Miller Cycle and Variable Geometry Manifold Implementations for Performance and Emissions Improvements

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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 2015 SAE International Clean Snowmobile Challenge. Built on a 2013 Ski-doo MXZ chassis, the design features a Rotax 600cc ACE port fuel-injected turbocharged four-stroke engine equipped to operate efficiently on gasoline and alcohol based fuel blends. The engine has been customized with a Woodward control system which allows for full engine optimization with complete flex-fuel 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 Continetal Emitec GmbH, this sled reduces NO_X, HC, and CO emissions by up to 95%. Optimized intake and exhaust camshafts were developed to optimize Miller cycle operation. An external wastegate, electronic boost control, and charge air cooler have been fitted to enable complete control of the turbocharger. A variable geometry intake manifold was implemented to account for the cylinder air-filling imbalance caused by a 270 degree crankshaft. 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 69 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 2015 CSC will be held in Michigan’s Keweenaw Peninsula from March 2-7th.

The following paper discusses how the University of Wisconsin – Madison team has engineered an entry for the 2015 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 discusses engine simulations and implementation of Miller Cycle camshafts. 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

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

The survey asked riders to rank from least important (1) to most important (7) several characteristics they considered when investing in a new snowmobile. The characteristics surveyed were acceleration, handling, price, fuel economy, emissions and sound output. As shown in Figure 1 handling, along with price and fuel economy were valued more than emissions and sound output.

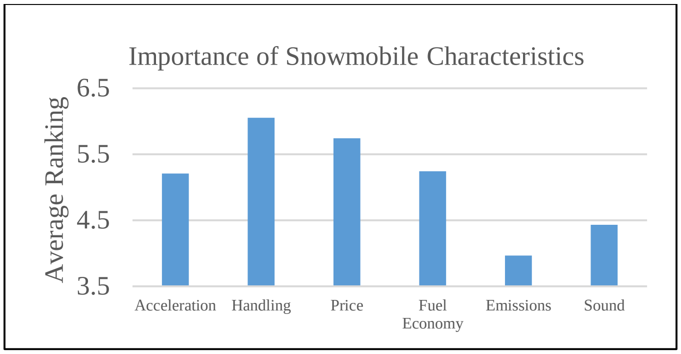

Figure 1. A survey of 25 snowmobile clubs across Wisconsin showing handling, price and fuel economy as the most important considerations when investing in a snowmobile.

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

ENGINE OPTION EVALUATION

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

It is well known that conventional two stroke and SDI two-strokes have significantly higher power-to-weight ratios than current four-stroke models. However, snowmobile emissions testing conducted by Southwest Research Institute (SwRI) states that commercially available four–strokes "…emit 98-95 percent less HC, 85 percent less CO, and 90-96 percent less PM" than conventional two-stroke snowmobile engines [4]. 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 considered by the team were listed as Best Available Technology (BAT) compliant [7]. 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) [9].

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

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

FINAL ENGINE SELECTION

With the focus of the Clean Snowmobile Challenge on emissions, the team compared four of the leading snowmobile engines for low emissions as shown in Table 1. Taking into consideration the results of the market survey, the team also valued the fuel consumption of each engine as well as the power and weight of each engine. The Rotax ACE (Advanced Combustion Efficiency) 600, which is available through BRP's Ski-doo snowmobile line, advertises 42 kW (56 hp) and is BAT compliant from the factory. Another model in the same product line is the ACE 900 which develops 67 kW (90hp) and is also BAT compliant. Other options considered were the Polaris FST and Ski-doo 4-TEC, which are both capable of higher power outputs than either of the ACE engines.

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***

It can be seen in Table 1 that all four engines have comparable HC and CO emissions and when coupled with an optimized catalyst, CSC E-Scores of over 205 could be reached.

While all four engine options fulfill current EPA emissions requirements, both the stock ACE 600 and 900 engines "set new standards in efficiency" giving them an advantage as fuel economy plays a fairly large role in the CSC [2, 3]. The ACE design also allows for integrated engine lubricant and cooling systems, which minimizes weight, complexity, and external plumbing, making it easier for modification and implementing Wisconsin's designs. Table 2 below shows the similar specifications of the two ACE engines.

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

CONTROL HARDWARE

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

The base Simulink control model underwent numerous modifications to incorporate ignition and fueling tables that are load, speed, and manifold pressure dependent. To create a more robust and marketable control strategy the model adapts to atmospheric conditions and cold start conditions, as well as engine protection features including limiting boost pressure, throttle opening, and fueling should the coolant temperatures or oil pressures reach unsafe levels. The model calculates optimized fueling rates in real time based on inputs from the wideband oxygen sensor and mass air flow sensor.

POWERTRAIN ENHANCEMENT

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

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

Several major components were installed to allow the complete optimization of the engine for a wide range of alcohol based fuels. The Bucky ACE Turbo 600 (BAT 600) makes use of an Electronic Throttle Body (ETB) which occupies the same space as the stock mechanical throttle body. Utilizing an ETB reduces complications of calibration, improves cold start ability, and when used in conjunction with the electronic boost controller, reduces pumping losses. This is done by opening the throttle with little or no boost to start followed by increasing boost pressure at high throttle requests. In addition to the ETB was the implementation of a mass air flow (MAF) sensor relaying intake mass air flow and temperature directly to the Motorola ECU. With the design of the variable geometry manifold (VGM) to ensure balanced cylinder air intake, multiple manifold pressure (MAP) sensors were installed; two sensors were in the new intake manifold and a third was added a the turbocharger.

The combination of the ETB, MAF sensor, MAP sensors and wideband oxygen sensor was used to calibrate and control fuel injection and develop a fuel control strategy. Part of the control strategy is used during large transients when the closed loop system is unable to keep the air-fuel ratio (A/F ratio) within one percent of the desired value and fuel injection control is determined by predefined fueling tables.

To modify the stock Rotax ACE 600 to operate a Miller Cycle, a Garrett GT 1241 turbocharger, charge air cooler, and external wastegate were installed. The Mototron engine controller coupled with the electronic boost controller allowed for an optimized boost control strategy shown in Figure 3.

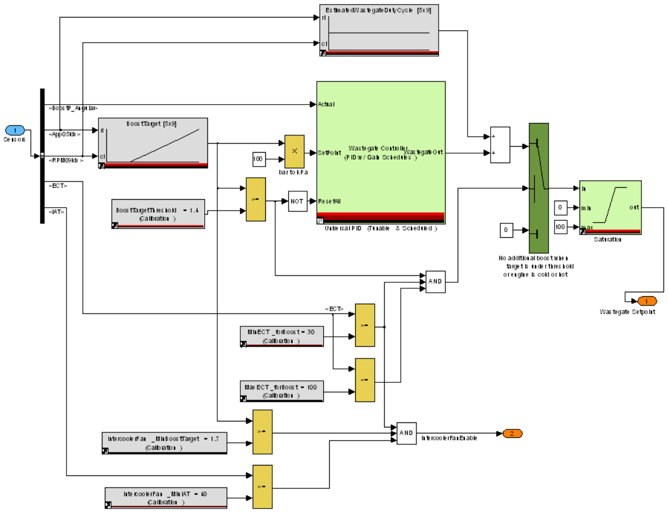

Figure 3. Image of control strategy Simulink Model for electronic turbo boost control.

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 optimized 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 [4]. These constraints define a window, shown in Figure 4, that the engine must be calibrated to operate within.

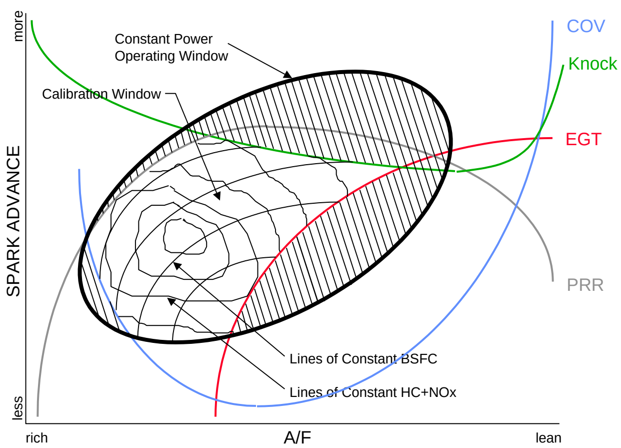

Figure 4. Graph of typical calibration window [8].

Calibration of the 2015 engine shown in Figure 5 was performed using a water-brake dynamometer. Wideband O_2 sensors, and exhaust thermocouple probes. By monitoring torque, exhaust temperatures, and A/F ratio values, spark timing and fueling could be properly calibrated.

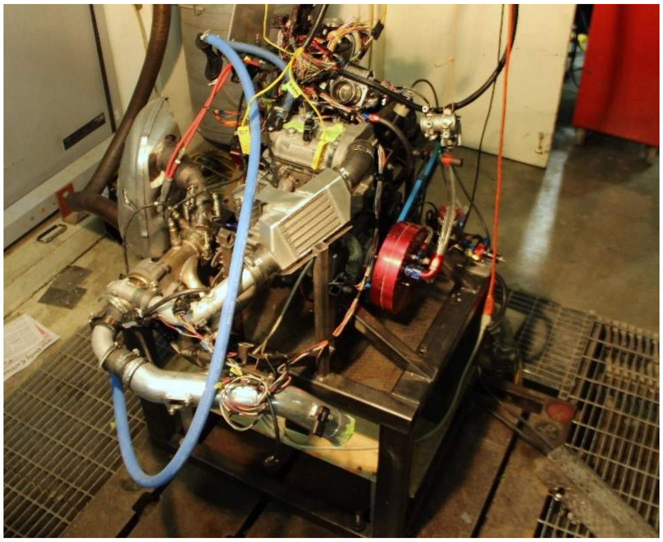

Figure 5. Dynamometer testing stand used for all calibrations.

Another improvement made to the powertrain to enhance efficiency was the addition of belt drive instead of the stock chain driven system. This eliminated the need for chain case oil which can be very viscous at lower temperatures. Like most drive shafts found on modern snowmobiles, the 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 concentric.

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.

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.

Ideal valve timing for Miller cycle was determined using a full factorial DOE using intake valve opening and closing, exhaust valve opening and closing, and boost pressure. The optimal result provided a good 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 6. 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.

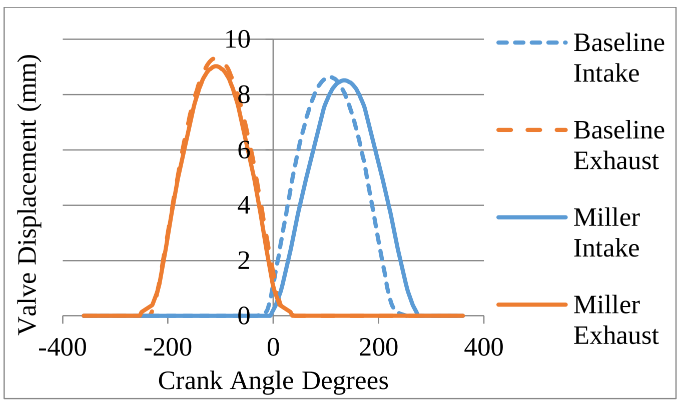

Figure 6. A comparison of baseline and Miller cycle valve lift profile used for modeling comparisons.

Figure 7 shows intake valve mass flow for the magneto (MAG) and power take off (PTO) cylinders as a function of crank angle for 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. It can also be see that that MAG cylinder receives more air than the PTO cylinder. The root cause of this imbalance is the 0, 540 degree firing order of the stock engine, furthermore the stock intake manifold inlet is asymmetric about the two runners and favors the PTO cylinder; the stock intake was design for below ambient pressures which has led to poor performance in boosted applications.

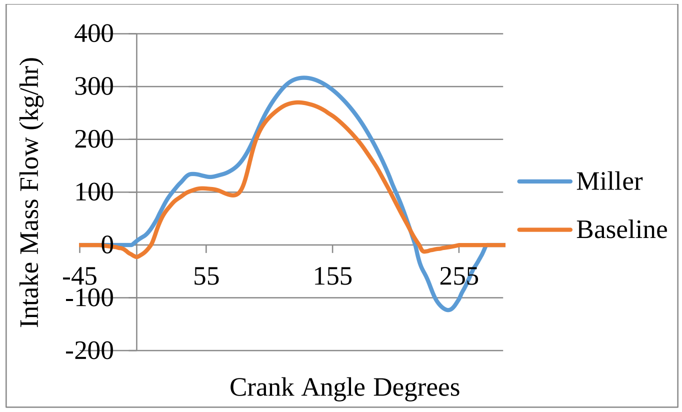

Figure 7. Modeled intake valve mass flow as a function of crank angle.

Last year the Wisconsin team observed this problem however there was insufficient time to implement a proper and reliable solution before the competition deadline. Instead, Bosch LSU4.2 lambda sensors were fitted in each exhaust primary tube before the collector, allowing for equivalency ratios for each individual cylinder to be measured; the readings of these sensors were skewed as a results of the higher pre-turbine exhaust pressures. However a reasonable assumption was made that both sensors were operating under the same pressure and therefore the observed difference in readings was accurate. Upon completion of final spark calibrations the fueling for each cylinder was trimmed such that a global equivalency ratio was maintained. The sensors were then removed after calibrations as their longevity at the high exhaust gas temperatures was questionable. This temporary solution worked however there was much room for improvement and several permanent solutions were investigated.

To equalize the cylinder filling imbalance, a new intake manifold was designed and built. The optimization process began by addressing some inaccuracies in the simulation by modeling the stock intake manifold geometry in 3-D, this model was then fed into the WAVE Mesher program to be accurately converted into the 1-D simulation parameters. The Miller valve timing, turbocharger, and associated piping were also updated to reflect recent design changes as were the intercooler, boost control strategy, and boost and fuel target maps. All simulations were conducted at mid to full load operating points from 3600 to 7600 rpm while key parameters such as BSFC, torque, volumetric efficiency, cylinder pressures, and intake port mass flow rates. All proposed solutions were bounded by the same envelope as the stock manifold, they must not negatively affect the aforementioned parameters, and maintain reliability.

A summary of initial simulations is shown below in Table 3.

Table 3. Initial simulations expressed as percent of stock manifold geometry.

Iteration	A	B	C
Plenum Volume (L)	2.0	4.0	6.0
Runner length (mm)	150	200	250

Plenum volumes and runner lengths above the values listed under iteration C were too large and would have required extensive modification to the fuel tank. Results of these simulations are shown below in Figures 8 and 9.

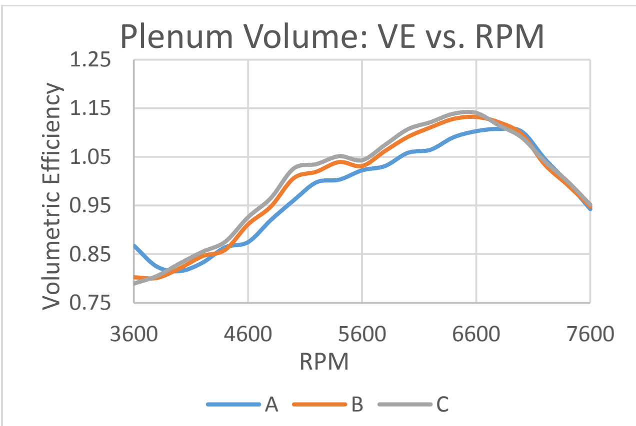

Figure 8. Effect of runner length on volumetric efficiency for the stock intake manifold.

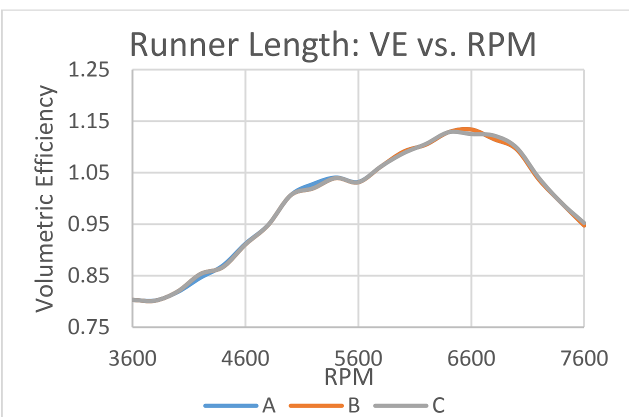

Figure 9. Effect of runner length on volumetric efficiency for the stock intake manifold.

Based on these simulation results a split plenum manifold was designed. Plenum geometry is loosely based on the stock manifold, however the new manifold is symmetric about the runners and does not favor a particular cylinder. From Figure 8 the volumetric efficiency increased with increasing plenum volume; to maintain good throttle response the total volume of the split VGM was design to be 4.2L plenum had the greatest volumetric efficiency. Furthermore, final runner length was unchanged from stock as this length produced a desirable torque curve, shown in Figure 9, with the low and high speed torque peaks occurring at 5000 and 6500 rpm, respectively.

The split plenum allows each cylinder to draw the intake charge from its own plenum that is separated from the other cylinder. The volume of each plenum was made equal to one half of the stock manifold which allowed peak power to be maintained without compromising throttle response. Initial split plenum designs reduced the cylinder filling imbalance, however the volumetric efficient and peak torque were significantly affected. To take advantage of the decreased cylinder filling imbalance and improved volumetric efficiency at low speeds while maintaining high speed performance, a variable geometry intake manifold (VGM) was designed. This design technique is well documented [6, 10] and has been proven to improve volumetric efficiency of naturally aspirated automotive engines however minimal literatures exists documenting the application to small Miller cycle engines.

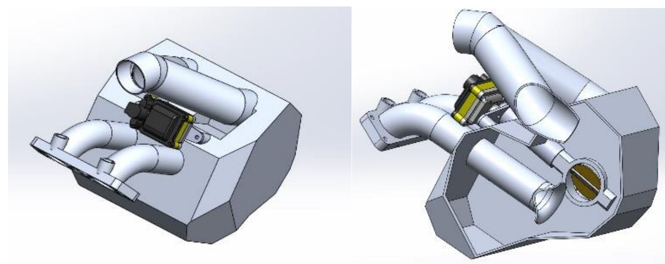

Figure 10. Model and section view of the optimized variable geometry intake manifold.

The 3D model of the final VGM is shown above in Figure 10. The internal plenum valve has a diameter of 46mm and is electronically actuated with position feedback. Initial valve target angles were determined in WAVE and validated on the engine dynamometer using a speed and load based table.

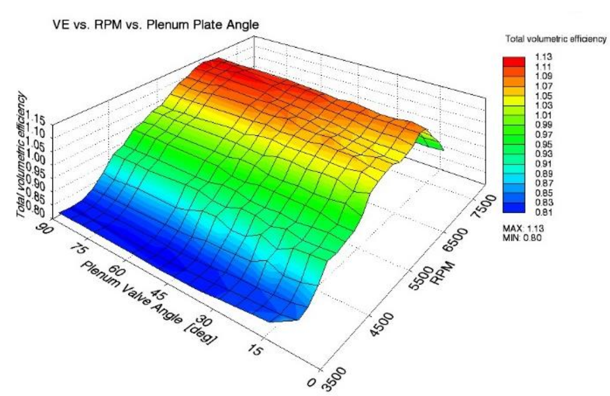

Figure 11. The effect of plenum valve angle on VGM volumetric efficiency.

As can be seen above in Figure 11, the valve angle has a significant effect on the engines volumetric efficiency. The plenum valve remains closed from idle to approximately 3600 rpm and is fully open at 6400 rpm; this significantly increases the overall volumetric efficiency of the engine. The torque curve of both designs is shown below in Figure 12. It can be seen that the addition of the VGM to the engine increases its low end torque which is better for drivability.

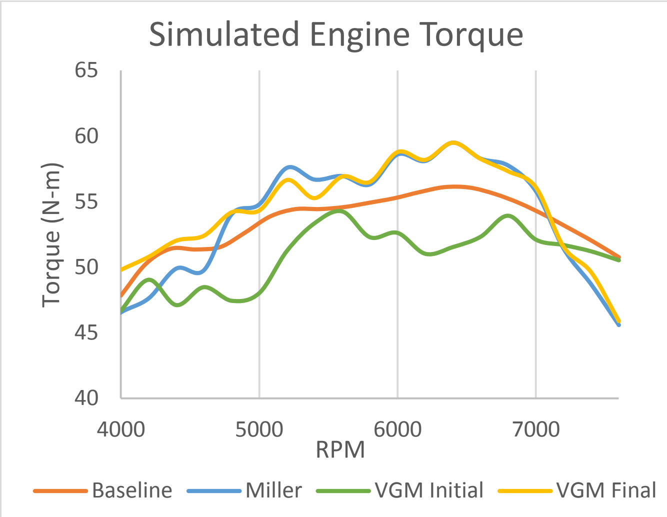

Figure 12. Simulated torque, final VGM design has improved low speed torque.

The difference in maximum cylinder pressure for the baseline stock and Miller engines, initial fixed split geometry manifold, and final VGM are shown below in Figure 13.

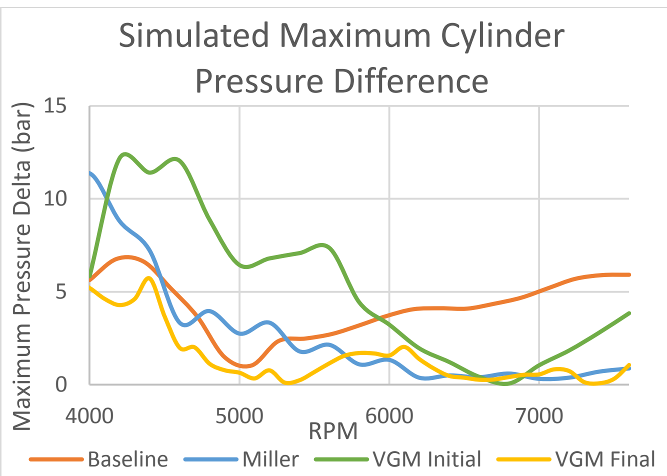

Figure 13: Simulated difference in cylinder pressures (MAG minus PTO); for reference, maximum cylinder pressures are 95-100 bar.

The initial split plenum design resulted in an undesirable cylinder filling imbalance from 4000 to 6000 rpm; low speed cylinder pressures we nearly equalized. Additionally, the initial split plenum greatly reduced brake torque, as shown above in Figure 12.

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. Modeled BSFC of the baseline and Miller design in g/kW-hr.

	Baseline	2014 Miller	2015 VGM	Relative Weighting
Mode 1	266	270	269	0.12
Mode 2	312	297	290	0.27
Mode 3	358	339	334	0.25
Mode 4	473	444	420	0.31

Table 4 is a comparison of the 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 Miller and VGM 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 VGM engine shows improved part throttle efficiency over the baseline and Miller. The relative weighting of each mode is also shown in Table 4. 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.

EMISSIONS

For the 2015 Clean Snowmobile Challenge, the Wisconsin team worked with Continental Emitec GmbH and W.C. Heraeus GmbH to reduce emissions on the BAT 600 to automotive standards. With a focus on HC, CO and NO_X, emissions a three-way catalyst was implemented before the muffler to effectively reduce the three targeted species.

To fully optimize the precious metal washcoat, exhaust gas was collected between the turbocharger and the muffler. Using a vacuum chamber case, exhaust gases were pulled into sampling bags through a super cooler to remove condensing water vapor from the stream. While sampling, fuel flow, mass air flow, equivalence ratio, and exhaust gas temperatures. The collected exhaust gases were then analyzed with a ThermoNicolet Nexus 670 FTIR which reported emission concentrations using the Omnic 6.1 software.

Working with Heraeus, a platinum/palladium/phodium based washcoat was applied to Emitec's SuperFoil metal honeycomb substrate. The loading characteristics as well as substrate description are shown in Table 5. The high loading of palladium is used to effectively oxidize the CO and HC without the unwanted reactions that can occur with high platinum loading.

Table 5. Catalyst substrate and washcoat data.

Manufacturer	W. C, Heraeus GmbH
Diameter	70 mm
Length	149 mm
Foil thickness	0.03 mm
Substrate	Emitec SuperFoil® Metal Honeycomb
Density	600 cpsi
Loading	Platinum 11.1 g/ft^3
	Palladium 55.6 g/ft^3
	Rhodium 8.3 g/ft^3

To optimize the reduction of CO, HC and NO_X, the exhaust gases entering the three-way catalyst must alternate between slightly rich and slightly lean. As seen in Figure 14 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 [4].

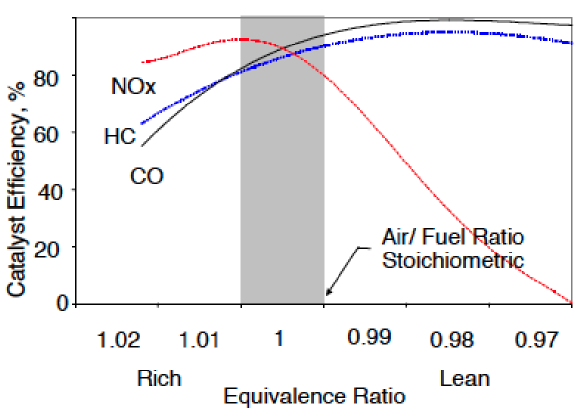

Figure 14. Shows the NO_X, CO, and HC conversion efficiency for a three-way catalytic converter as a function of exhaust gas air/fuel ratio operating on gasoline (Adapted from [4]).

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 15. 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.

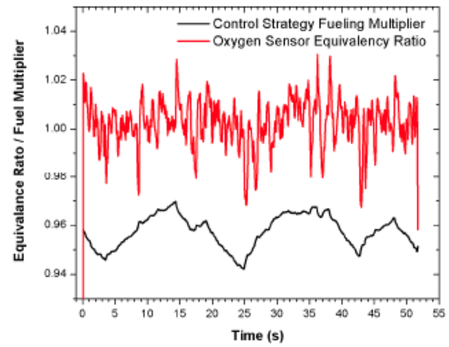

Figure 15. Engine equivalence ratio oscillating near stoichiometric as a result of closed-loop control.

In Wisconsin's Student Automotive Center the engine is roughly calibrated on the engine dynamometer to within 0.2% of the target exhaust oxygen content. From here 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. 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 16.

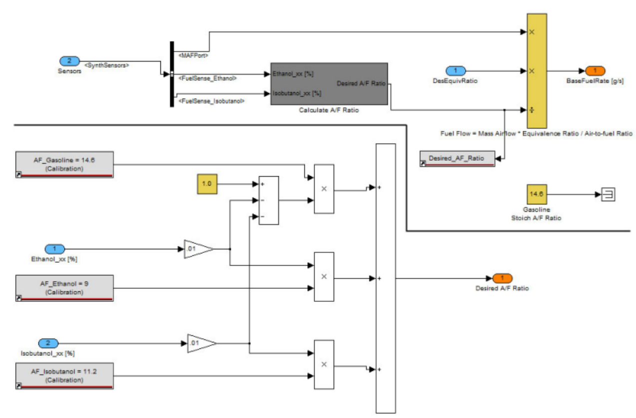

Figure 16. Simulink block diagram for flex-fuel and iso-butanol engine control strategy.

The combination of the optimized washcoat and the closed loop fuel algorithm with the wideband oxygen sensor allowed for optimized emission reductions to be achieved in 2015. The projected E-score for Wisconsin's 2015 CSC entry is calculated to be 207.04. Table 6 shows projected 2015 5-mode lab emissions results against stock ACE 600 emission results [3]

Table 6. Projected 2015 emissions comparison between eco and performance mode.

	BAT 600	Stock [5]
CO (g/kW-hr)	8.1	90
HC (g/kW-hr)	0.3	8
NO_x (g/kW-hr)	1.11	N/A
E-Score	207.04	190

MECHANICAL NOISE REDUCTION

The team used a stock 2013 Ski-Doo MXZ 600 ACE to identify sources of mechanical noise emitted from the snowmobile. Testing consisted of a drive-by at a speed of 72 km/hr and WOT acceleration. The protocol for the WOT tests was an entry at 24 km/hr with a transition to WOT at a point 22.5m before the plane of the microphones. A spectral noise analysis was performed using dual microphones at a distance of 15m on both the drive-by and WOT tests. The data was recorded using a Hi-Techniques HT-600 data acquisition system able to process the sound density vs. frequency.

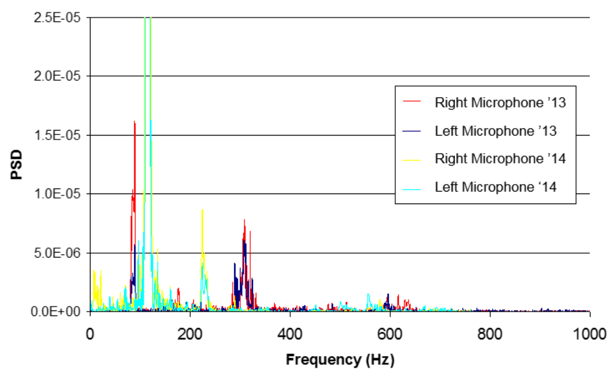

Figure 17. Spectral sound density of past Wisconsin CSC entries to determine typical sources of noise from a snowmobile.

Figure 17 shows a Power Spectral Density plot from the BAT 600. 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.

The application of LizardSkin® Sound Control coating to the underside of the tunnel, shown in Figure 18, was applied to reduce noise resonating from the drive paddles and rear suspension. The Lizard Skin is designed to dampen rattles, vibrations, and road noise all of which are helpful in ensuring a quiet experience for bystanders and the rider.

Figure 18. View of tunnel underside lined with Lizard Skin material.

To help reduce driveline noise, the common chain final drive was replaced with a quieter, more efficient belt drive from C3 Powersports. By reducing the amount of metal on metal contact in the drive system, the sled's driveline noise became noticeably lower.

The 2015 BAT 600 has a Camoplast Ripsaw II track which reduced track noise from the 2014 Wisconsin entry. The Ripsaw II has a 1/4 inch shorter lug to reduce resonance compared to the 2014 track, an Ice Attak track with a 1.25" lug. A second source of track noise on the 2014 entry was the use of a pre-studded track. The 2015 Wisconsin track does employ studs eliminating noise caused by the metal stud to ground impact.

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

WEIGHT REDUCTION

Weight reduction on the BAT 600 was one of the focuses to improve fuel economy. Through design, research, and implementation the BAT 600 dropped 60 pounds of "wet weight" and 27 pounds "dry weight" from the entry in the 2014 Clean Snowmobile Competition. Table 7 shows the weight reduction of parts from the 2014 entry to the 2015 entry. Key components include the use of smaller gas tank with a capacity of 6 gallons vs the stock tank of 11 gallons, the use of a belt drive compared to the stock chain case, and installing lighter front shocks.

Table 7. Summary of Weight lost from 2014 to 2015 Competition Sled

2014 Sled Component	Weight(Lb)	Replacement (Lb)
Front Shocks	9.6	6
Rear Shock	3.6	2.6
Gas Tank	64.37	30.37
Ethanol Sensor	1.4	0
Intercooler Fan	0.8	0
Trunk	2.2	0
ECU Mount	1.4	0.6
Intercooler	3.6	2.2
Chain Case	13.2	5
Track	39	32
Total Weight Lost:		60.4

COST ESTIMATES

Every component of the BAT 600 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 calibration and sound reduction. While these modifications add value to the sled, they would not significantly increase the price to the end user. The retail price of many of the components that replaced stock parts was less expensive. This is not reflected in the MSRP as competition rules require a 50% premium be added to any component which increases perceived customer value compared to the stock snowmobile. With an attractive MSRP of $11,301.29 the 2015 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 Artic Cat ZR5000 LXR. If key components of the BAT 600 such as the catalyst 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 2015 University of Wisconsin-Madison Clean Snowmobile Challenge Entry improves upon the Best Available Technology in performance and emission standards for over-snow recreational vehicles. Taking into consideration consumer performance requirements as well as CSC competition guidelines, the team implemented a VGMand Miller Cycle to further improve on the ACE 600 design. The BAT 600's flex fuel capability gives customers the ability to use a variety of less polluting fuels renewable fuels. The redesigned exhaust after treatment system as well as many of the other implement designs ensure that Wisconsin's sled is both consumer and environmentally friendly. Designed for manufacturability with an aesthetically pleasing package, the Bucky Ace Turbo 600 is a cost effective solution for performance oriented riders seeking a cleaner, quieter snowmobile.

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