Flex-Fuel Capability Implementation and Performance and Emissions Improvements of the Rotax ACE 600

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ABSTRACT

The University of Wisconsin-Madison Snowmobile Team has designed and constructed a clean and quiet, high performance snowmobile for entry in the 2014 SAE International Clean Snowmobile Challenge. Built on a 2013 Ski-doo MXZ chassis, this machine features a Rotax 600 cc ACE port fuel-injected turbocharged four-stroke engine equipped with a fuel sensor allowing the engine to operate efficiently on gasoline or any ethanol or iso-butanol blend. The engine has been customized with a Woodward control system which allows for full engine optimization with complete flex-fuel ethanol and iso-butanol capabilities. An electronic throttle body and mass airflow sensor are used in conjunction with a heated wide-band oxygen sensor to enable closed-loop fuel control. Utilizing a 3-way catalyst designed by Emitec, this sled reduces NOx, HC, and CO emissions by up to 97% to an average specific mass of 9.09, 0.13 and 1.25 g/kW-hr, respectively. Custom intake and exhaust camshafts were developed for Miller cycle operation and an external wastegate, electronic boost control, and charge air cooler have been fitted, enabling complete control of the turbocharger. With all of the modifications, the clean turbocharged Rotax ACE is capable of a power output of 45 kW and utilizes a catalytic muffler system to reduce sound levels to 70 dB(A) using SAE test procedure J192. The lightweight combination of the MXZ chassis and revolutionary ACE engine results in a rider-friendly package that meets the criteria to succeed at the Clean Snowmobile Challenge and is 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, carbon monoxide, nitrous oxide, and noise emissions while maintaining a consumer acceptable level of performance. Successful CSC entries must also demonstrate reliability, efficiency, and cost effectiveness. The 2014 CSC will be held in Michigan’s Keweenaw Peninsula from March 3-8th.

The following paper discusses how the University of Wisconsin – Madison team has engineered an entry for the 2014 CSC that improves upon the industry’s best available emissions and sound technology, while maintaining exceptional riding characteristics. The first section addresses the engine selection process and modifications to the snowmobile’s drivetrain. The second section describes the fuel system modifications necessary for flex fuel iso-butanol capability. The third section focuses on emissions and emissions reduction techniques. The next section discusses specific design enhancements that reduce overall snowmobile noise. Finally, the paper addresses general snowmobile modifications employed to enhance the previously mentioned technologies. In addition, the paper summarizes the implementation costs compared to a comparable production snowmobile.

MARKET SURVEY

Performance, practicality, and efficiency are the guiding principles for the 2014 UW-Madison CSC entry. To win the challenge, each team must modify a snowmobile with a cost-effective design strategy that reduces both exhaust and sound emissions, improves fuel economy and meets or exceeds the performance exhibited by today’s modern snowmobiles. To market a product to current snowmobile consumers, the team first determined the characteristics which are important in this demographic sector.

In 2012, the team surveyed the Northern Lights Snowmobile Club of Three Lakes, WI and the Prairie Riders Club of Pleasant Prairie, WI to determine which attributes are most important to the average snowmobile enthusiast. The survey asked volunteers to rank several characteristics that are important to a consumer when buying a new snowmobile from least important (1) to most important (5); the list of characteristics are: acceleration, handling, price, fuel economy, and emissions. The results of the survey are tabulated below in Figure 1 and show that handling and acceleration influence a consumer significantly more compared to price, fuel economy, and emissions.

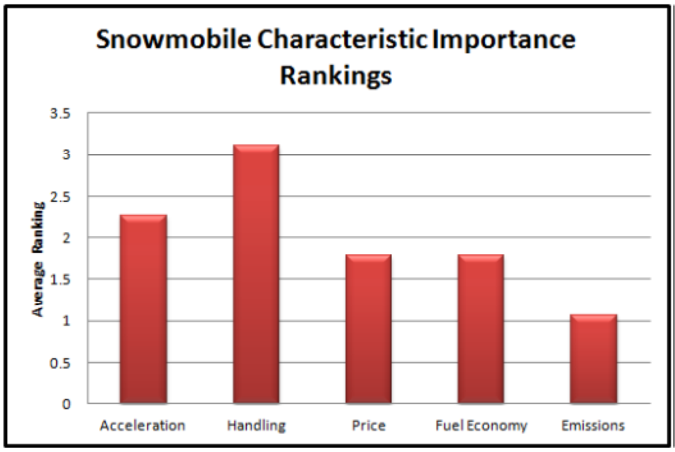

Figure 1. A survey of 120 snowmobilers shows that handling and acceleration are the two most important considerations when purchasing a snowmobile.

The survey results are in agreement with the guiding principles of the UW-Madison Team. An environmentally friendly snowmobile must also exhibit good acceleration and handling characteristics to be enjoyed by the average snowmobile enthusiast.

Engine Option Evaluation

Given the market survey results demanding a snowmobile with excellent acceleration and handling, the team searched for engines with good power-to-weight ratios, emissions, and cost. To match the design to CSC competition objectives, emissions, fuel efficiency, and sound output were given the highest weighting. Power-to-weight ratio and cost sequentially followed to tie in consumer demand with CSC objectives. The following engine options were considered by the team:

- Two-stroke (conventional) snowmobile engines
- Semi-direct injection (SDI) snowmobile two-strokes
- Four-stroke snowmobile engines
- Turbo-charged four-stroke snowmobile engines
- Direct Injection (DI) two-stroke snowmobile engines
- Four-stroke personal watercraft (marine) engines
- Compression ignition (CI) engines

The choice between current snowmobile engine technologies is fairly straightforward. Conventional and SDI two-strokes have significantly higher power-to-weight ratios than current snowmobile four-strokes. However, snowmobile emissions testing conducted by Southwest Research Institute (SwRI) clearly 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]. Though four-strokes have significantly higher NO_x than two-strokes, the study notes that the use of a catalyst system on a four-stroke can nearly eliminate NO_x, while further reducing HC and CO.

While the SwRI study did not evaluate DI two-stroke technology, none of the Ski-Doo E-Tec engines are listed as Best Available Technology (BAT) compliant [2]. While DI engines are a significant improvement compared to conventional two-stokes, they cannot attain current four-stroke emission levels. Aside from the three pollutants measured for competition scoring, 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) [3].

The team evaluated Compression Ignition (CI) engines, recognizing their excellent HC and CO emissions. However, CI engines were eliminated from consideration due to their poor power-to-weight ratio, difficulty of implementation, costly modifications, and their planned exclusion from 2015 CSC. 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.

To aid in our 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 claimed they would choose a four-stroke engine to power their snowmobile.

Final Engine Selection

Given the heavy weighting on emissions in CSC competition scoring, the team reviewed engine-out emissions produced by four-strokes. It is generally accepted that a properly calibrated four-stroke will have substantially less HC and CO emissions than a two-stroke. The Rotax 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 new model in the same product line is the ACE 900 which develops 67 kW (90hp) and is also BAT compliant. Other options considered were the Polaris FST and Ski-doo 4-TEC, which are both capable of a power output of 97 kW (130 hp)

Table 1. 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 4tec	97	64	7.2	6.2	79.9	N/A
Polaris FST	97	62	7.6	9	116	N/A

Eco mode operation. **Sport mode operation

Table 1 shows the four engines that best suited the Wisconsin team's design goals and objectives. A quick review of each engine's HC and CO emissions shows that all four engines are comparable and, with proper after-treatment, could be made clean enough to surpass an Emissions Score (E-Score) of 205 out of 210, which is extremely clean for snowmobiles.

While all four engine options fulfill current EPA emissions requirements, both the 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 [4,5]. The revolutionary ACE design also allows for integrated engine lubricant and cooling systems, which minimizes weight, complexity, and external plumbing, resulting in easy implementation and modification for Wisconsin’s design. Table 2 below shows how similar the specifications of the two ACE engines are.

Table 2. 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 1	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 UW considered. The ACE 900 is the first production snowmobile to feature an Electronic Throttle Body (ETB), a device used by the Madison team since 2009, and multiple engine operating modes; 2013 CSC was the first time teams were allowed to incorporate a user-selectable switch to alter the operation of their engine. Several drawbacks of the ACE 900 are its increased weight, fuel consumption, and proprietary Intelligent Throttle Control. The combination of these drawbacks, the team’s prior experience with electronic throttle control systems, and multiple engine operating modes made the ACE 600 the power plant of choice for the Madison team.

One problem slightly hindering the performance appeal of the stock Rotax ACE 600 is its lower rated power output of 42 kW (56 hp). The UW-Madison team designed and installed custom camshafts, allowing for Miller Cycle operation and lowering the engine’s effective compression ratio. With effective compression down to more tolerable levels, a turbocharger and charge air cooler were fitted to increase the engine’s power output to levels most consumers demand. The turbocharger of choice is a Garrett GT1241; this turbocharger is shown below in Figure 2 and is best suited for applications between 37 and 88kW (50-120 hp).

Figure 2. Garrett GT1241 turbocharger; the OEM internal wastegate actuator has been removed.

Additionally, a custom charge air cooler with integrated cooling fan was mounted in the front of the vehicle to lower intake air temperatures. Finally, a large external wastegate was plumbed into the exhaust system to control boost pressures depending on whether the engine is operating in eco or performance modes.

Control Hardware

The team was unable to acquire the necessary software tools to reprogram the stock engine controller used on the ACE. This year Wisconsin is utilizing a Motorola PCM565 Powertrain Control Module (PCM) embedded system that is specifically designed for automotive applications. The PCM, which uses an operating system developed by Woodward, is hermetically sealed and suitable for the under-hood environment. It can withstand temperatures from -40°C to 105°C, vibrations up to 18G, and submersion in water to a depth of 3 m. It 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 base control strategy was supplied by Woodward and its Motohawk software auto-code generates the control code from this Simulink model. The engine control model underwent several modifications to allow the use of ignition and fueling tables that are load, speed, and manifold pressure dependent. In addition, the model has adaptation for atmospheric conditions and cold starts, as well as a multitude of engine protection features that limit boost pressure, throttle opening, and fueling should the coolant temperatures or oil pressures reach unsafe levels. The model calculates fuel rates for the stipulated air/fuel ration using inputs from the alcohol and mass air flow sensors. New for this year is the ability to adjust fueling for each individual cylinder to account for the cylinder filling imbalance, caused by the 270 degree crankshaft, which our simulations predicted.

Powertrain Enhancement

The stock Rotax ACE shown below in Figure 3 is already a highly efficient engine, featuring specialized coatings on valve tappets to reduce friction and self contained cooling and oiling systems [4]. While Rotax didn’t leave much room to improve this engine, the Madison team found some places to improve efficiency, power, and fuel economy.

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

Taking full advantage of the all the capabilities of the Motorola PCM565 control unit, the Madison team installed several major components to allow complete optimization of all engine parameters for a wide range of iso-butanol based fuels. The first improvements came from the ETB, which occupies the same space as the stock mechanical throttle body. When used in conjunction with an electronic boost controller the ETB significantly reduces engine pumping losses by opening the throttle first with little or no boost followed by increasing the boost pressure at high throttle requests. Another major change was the addition of a Mass Airflow (MAF) sensor which directly supplies the ECU with the intake mass air flow rate and the inlet temperature. The MAF sensor has greatly simplified the calibration process and the control code as the MAF can be used to self-populate the Volumetric Efficiency (VE) tables which are used as a default if the MAF is not functioning.

Fuel injection calibration and control was made possible by utilizing the ETB, MAF sensor, fuel sensor, wideband oxygen sensor, and a fuel control strategy developed in Matlab Simulink. A Bosch Wideband O_2 sensor was utilized in the Bucky ACE Turbo for closed loop control of the fuel injection; the same O_2 sensors were installed in the individual exhaust primary tubes to adjust fueling for each cylinder, correcting the cylinder mass air flow imbalance. During large transients where the closed loop system is unable to keep the air fuel ratio within one percent of stoichiometric, fuel injection control is determined by predefined, stoichiometric fueling tables.

A major change to the stock Rotax ACE to improve engine efficiency, power, and reduce emissions was the utilization of a Garrett GT1241 turbocharger, charge air cooler, and external wastegate. The Mototron engine controller coupled with the electronic boost controller allowed students to create their own turbo boost control strategy, shown in Figure 4. This allowed for optimization of fuel consumption depending on the engine operating modes, eco or performance, and when boost was not needed while also minimizing lag. This also allowed for safeties to be built into the control strategy to limit boost in certain situations. When coolant temperature is below 20˚ C boost pressure is limited to 1.25 bar. As temperature increases to 60˚ C pressure is linearly increased to 2 bar at full power. Boost is also reduced if coolant temperature exceeds 90˚ C. These safeties protect the engine and turbo from excessive wear and damage.

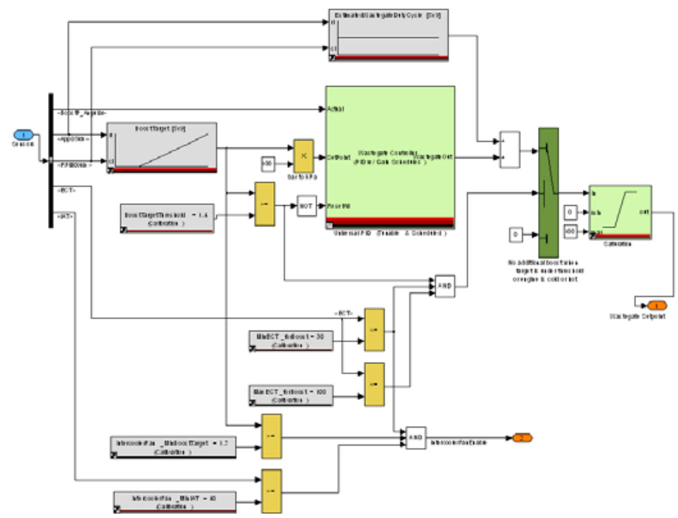

Figure 4. Image of control strategy Simulink Model for electronic turbo boost control.

To further build upon the benefits offered by the new, electronically controlled turbocharger system the stock 12:1 compression ratio needed to be dealt with. Students designed and installed custom intake and exhaust camshafts, allowing Miller Cycle operation of the engine. The intake camshaft delays intake valve closure, reducing the trapped mass of fuel and air in the cylinder and decreasing the dynamic compression ratio from 12:1 down to 7.7:1.

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 [6]. These constraints define a window, shown in Figure 5, that the engine must be calibrated to operate within.

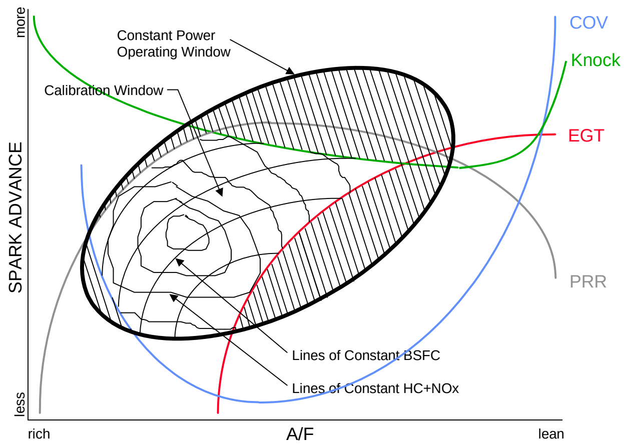

Figure 5. Graph of typical calibration window [1].

Calibration of the 2014 engine shown in Figure 6 was performed using a water-brake dynamometer. Wideband O_2 sensors, and exhaust thermocouple probes. By monitoring torque, exhaust temperatures, and air-fuel ratio (AFR) values, spark timing and fueling could be properly calibrated.

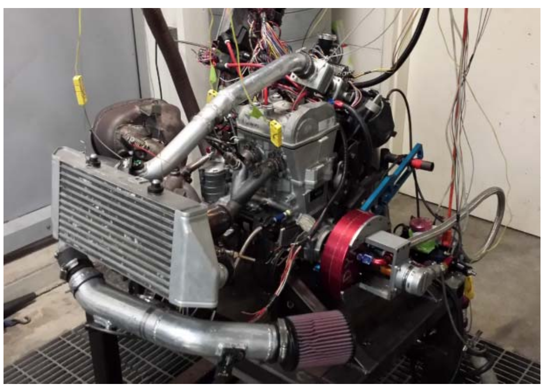

Figure 6. Dynamometer testing stand used for all calibrations.

Another improvement made to the powertrain to enhance efficiency was to machine the driveshaft paddles into true circles. Like most drive shafts found on modern snowmobiles, the ACE drive shaft has plastic molded drive paddles that were un-machined. The molding process of these drive paddles do 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 symmetrical in shape.

Engine Simulation and Optimization

A 1-D model of the engine was developed using Ricardo Wave, allowing quick evaluation of many different designs. Initially, three different designs were compared by simulating Modes 1-4 of the 5 mode EPA 40 CFR Part 1051 emissions test cycle: baseline, Atkinson, and Miller. The Atkinson and Miller cycles are similar in that they are both over-expanded cycles, meaning the expansion ratio is higher than the compression ratio. The primary difference between the two is that the Miller cycle uses forced induction. An over-expanded cycle can be accomplished by very late closing of the intake valve. Essentially, at the end of the intake stroke, the valve remains open. As the piston travels upward, a portion of the intake charge is expelled back to the intake plenum. The consequence is a reduction in volumetric efficiency and effective compression ratio. A reduced volumetric efficiency means a larger throttle opening is required for a given torque output, resulting in a reduction in pumping losses and increase in efficiency at part load. The decrease in effective compression ratio can increase efficiency by extending the knock limit of the engine. For a naturally aspirated engine a higher geometric compression ratio can be used, increasing the expansion ratio. For a naturally aspirated engine, a higher boost pressure can be used. The major downside to an over-expanded cycle is that the reduction in volumetric efficiency corresponds with a reduction in power output. The Miller cycle uses forced induction to somewhat mitigate this power loss.

The 4 mode results of an initial comparison between the baseline, Atkinson, and Miller engines demonstrated that, as expected, the Atkinson and Miller engines have a slightly improved efficiency over the baseline. The Atkinson engine showed a reduction of peak power and torque, however the Miller engine had better efficiency, more power, and more torque. Additionally, it's expected that the turbocharger used in the Miller cycle will provide additional sound attenuation. Based on these results, it was decided that the Miller cycle engine should be further investigated.

DOE optimization was used to determine the ideal valve timing for Miller cycle operation to maximize efficiency for the 4 mode test. A full factorial DOE was performed using intake valve opening and closing, exhaust valve opening and closing, and boost pressure. The optimal result provided the best balance between efficiency, power and torque output, while minimizing knock intensity. The valve lift as a function of crank angle of the final design compared with the baseline design can be seen in Figure 7. As expected, the IVC was delayed until late in the compression stroke. Additionally, intake valve opening was delayed, and the exhaust valve was closed slightly earlier.

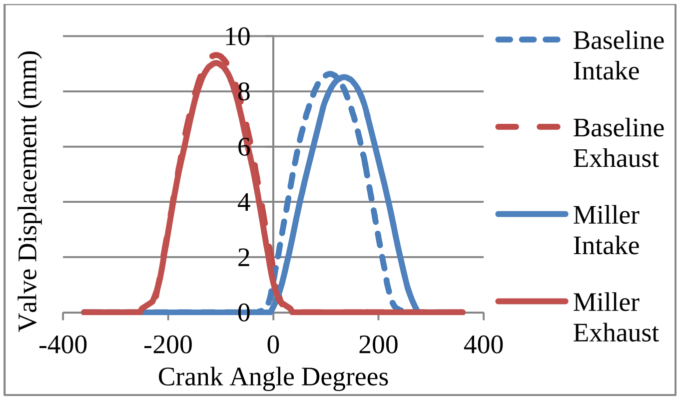

Figure 7. A comparison of baseline and Miller cycle valve lift profile used for modeling comparisons.

Figure 8 shows intake valve mass flow as a function of crank angle of both engines operating at Mode 2. In this plot, negative mass flow indicates mass flowing out of the cylinder and into the intake plenum. The Miller cycle engine can be seen to return a rather large portion of the intake charge to the plenum. As previously discussed, this results in a decrease in volumetric efficiency.

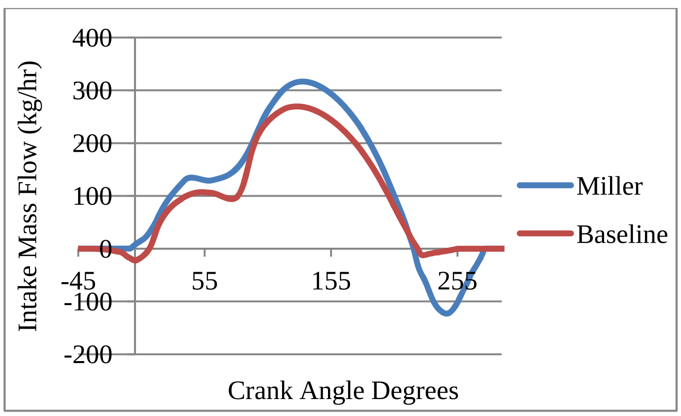

Figure 8. Modeled intake valve mass flow as a function of crank angle.

Table 3 is a comparison of the Brake Specific Fuel Consumption (BSFC) for the baseline and optimized design at each mode, as well as the respective weighting of each mode. From the table, it can be seen that the optimized design has a slightly reduced efficiency at Mode 1. This is caused by the increase in pumping losses at wide open throttle from the turbocharger, as well as the slight penalty of returning a portion of the intake charge back to the intake plenum during the compression stroke. However, the optimized design shows an improvement at Modes 2, 3, and 4. As expected, the Miller engine shows improved part throttle efficiency over the baseline. The relative weighting of each mode is also shown in Table 3. Because the part load modes are weighted much more heavily than Mode 1, the part load gains more than offset the small loss of full load efficiency.

Table 3. Modeled BSFC of the baseline and Miller design.

	Baseline BSFC (g/kW-hr)	Miller BSFC (g/kW-hr)	Relative Weighting
Mode 1	266	270	0.12
Mode 2	312	297	0.27
Mode 3	358	339	0.25
Mode 4	473	444	0.31

To demonstrate the mechanism by which the optimized engine improves efficiency, Figure 9 shows the ratio between pumping work and gross indicated work at each mode. Figure 10 shows the ratio of brake work to indicated work at each mode. It is evident from these two figures that the Miller engine provides a larger percentage of its indicated work to brake work, thus demonstrating improved brake specific efficiency.

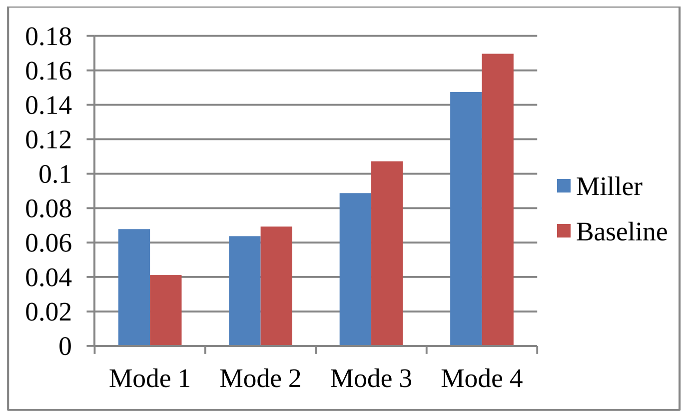

Figure 9. Modeled fraction of gross indicated work lost to pumping work at each mode.

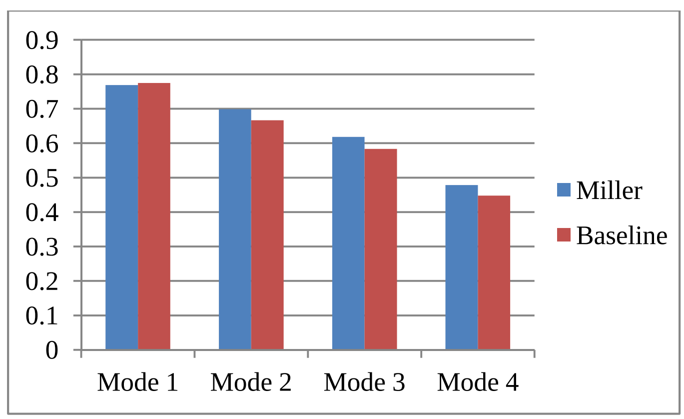

Figure 10. Fraction of gross indicated work converted to brake work at each mode.

The Pressure-Volume diagram of both engines operating at Mode 4 is compared in Figure 11. The ratio between pumping work and gross indicated work is related by the relative area of the pumping loop to the area during the compression and combustion strokes.

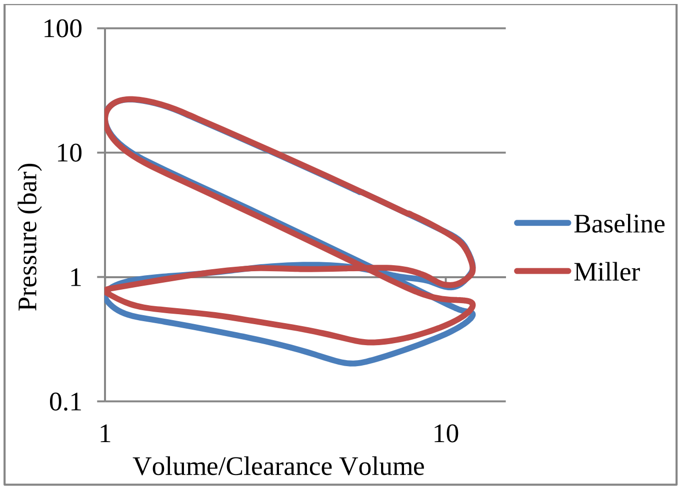

Figure 11. Pressure-Volume diagram of baseline and optimized Miller cycle engines at Mode 4.

The torque and power curve of both designs is shown in Figure 12. It can be seen that the Miller cycle engine provides slightly higher torque and horsepower than the baseline engine, especially at higher RPM.

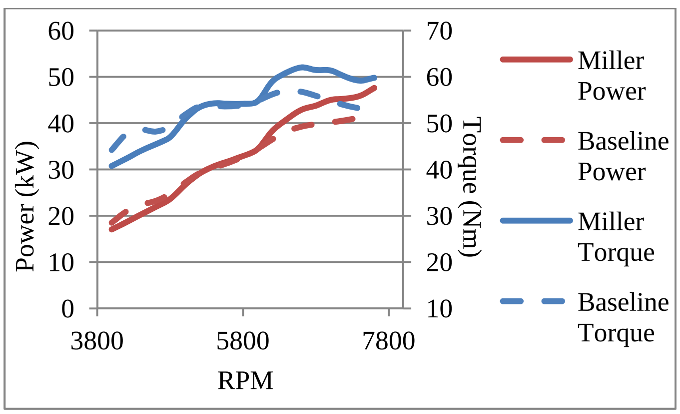

Figure 12. Torque and horsepower curves for the baseline and optimized Miller cycle engines.

Engine dynamometer testing was completed using a Land & Sea DYNO-mite water brake dynamometer. A pair of Optrand AutoPSI-TC spark plug pressure transducers were used to measure in cylinder pressure for both cylinders simultaneously. A BEI H25 optical rotary encoder and a National Instruments CompactDAQ-9178 modular data acquisition system allowed for crank angle resolved measurements to be taken at a resolution of 1/6 degree. This equipment allows for combustion analysis for model validation and correlation. Additionally, the system improved accuracy of maximum brake timing determination and knock detection during the calibration process. Table 4 provides a comparison between the simulation results and physical testing results at Modes 2, 3, and 4. The model shows very good agreement with the physical data for nearly all parameters.

Table 4. Comparison between simulation and physical testing results for Modes 2, 3, and 4.

		Simulated	Physical	% Error
Mode 2	Torque (N-m)	31.2	31.4	0.6
	Net IMEP (Bar)	8.77	8.39	-4.5
	BSFC (g/kW-hr)	297	295	-0.7
Mode 3	Torque (N-m)	20.0	20.2	0.9
	Net IMEP (Bar)	6.17	6.39	3.5
	BSFC (g/kW-hr)	339	352	3.7
Mode 4	Torque (N-m)	10.7	10.8	1.1
	Net IMEP (Bar)	3.99	4.18	4.6
	BSFC (g/kW-hr)	443	497	10.9

A Pressure-Volume diagram of the engine operating at Mode 4 is shown in Figure 13 and IMEP and PMEP data for each cylinder is shown in Table 5.

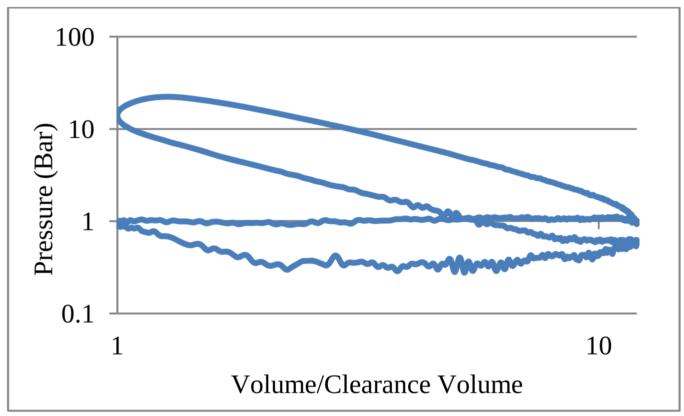

Figure 13. Pressure-Volume diagram of physical engine during mode 4 operation.

Table 5. IMEP and PMEP pressure data for both cylinders.

	IMEP	PMEP
Cylinder 1	3.71	-0.63
Cylinder 2	4.8	-0.7

Fuel System Modifications

In order to run iso-butanol 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 and forced induction. The replacement injector specifications are given in Table 6.

Table 6. Fuel injector specifications.

	Stock Injector	Iso-butanol 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 is 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 insures adequate fuel flow to the pressure regulator, injectors, and fuel sensor.

To accommodate a range of fuels containing 16-32% iso-butanol for the 2014 CSC, the team installed a Continental Flex-Fuel sensor which then underwent recalibration for use with iso-butanol. 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 air-to-fuel ratio which then undergoes manipulation to account for the filling imbalance between the two cylinders. The computing power of the Mototron controller is used to continually calculate the correct fuel injection amount utilizing the intake mass air flow rate, the fuel density, and the desired fuel air ratio, shown in Figure 14.

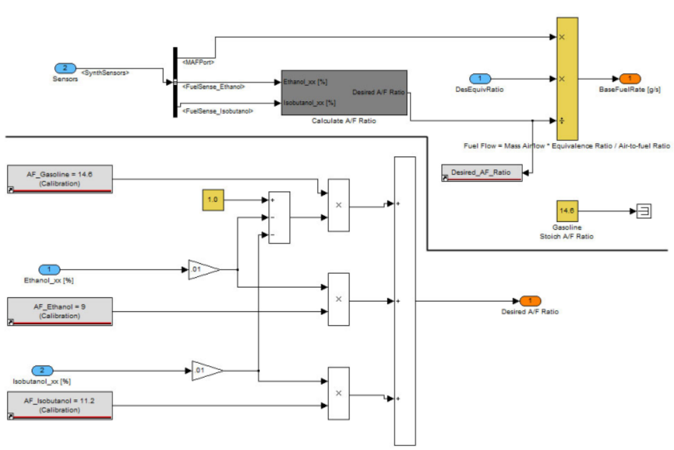

Figure 14. SimuLink block diagram for flex-fuel and iso-butanol engine control strategy.

Once the engine is 'roughly' (within 0.2% of target exhaust oxygen content) calibrated on the engine dynamometer, the closed loop fuel trim algorithm which utilizes the heated wide-band oxygen sensor is activated and is responsible for fine tuning the air-fuel ratio to a stoichiometric level.

Emissions

In order to further reduce emissions to automotive standards, the Wisconsin team worked with W.C Heraeus GmbH to customize a catalyst specifically for this engine's operating regime. Since the CSC emission scoring is based on a combination of HC, CO and NOx levels, a three-way, Platinum/Palladium/Rhodium-based catalyst was chosen for its ability to effectively reduce all three pollutants simultaneously.

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 15 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.

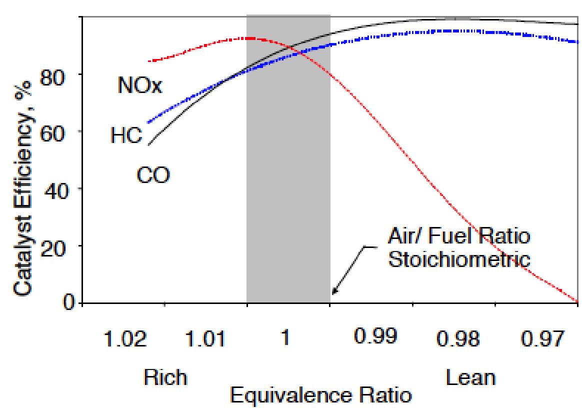

Figure 15. Shows the NO_X, CO, and HC conversion efficiency for a three-way catalytic converter as a function of exhaust gas air/fuel ratio operating on gasoline (Adapted from [6]).

This lean-to-rich oscillation of the engine is controlled using the team's closed-loop fuel trim algorithm, maximizing emissions reduction. These fluctuations in oxygen sensor output in addition to the fueling multiplier are show below in Figure 16. In this area of engine operation, the base calibration is slightly rich and so the emissions control algorithm has adjusted the fuel multiplier to oscillate around the stoichiometric value of 0.96. Furthermore, the lean/rich parameters were tuned to maintain smooth engine operation while correcting the cylinder mass flow imbalance; the resulting cycle is longer than a normal automobile engine.

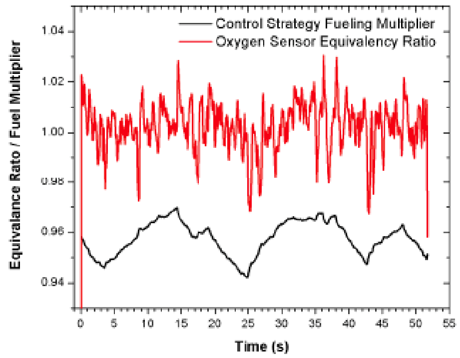

Figure 16. Engine equivalence ratio oscillating near stoichiometric as a result of closed-loop control.

Conversely, the same control strategy is used to maintain a 10% extended lean burn during operation in eco mode in order to maximize fuel economy. The team determined that in performance mode a rich mixture was not required for protection of the 2014 Miller Cycle engine and chose to run a stoichiometric air-fuel ratio with the three-way switching to maximize emissions reduction.

Having determined the fueling strategy for each mode, the team worked with Hereaus to develop a washcoat specifically for our engine. The optimized washcoat was then applied to a metal honeycomb substrate utilizing Emitec's SuperFoil® technology; full description of catalyst and active materials are presented in Table 7. This substrate technology influences the flow distribution causing turbulence within the cell channels. The turbulence increases the conversion rate by maximizing contact time between the exhaust gases and washcoat, allowing the use of smaller volume catalysts and/or reducing back pressure [8].

Table 7. Catalyst substrate and washcoat data

Manufacturer	W. C, Heraeus GmbH
Diameter	70 mm
Length	149 mm
Substrate	SuperFoil® Metal Honeycomb
Density	600 cpsi
Loading	Platinum 11.1 f/ft3
	Palladium 55.6 g/ft3
	Rhodium 8.3 g/ft3

The combination of the substrate, engine specific washcoat, and closed-loop fuel trim algorithm allowed for further emissions reductions to be achieved in 2014. Using lab emissions data from the 2013 CSC the Madison team calculated that an emissions reduction of 97% is realized with the new integrated catalyst. Listed below in Table 8 is the summarized emissions data obtained from our 2013 snowmobile during the 5-mode lab emissions test for both eco and performance modes; emissions data from the stock ACE 600 has also been included.

Table 8. Emissions comparison between eco and performance mode as well as stock ACE 600.

	Eco-Mode	Performance	Stock [4]
CO (g/kW-hr)	1.25	5.89	90
HC (g/kW-hr)	0.12	0.19	8
NO_x (g/kW-hr)	9.09	8.3	N/A
E-Score	203.55	202.86	190

Extensive emissions testing using a traditional California Analytical emissions bench was conducted on the 2014 sled; the results of these tests were used to determine emission levels, which are shown in Figure 18, along with catalyst efficiencies.

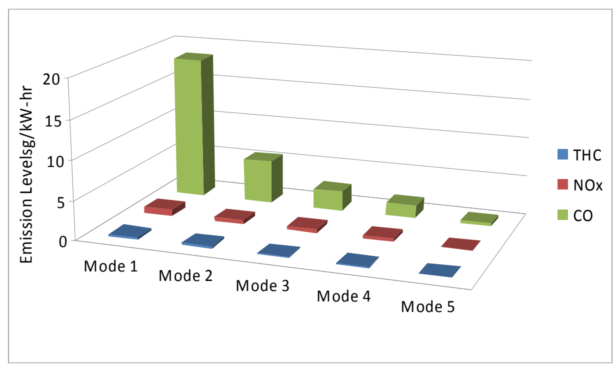

Figure 17. Emissions breakdown of modes 1 through 5 for the 2014 CSC entry.

The projected E-score for UW-Madison's 2014 CSC entry is calculated to be 207.04; an 87% improvement in catalyst efficiencies was also calculated. Table 9 shows projected 2014 5-mode lab emissions results for eco and performance modes against stock ACE 600 emission results [4]

Table 9. Projected 2014 emissions comparison between eco and performance mode.

	Eco-Mode	Performance	Stock [4]
CO (g/kW-hr)	.5	8.1	90
HC (g/kW-hr)	0.12	0.3	8
NO_x (g/kW-hr)	5.11	1.11	N/A
E-Score	206.39	207.04	190

Muffler Design

Wisconsin's primary goal for sound reduction on the Bucky ACE Turbo was to reduce A-weighted sound pass-by levels below those of the current standard set by the International Snowmobile Manufacturers Association (ISMA), which is 78 dB(A) using SAE test procedure J192. A secondary goal was to reduce perceived sound levels to bystanders.

As a starting point, redesigning the ACE 600 exhaust system offered the most potential for noise reduction in the space available. In addition, Wisconsin's emission strategy required the implementation of a single large catalyst. After close examination of the internals of the stock ACE muffler with the team's knowledge of muffler design, it was decided that, out of reliability, simplicity, and spatial constraints, the stock muffler would be utilized. With only modified inlet tubes to accommodate the catalyst; the exhaust and muffler system utilizes the stock mounting locations and exit location of the snowmobile. This allows for the attractive stock visual appeal to be maintained and avoids any complicated manufacturing requirements as well as reducing sound to an acceptable level.

Mechanical Noise Reduction

With the redesigned muffler greatly eliminating exhaust noise, the team focused on mechanical noise emitted from the snowmobile. In order to identify the main contributors of the sound from the snowmobile, pass-by sound testing data was obtained.

To quantify typical noise levels from a snowmobile chassis, Wisconsin performed various different sound tests including drive-bys at constant speed and during WOT acceleration on a snowmobile with a chassis and engine comparable to the 2014 entry. The protocol for the WOT tests was an entry at 24 km/hr with a transition to wide-open throttle at a point 22.5 m before the plane of the microphones (speed at the point crossing the plane of the microphones was 69 km/hr). To best determine the major source of noise the team did a spectral noise analysis, using dual microphones at a distance of 15 m on several 72 km/hr pass-by tests. This data was recorded using a Hi-Techniques HT-600 data acquisition system, allowing a thorough analysis of sound emissions.

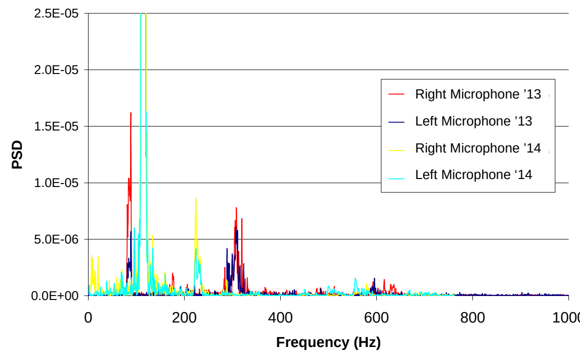

Figure 18. Spectral sound density of past UW-Madison CSC entries to determine typical sources of noise from a snowmobile.

Figure 18 shows a Power Spectral Density plot from the Bucky ACE Turbo. This plot shows the sound power emitted from the sled as a function of frequency. Three distinct peaks can be seen near 100, 225, 300, and 600 Hertz. By calculating the first and second order contributions of the snowmobile components at 72 km/hr, the sources of the peaks were discovered. The 100 Hz peak is first order engine noise, the 225 Hz peak is second order engine noise, and the 300 and 600 Hz peaks are first and second order noise produced where the track paddles interface the track. The right side 100 Hz and 225 Hz peak is much higher than the left side because the exhaust outlet is on the right side of the snowmobile.

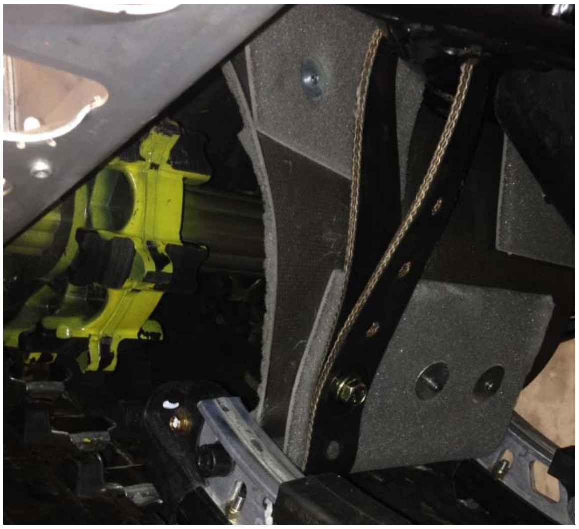

Figure 19. Drive paddle noise dampener.

The drive paddle sound dampener shown in Figure 19 isolates the sound produced by the drive paddles contacting the drive lugs on the track. This contact noise on the Bucky ACE Turbo was seen as a peak at 300 Hz in the 2013 test data. As the 2014 data shows in Figure 18, this 300 Hz peak is effectively reduced to zero with this modification.

Further improvement upon the drive paddle sound dampeners was realized with the application of LizardSkin® Sound Control coating to the underside of the tunnel, as shown in

Figure 20. 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 20. View of tunnel underside lined with Lizard Skin material.

In addition to the mechanical sound reducing enhancements outlined above, the UW-Madison team decided to investigate the resonant frequency of the tunnel, looking for a possible track-tunnel sound amplification. Using a Hi-Techniques data acquisition system and PCB Piezoelectric accelerometer, the team discovered that the tunnel had a resonant frequency close to the 300 Hz track vibration shown in Figure 18.

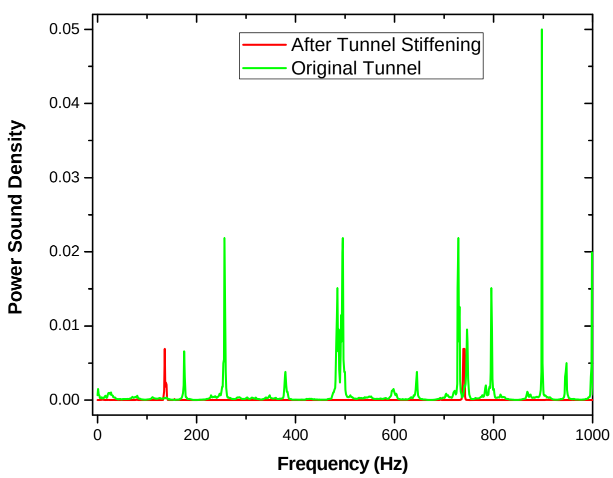

Figure 21. Chassis frequency spectrum before and after tunnel stiffeners.

This meant that any vibration from the track was being amplified by the tunnel, greatly increasing noise. In an effort to change the resonance frequency of the tunnel, the team decided to add tunnel-stiffening angle brackets, shown below in Figure 22, to the sides of the tunnel near the foot wells.

Figure 22. Tunnel stiffening brackets.

The frequency response graph in Figure 21 clearly shows the elimination of the natural frequency near 300 Hz of the tunnel through the use of the tunnel stiffeners.

Although the Ski-doo MXZ Sport ACE 600 is relatively quiet in its stock form, the addition of the catalyst and turbocharger has reduced the low frequency engine exhaust noise levels. A majority of the higher frequency noise is emitted from other mechanical systems such as the intake, clutches, final drive, and suspension. To reduce the effects of the air intake and clutches, 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. A summary of sound reduction data can be found in Table 10.

Table 10. Summary of sound reduction comparing 2013 competition to pre-2014 competition results.

Stock	75 dB(A)
2013	72 dB(A)
2014	70 dB(A)

Traction

Due to consumer demand for a snowmobile with responsive handling and acceleration, the effects of a studded track on driveline efficiency was investigated. Shown below in Figure 23 are the results of testing conducted by the Wisconsin Team in 2011 with the Buck EV2 electric snowmobile.

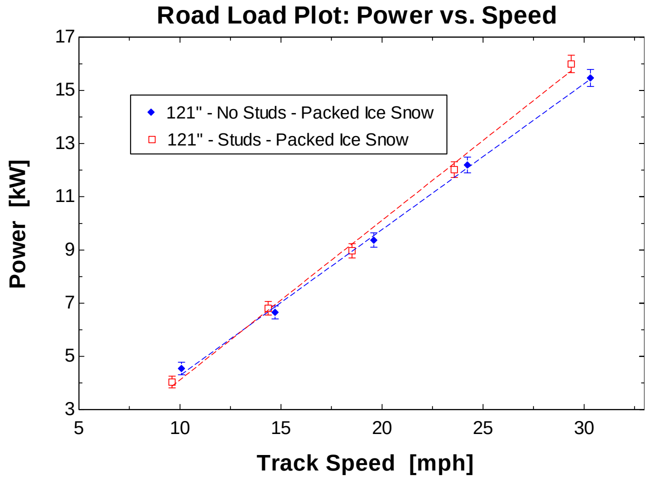

Figure 23. Plot showing the effect adding studs had on the power required at various speeds.

It was determined that the addition of 84 conventional studs changed the total road load power required at 40 km/hr from 12.16 kW (16.3 hp) to 12.38 kW (16.6 hp). However, at low speeds the studded track leads to slightly decreased road loads due to better traction. For 2014 the Wisconsin team is using a Camoplast Ice Attack track which comes with 264 studs molded into the lugs. This provides the rider with all of the benefits of a studded track while reducing weight by 3.73 kg (8.21 lbs) when compared to a conventionally studded track with 96 studs. Using a pre-studded track also eliminates of the possibility of studs pulling out of the track and leaving it in a compromised condition. While this pre-studded track does slightly reduce the overall efficiency of the driveline at higher speeds, the increased performance and safety greatly outweigh this detriment.

Cost Estimates

Every component of the Bucky ACE Turbo is designed for manufacturability. In fact, many of the technologies are currently in use in other transportation applications such as the three-way catalyst, electronic throttle body, 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 calibrations, sound reduction through good design, etc. 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 $10,769, the 2014 BAT 600 has a comparable price to other commercially available 4-stroke sleds with similar power-to-weight ratios, such as the Yamaha Phazer and Polaris FST. If key components of the Bucky ACE such as the catalyst, ethanol sensor, and electronic throttle body became standard parts within the snowmobile industry, the base price would likely only be about $1500 greater than today's stock MXZ Sport ACE 600 configuration.

CONCLUSIONS

The 2014 University of Wisconsin–Madison Clean Snowmobile Challenge entry drastically improves upon the best available technology in performance and emissions standards for over-snow recreational vehicles. Taking into consideration consumer performance requirements for an environmentally friendly snowmobile, the team installed new camshafts and a powerful forced induction system to further improve on the revolutionary four-stroke ACE powerplant, combining performance with EPA 2014 emissions compliance. The BAT 600 flex-fuel ethanol and iso-butanol capability gives consumers the ability to utilize a variety of less polluting, renewable fuels. The redesigned exhaust after-treatment system ensures that Wisconsin's sled does not damage the environment it uses. Designed for manufacturability with an aesthetically pleasing package, the BAT 600 is a cost-effective solution for performance-oriented riders seeking a cleaner, quieter snowmobile.

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REFERENCES

1. Lela, C., White, J., Haines, H., and Sacklin, J. “Laboratory Testing of Snowmobile Emissions: Southwest Research Institute.” Report number SwRI 08.05486. July 2002. Montana Department of Environmental Quality. Helena, Montana, and National Park Service, Yellowstone National Park, Wyoming.
2. National Parks Service. United States. Department of the Interior. Snowmobile Best Available Technology (BAT) List. 2013. Web. *<http://www.nps.gov/yell/parkmgmt/current_batlist.htm>*. (Website accessed 2/15/2014)
3. “The Clean Air Act Amendments of 1990 List of Hazardous Air Pollutants.” U.S. Environmental Protection Agency. *http://www.epa.gov/ttn/atw/orig189.html.* (Website accessed 2/12/2014)
4. Gumpesberger, M., Gruber, S., Simmer, M., Sulek, C. et al., "The New Rotax ACE 600 Engine for Ski-Doo," SAE Technical Paper 2010-32-0001, 2010, doi:10.4271/2010-32-0001.
5. BRP-Ski-doo. Engine Technologies-Rotax ACE 600. *http://www.ski-doo.com/technologies/engine-technologies/4-strokes.aspx*. (Website accessed 2/13/2014)
6. Heywood, J.B. “Internal Combustion Engine Fundamentals.” McGraw Hill, Inc 1988
7. Continental Flex Fuel Sensor. http://usa.vdo.com/products_solutions/cars/powertrain/sensors/powertrain/flex-fuel-sensor/ (Website accessed 2/15/2014)
8. Emitec Innovations. http://www.emitec.com/index.php?lang=en&mid=e4&doc=50 (Website accessed 2/12/2014)