoxides
cpsi	cells per square inch
CSC	Clean Snowmobile Challenge
ECU	Electronic Control Unit
EES	Engineering Equation Solver
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
ETB	Electronic Throttle Body
FFT	Fast Fourier Transform
HC	Hydrocarbons
MAF	Mass Air Flow
MAP	Mass Air Pressure
MBT	Maximum Brake Torque
MSRP	Manufacturer Suggested Retail Price
NO_X	Nitric Oxides
OEM	Original Equipment Manufacturer
PID	Proportional Integral Derivative
RPM	Revolutions per Minute
SAE	Society of Automotive Engineers
WOT	Wide Open Throttle
WRACE	Wisconsin Rotax Advanced Combustion Efficiency

Appendix