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

Derek Landwehr, Mike Solger
Glenn R. Bower, Ethan K. Brodsky
University of Wisconsin-Madison

ABSTRACT

The University of Wisconsin-Madison Snowmobile Team has designed and constructed a clean and quiet, high performance snowmobile for entry in the 2013 SAE International Clean Snowmobile Challenge. Built on a 2013 Ski-doo MXZ chassis, this machine features a turbocharged 600 cc Rotax ACE fuel-injected four-stroke engine equipped with a flex-fuel sensor and Woodward control system which allows for full engine optimization using a range of fuels from E0 to E85. An electronic throttle body, mass airflow sensor and a closed-loop oxygen sensor are used to control spark and fueling. Utilizing a 3-way catalyst designed by W.C. Heraeus-GmbH, this sled reduces carbon monoxide (CO) and hydrocarbons+oxides of nitrogen ($HC+NO_x$) emissions to far surpass BAT and current EPA standards. With all of the modifications, the clean turbocharged Rotax ACE is capable of a power output of 55 kW and utilizes a catalytic muffler system to reduce sound levels to 72 dBA using SAE test procedure J192. The entire engine and exhaust system is packaged in a manner that builds on the snowmobile's aggressive OEM appearance. 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

SAE International 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 HC, CO, 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 2013 CSC will be held in Michigan's Keweenaw Peninsula from March 4-9th, 2013.

The following paper discusses how the University of Wisconsin–Madison team has engineered an entry for the 2013 CSC that improves upon the industry's best available emissions technology, while maintaining exceptional riding characteristics and low cost. After a brief discussion of results from a snowmobile consumer survey, the first section addresses the engine selection process, modifications to the snowmobile's drivetrain, and engine control strategy. The next section describes the fuel system modifications necessary for flex-fuel capability. The third section focuses on emissions output and emissions reduction techniques. Specific design enhancements that reduce overall snowmobile noise are included in the following section. Finally, the paper summarizes the implementation costs needed to construct the Bucky ACE Turbo.

MARKET SURVEY

The guiding principles for the 2013 UW-Madison clean snowmobile design are performance, practicality, and efficiency. The design objective is to win the Clean Snowmobile Challenge with a snowmobile that is not only clean and quiet, but maintains the speed and handling characteristics that consumers expect from a modern snowmobile. In order 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, Wisconsin and the Prairie Riders Snowmobile Club of Pleasant Prairie, WI. While attending the annual Vintage Oval Races and Radar Run on Spirit Lake in Three Lakes and through an online survey, the team surveyed 120 snowmobile enthusiasts with the goal of determining the performance requirements of the average consumer. The survey asked volunteers to rank several characteristics that are important to a consumer when buying a snowmobile from least important (1) to most important (5) from the following list: acceleration, handling, price, fuel economy, and emissions. The results, as shown in Figure 1, show that handling and acceleration influence a buyer significantly more than price, fuel economy or emissions.

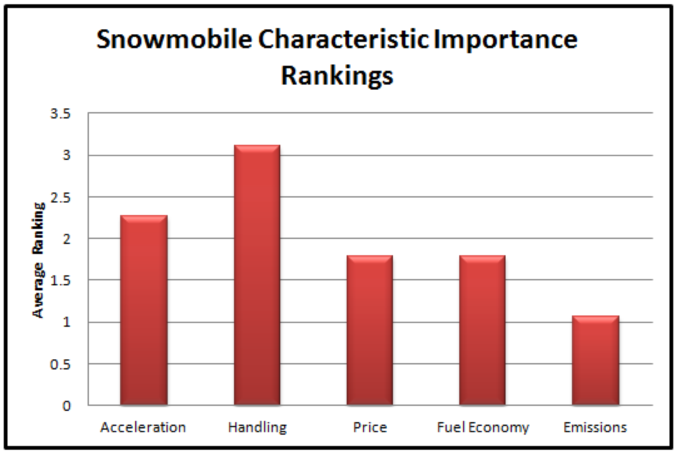

Figure 1. A survey of 120 snowmobilers shows that handling and acceleration are the most important considerations when purchasing a snowmobile.

The survey results confirm the guiding principles of the Madison Clean Snowmobile Team. Across every age group, snowmobilers will not enjoy an environmentally friendly snowmobile if it does not exhibit acceptable acceleration and handling performance.

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:

- Naturally aspirated four-stroke snowmobile engines
- Turbocharged four-stroke snowmobile engines
- Direct-injection (DI) two-stroke snowmobile engines
- Compression ignition (CI) engines

The choice between current snowmobile engine technologies is fairly straightforward. Conventional and DI 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 NOx, 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 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 and costly modifications. CSC 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 AND CHASSIS SELECTION

Given the heavy weighting on emissions in CSC competition scoring, the team reviewed engine-out emissions produced by two-strokes and 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 (Advanced Combustion Efficiency) 600, which is available through BRP's Ski-doo snowmobile line, advertises 42 kW (60 hp) and is BAT compliant from the factory. Other options considered were the Polaris FST and Ski-doo 4-TEC, which are both capable of power output of 97 kW (130 hp).

Table 1. Engine Comparison of Leading 4-Stroke Snowmobiles

	Power (kW)	Weight (kg)	Fuel Economy (km/L)	Emissions (g/kW-hr)		
				HC	CO	NOx
Ski-Doo ACE 600	42	40	12.3	8	90	N/A*
Polaris FST	112	64	7.2	6.2	79.9	N/A
Ski-Doo 4-Tec 1200	97	62	7.6	9	116	N/A

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

While all three engine options fulfill current EPA emissions requirements, the ACE 600 "sets new standards in efficiency" giving it an advantage as fuel economy plays a fairly large role in the CSC [4]. 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 outlines further specifications of the Rotax ACE. More importantly, the ACE is the lightest 4-stroke engine UW considered. When paired with a lightweight Ski-doo REV-X chassis and suspension, this package allows for higher fuel economy and a more comfortable rider experience.

Table 2. Rotax ACE 600 Engine Specifications

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

One problem slightly hindering the performance appeal of the stock Rotax ACE 600 is its rated 42 kW (60 hp) power output. The UW-Madison team decided to add a small turbocharger to increase the power enough to appease most consumers. To compliment the ACE powerplant, the UW-Madison team has implemented a Garrett GT1241 turbocharger, which is suited for applications between 37 and 88kW (50-120 hp). With the turbocharger being small in physical size and perfectly fit for the ACE power-wise, it was a natural choice.

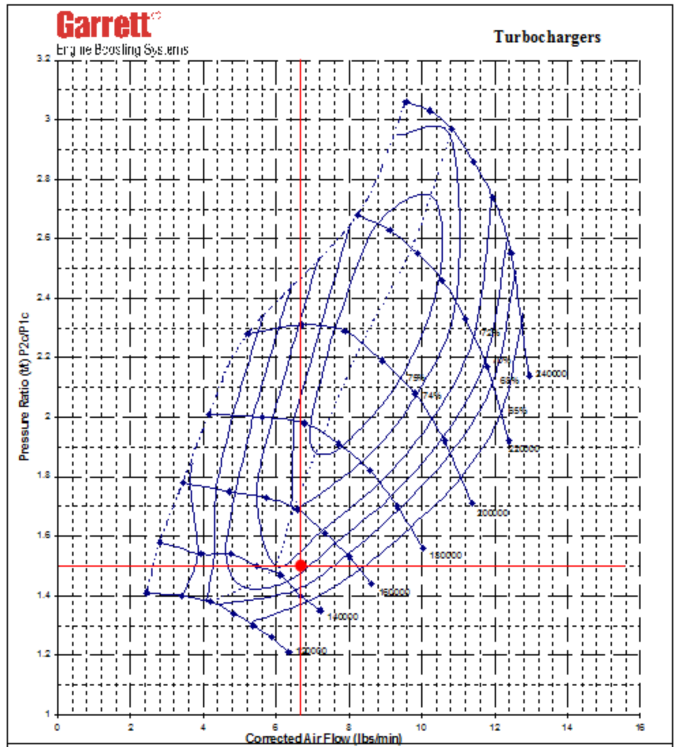

Figure 2. Garrett GT1241 compressor efficiency map; 72% efficiency at pressure ratio of 1.5 at maximum RPM and maximum manifold pressure.

CONTROL HARDWARE

Since Ski-doo would not supply the tools to reprogram the stock ACE engine controller to operate on ethanol blended fuels, 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 130°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 Mototron model was modified for this particular application and has ignition and fueling tables that are load, speed, and manifold pressure dependent. In addition, the model has adaptation for atmospheric conditions and cold starts. Finally, the model calculates fuel rates using inputs from the ethanol sensor and the target air-fuel ratio, which provides seamless switching between gas and ethanol fuels.

POWERTRAIN ENHANCEMENT

The Rotax ACE is already a very efficient and advanced engine, utilizing components like "Diamond-like-Carbon" coating on valve tappets, a moveable chain tensioning rail, and self-contained lubrication and cooling systems [5]. While there weren't many areas that the Madison team could improve the engines efficiency, there were several areas modified to increase the engines tune-ability and adjustment to the range of fuels.

To improve tune-ability, efficiency and consistency, the Bucky ACE Turbo utilizes an electronic throttle body (ETB) in the intake system in conjunction with a pedal position unit (PPU). This enhancement reduces complications of calibrating the engine, improves cold starting, and improves idle conditions over an idle air controller. Another major change to UW's traditional engine control strategy is the addition of a mass air flow (MAF) sensor. The MAF sensor not only measures the air velocity through the engine intake, but also measures relative mass of the air so changes in pressure and temperature are no longer variables in engine calibration. The use of a MAF sensor has allowed for simpler tuning of the engine as it eliminates the need for volumetric efficiency tables from speed density calibrations. Fuel injection calibration and control was made possible by utilizing the electronic throttle body, a wideband oxygen sensor, and a fuel control strategy developed in Matlab Simulink. A Bosch wideband O_2 sensor was utilized in the Bucky ACE for closed-loop control of the fuel injection.

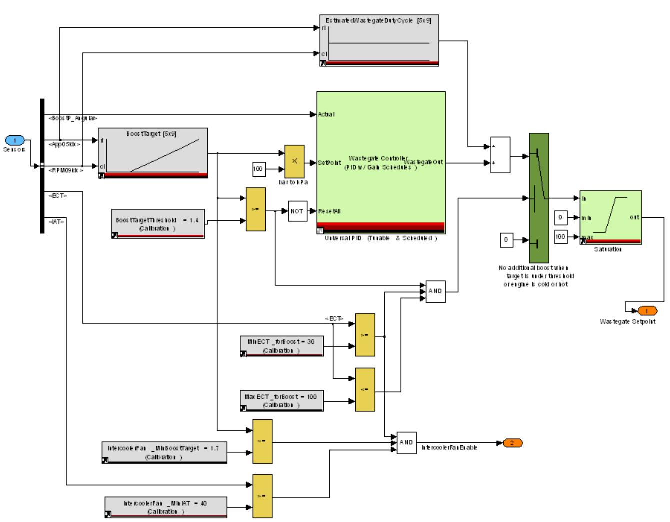

Figure 3. Image of UW-Madison's control strategy Simulink model

The Motohawk software also allows for safeties to be built into the control strategy. Boost can be limited in certain situations, such as when coolant temperature is below 20˚ C (68˚ F) or exceeds 87˚ C (188.6˚ F). These safeties protect the engine and turbo from excessive wear and damage.

Typically, when calibrating an engine, there are two main goals to adhere to: minimize BSFC under part-throttle operation and to maximize torque at 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 that the engine must be calibrated to operate within (Figure 4).

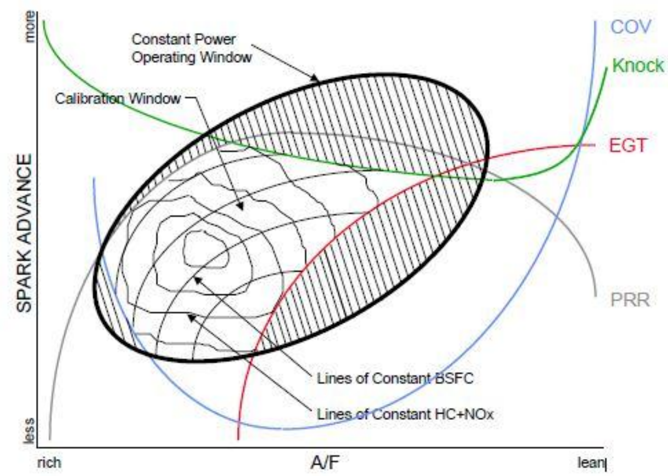

Figure 4. Graph of the typical calibration window [6].

Calibration of the 2013 Madison engine was performed using a water-brake dynamometer, a wideband O_2 sensor, and exhaust thermocouple probes. By monitoring torque, exhaust temperatures and air-fuel ratio (AFR) values, spark timing and fueling could properly be calibrated.

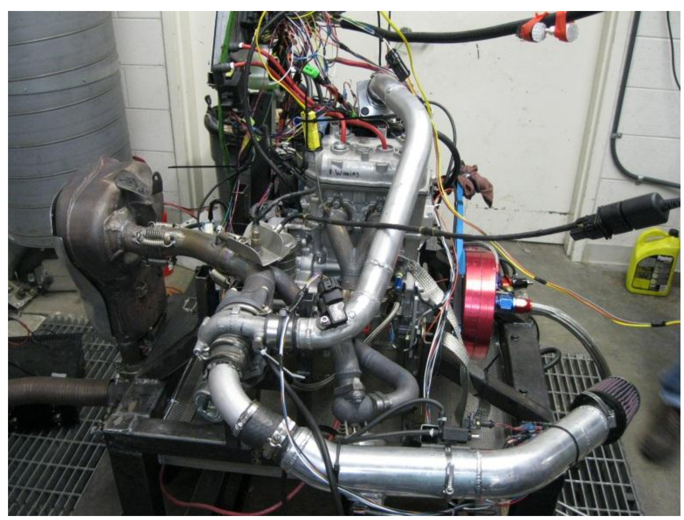

Figure 5. The UW-Madison dynamometer test stand for engine calibration.

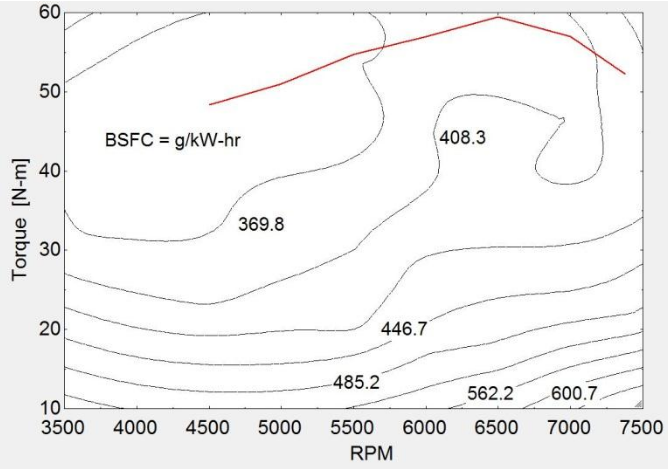

Figure 6. Bucky ACE Turbo brake-specific fuel consumption and torque data

Figure 6 shows brake-specific fuel consumption (BSFC) and torque results from the Bucky ACE Turbo on the UW dynamometer stand. Maximum BSFC is achieved near the cruising trail speed of the Bucky ACE Turbo and peak torque is achieved at 6500 RPMs.

FUEL SYSTEM MODIFICATIONS

In order to run on a wide range of ethanol fuel blends and due to the use of forced induction, modifications to the fuel delivery system were necessary. Because of ethanol's corrosive properties, the team upgraded all fuel system components to an ethanol compatible material. The fuel injectors needed to be changed to accommodate the higher fueling rates needed for ethanol fuels and turbocharging. Madison identified a Bosch fuel injector that was capable of delivering 50% more fuel than the stock injector. The injector specifications are given in Table 3.

Table 3: Fuel Injector Specifications

	Stock Injector	**Ethanol Injector**
Manufacturer	Continental	Bosch
60 Sec Flow	160 g	237g
Rail Pressure	400 kPa	300 kPa
Bent Angle	0º	0º
Spray Angle	20º	20º

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. Ethanol dissolves impurities in poor fuel requiring a larger, finer fuel filter to protect the fuel system.

To allow for flex-fuel capability, the team installed a Continental Flex-Fuel sensor. It uses a dielectric measuring principle to detect the amount of alcohol in the fuel. The sensor also reports fuel conductivity and temperature [7]. Since air-fuel ratios are calculated on a gravimetric basis and fuel injectors are measured on a volumetric basis, the fuel temperature is measured to allow for density compensation.

These fuel properties, along with the mass airflow measurements, are supplied to the Mototron controller. The engine management system is based on the physical models of the combustion process instead of simply using correction tables for deviations from the base calibration. Wisconsin's calibration is designed to provide a prescribed global air-to-fuel ratio. The computing power of the Mototron controller is used to continually calculate the correct fuel injection amount utilizing the intake mass airflow rate, the fuel density and the desired fuel-air ratio (Figure 7). 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 the desired value.

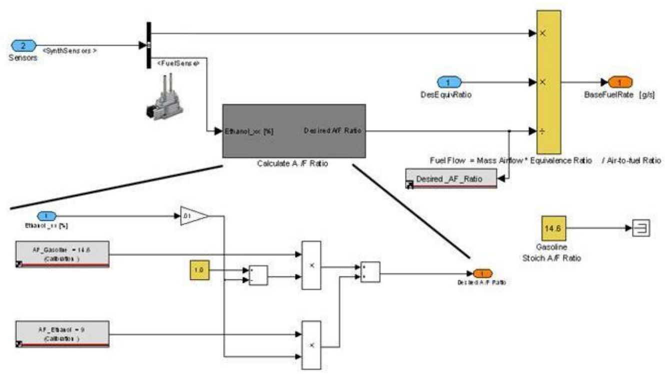

Figure 7. SimuLink block diagram for flex-fuel engine control strategy utilizes inputs from Continental flex-fuel and MAF sensors to determine desired fueling rate.

EMISSIONS AND EXHAUST DESIGN

In order to further reduce emissions to automotive standards, the Wisconsin team worked with W.C. Heraeus GmbH to select a catalyst for the described engine set-up, emissions goals, and size constraints. Because the CSC emissions scoring is based on a combination of HC, CO and NO_x levels, a three-way platinum/palladium/rhodium-based catalyst was chosen for its ability to effectively reduce all three pollutants simultaneously. Although a slight lean-burn fuel strategy is used for the improved fuel economy (which inherently results in higher NO_x emissions), the chosen catalyst is capable of reducing NO_x emissions to a CSC acceptable level without effecting UW's E-Score significantly. The Heraeus washcoat was applied to a metal honeycomb substrate utilizing Emitec's SuperFoil® technology. This technology influences the flow distribution causing turbulence within the cell channels. The turbulence increases the conversion rate by increasing exhaust gas/washcoat contact time, allowing for the use of smaller volume catalyst and/or reduced back pressure [8].

Table 4. Catalyst Specifications.

Manufacturer	W.C Heraeus GmbH
Diameter	70mm
Length	149mm
Substrate	SuperFoil® Metal Honeycomb
Density	600 cpsi (cells per square inch)
Loading	Platinum 11.1 g/ft3 Palladium 55.6 g/ft3 Rhodium 8.3 g/ft3

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.

NOISE REDUCTION

Although the Ski-doo MXZ Sport ACE600 is relatively quiet in its stock format, the addition of the catalyst and turbo 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, and final drive and suspension assemblies. To reduce the effects of the intake and clutch area, a rubber sound attenuation material was used to coat the clutch cover and air box. Further reduction of engine area noise was accomplished by adding a foam material with a silver heat reflective lining in the under-hood area.

TRACTION

Due to consumer demand for a snowmobile with responsive handling and acceleration, a studded track was a necessity. For 2013, 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 weighing 3.73 kg (8.21 lbs) less than 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 Wisconsin did find that studs slightly decrease the overall driveline efficiency, 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 $10,371.63, the 2013 Bucky ACE Turbo 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 ACE600 configuration.

CONCLUSION

The 2013 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 implemented a forced induction system into the revolutionary four-stroke ACE powerplant, combining performance with EPA 2012 emissions compliance. The Bucky Ace Turbo's flex-fuel capability gives consumers the ability to utilize 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 Bucky ACE Turbo is a cost-effective solution for performance-oriented riders seeking a cleaner, quieter snowmobile.

ACKNOWLEDGMENTS

The University of Wisconsin Clean Snowmobile team gratefully acknowledges the support of the College of Engineering and specifically the other UW vehicle projects. The team also thanks its many sponsors, especially United Wisconsin Grain Producers LLC and the Wisconsin Corn Promotion Board for their extensive support. Additionally, thanks go out to Ron Hallstroms Sports & Marine, Garrett, National Instruments, Mototron Control Solutions, W.C Heraeus, Owens Corning, Emitec, 3M, Continental Corp., Camoplast, Goodyear Engineered Products, and Castle Racing for supporting us with the best available products. The team also wishes to thank Signs by Tomorrow for the donation of the snowmobile graphics and sponsor logos. The team would also like to thank their advisors, Ethan K. Brodsky, Glenn R. Bower, and graduate advisor, Shawn Spannbauer. 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.

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. 2011. Web. *<http://www.nps.gov/yell/parkmgmt/current_batlist.htm>*. (Website accessed 2/23/2012)
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 2/19/2013)
4. BRP-Ski-doo. Engine Technologies-Rotax ACE 600. *http://www.ski-doo.com/technologies/engine-technologies/4-strokes.aspx*. (Website accessed 2/19/2013)
5. 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.
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 2/20/2009)
8. Emitec Innovations. *http://www.emitec.com/index.php?lang=en&mid=e4&doc=50* (Website accessed 2/20/2008)