Performance-driven Design and Implementation of Clean Four-Stroke Engine into Lightweight Chassis

Shawn Spannbauer, Derek Landwehr
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 2012 Society of Automotive Engineers' Clean Snowmobile Challenge. Built on a 2011 Polaris Rush Pro-R chassis, this machine features a Weber AG 750 cc port fuel-injected turbocharged 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 and a closed-loop oxygen sensor are used to control fuel-injection. Utilizing a 3-way catalyst customized for this engine by W.C. Heraeus-GmbH, this sled reduces carbon monoxide (CO) and hydrocarbons+oxides of nitrogen (HC+NO_x) emissions by up to 98% to an average specific mass of 12.04, and 0.17 g/kW-hr respectively. Equipped with a specialized camshaft with low valve overlap, Wisconsin reduced both engine-out emissions and fuel consumption by approximately 10%. With all of the modifications, the clean turbocharged MPE 750 is capable of a power output of 65 kW and utilizes a custom catalytic muffler system to reduce sound levels to 71 dBa using SAE test procedure J192. The entire engine and muffler system is packaged in a manner that builds on the snowmobile's aggressive OEM appearance. The reduced weight of the revolutionary Pro-Ride chassis in conjunction with other light-weight components results in a rider-friendly package that meets the criteria to succeed at the Clean Snowmobile Challenge and is desirable to the snowmobiling public.

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 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 2012 CSC will be held in Michigan's Keweenaw Peninsula from March 5-10th.

The following paper discusses how the University of Wisconsin–Madison team has engineered an entry for the 2012 CSC that improves upon the industry's best available emissions and sound technology, while maintaining exceptional riding characteristics. 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 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

The guiding principles for the 2012 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.

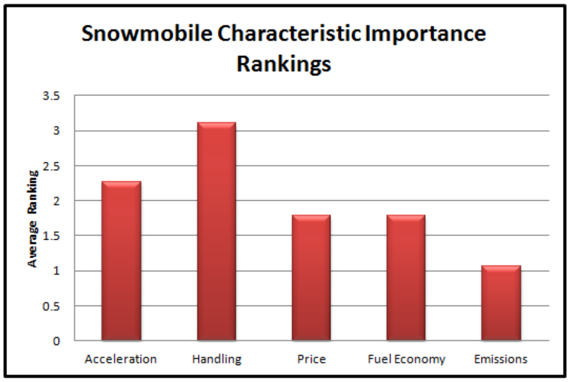

Figure 1: A survey of 120 snowmobilers from the Northern Lights Snowmobile Club of Three Lakes, WI and Prairie Riders of Pleasant Prairie, WI shows that handling and acceleration are the most important considerations when purchasing a snowmobile.

The survey results confirm the guiding principles of the Madison Clean Snowmobile Team. Across every age group, snowmobilers will not accept an environmentally friendly snowmobile if it does not exhibit acceptable acceleration and handling performance. To more broadly confirm the survey results, the team checked the industry market share for the 2011 season. The manufacturer with the highest market share, Bombardier Recreational Product’s Ski-Doo line, builds primarily lightweight high-performance two-strokes that demonstrate excellent acceleration and handling characteristics. Also, the best selling model from Polaris in 2010 was their 600 Rush which has excellent handling and acceleration [1]. These results clearly fall in line with the data collected in the consumer survey.

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, cost, and ease of implementation. To match the design to CSC competition objectives emissions was given the highest weighting. Power-to-weight ratio, ease of implementation, 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 [2]. 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 BAT compliant [3]. While DI engines are a significant improvement compared to conventional two-stokes, they cannot attain current four-stroke emission levels, and the DI fuel injectors have not been design validated for E85 operation. Aside from the three pollutants measured for competition scoring, two-stroke spark ignition engines are known emitters of benzene, 1,3-butadiene and gas-phase and particle-phase polycyclic aromatic hydrocarbons, all of which are classified as known or probable carcinogens by the U.S. Environmental Protection Agency (EPA) [4].

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 and cold start limitations. CSC rules restrict peak horsepower to 130 horsepower, and at these power levels, four-stroke engines designed for snowmobiles offer far easier implementations.

To aid in our engine selection, the survey we 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 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. Commercially available versions of the Polaris FST and Ski-doo 4-TEC are capable of power output of 97 kW (130 hp). Another option is the Rotax ACE 600 from Ski-Doo which produces 42 kW (60 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**
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
Ski-Doo ACE 600	42	40	12.3	8	90	N/A*

Table 1 shows the three engines which suited the Wisconsin team's needs the best. 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 nearly achieve the maximum e-score of 210 that is traditionally used to rate snowmobile cleanliness. Ski-Doo claims that the ACE 600 "sets new standards in efficiency" giving it an advantage as fuel economy plays a fairly large role in the CSC [5]. This is accomplished by a lean burn fuel strategy which inherently leads to a much higher NO_x output. Because of its lean burn, a three-way catalytic aftertreatment is impossible. Instead, a stoichiometric burn would have to be used--sacrificing much of the ACE's fuel economy. One could use a selective catalytic reduction (SCR) to reduce NO_x during a lean burn, but these systems are expensive, inconvenient, and are prone to issues in cold climates making them not practical on snowmobiles [6].

Another problem hindering the Ski-doo ACE 600 is its low 42 kW (60 hp) power output. In an effort to increase the ACE's power output to a more consumer acceptable amount the Wisconsin team discussed adding a turbocharger to the ACE 600 with Ski-Doo engineers, but were informed that the engine cannot be pushed beyond its stock design. Left with only the option of custom internal modification, our team chose to avoid using the ACE 600 and utilize a simple design consisting of as many off the shelf parts as possible.

Given the CSC core objectives of clean, quiet, and powerful the team chose to use the Weber AG 750 cc turbocharged four-stroke recreational engine retrofit with a custom camshaft with reduced valve overlap. This creates a higher effective compression ratio which increases in-cylinder temperatures and engine-out NO_x emissions. The reduced valve overlap also reduces the engine's peak engine speed from 8500 rpm to 6500 rpm with a corresponding decrease in peak power from 100 kW to 65 kW. The reduced valve overlap ultimately increases fuel efficiency while reducing engine-out CO and HC emissions.

Testing by Weber AG shows that retarding ignition timing by 15 degrees significantly reduces HC and NO_x emissions by reducing combustion temperatures and allowing continued reactions in the manifold and turbine [7]. The 3K-Warner turbocharger can produce up to 2000 mbar of boost. Transient response is improved with the following features:

- Pulse charging with 360˚ crank angle
- Volume-minimized exhaust system
- Reduced duct lengths and volume on intake
- Use of a small turbine

On a production engine, full boost can be achieved in 1.15 s. This combination provides plenty of power to satisfy the performance demands of the snowmobile enthusiast, while maintaining low emissions required by law. The engine also implements a short stroke, single camshaft with rocker arms, 20° valve angle and dry sump lubrication for a minimal build height of 455 mm, similar to a typical two stroke engine [7].

Table 2: Weber AG MPE 750 Engine Specifications [7]

Engine Type	Four-Stroke
Cooling	Liquid
Cylinders	2
Displacement	750 cc
Bore x Stroke (mm)	85 x 66
Ignition	Bosch
Exhaust	Single
Fueling	EFI
Compression Ratio	9:1

CONTROL HARDWARE

Since Polaris would not supply the tools to reprogram the stock FST engine controller to operate on E85, Wisconsin is utilizing a Motorola PCM555 Powertrain Control Module (PCM) embedded system that is specifically designed for automotive applications. The PCM, which utilizes 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 32 analog inputs, 6 digital inputs, 20 low side driver power outputs, 8 logic level outputs and a dual 2.0B CAN 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 spark and fueling tables that are load and speed dependent. In addition, the model has adaptation for atmospheric conditions and cold starts. Finally, the model estimates fuel rates using a global air-fuel ratio, which provides seamless switching between gas and ethanol fuels.

FUEL ECONOMY IMPROVEMENT

Building off of the 2011 Bucky CFS, an already extremely clean and quiet snowmobile, the team decided to focus on improving the fuel efficiency of the sled. This was accomplished in three major areas: cold start, driveline efficiency, and weight reduction.

Competition objectives for 2012 allowed for very precise calibration of the engine. Knowing the specific range of ethanol being used at competition this year allowed for the spark advance and turbo boost to be finely tuned. Testing was performed with an engine dynamometer to optimize these two parameters for fuels ranging from E10-E39 to achieve the best possible fuel consumption.

A major change to the stock Weber MPE 750 to improve fuel economy was the utilization of a new low rpm camshaft. This camshaft reduces intake and exhaust valve overlap by 32 crank angle degrees. This reduced overlap is effectively increasing the mean effective pressure of the engine. As a result, at a given engine speed, the low overlap camshaft will produce a higher torque. This allows for a lower normal operating speed, reducing the frictional losses in the engine. The higher mean effective pressure also results in a lower required fueling rate to produce the required torque. The result of reducing engine friction and fuel rate for a given required torque helps reduce overall fuel consumption.

The Madison team benefits from having a direct-drive electric snowmobile available to perform track drag studies. This benefit allowed for a detailed study to be done on improving driveline efficiency to reduce power and hence fuel consumption.

Details of these improvements are discussed in the following sections.

POWERTRAIN ENHANCEMENT

The stock turbocharged Weber MPE 750 engine (Figure 2) is a highly tuned and well developed engine made to be sporty and practical. While Weber did not leave much room to improve this engine, the Madison team found some places to tailor it to better meet our specific needs.

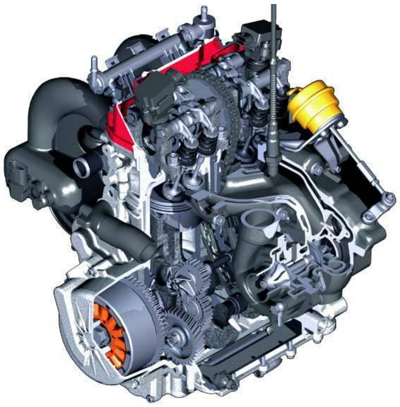

Figure 2: Model of the personal watercraft version of the Weber AG MPE 750 engine.

The crank train is made with a nitrided shaft and a four counterweight balance shaft that is gear driven. This balances 50% of the oscillating masses and reduces friction losses significantly over typical motorcycle engines as seen in Figure 3 [7].

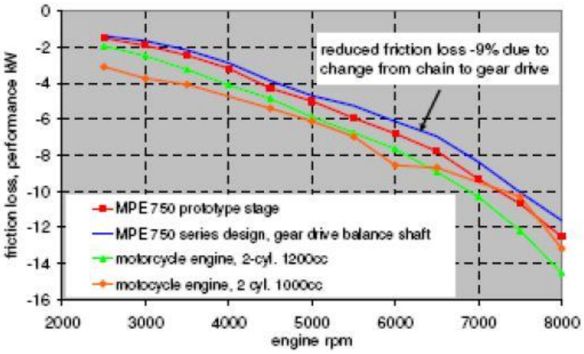

Figure 3: Results from friction loss testing on several engines conducted by Weber AG [7].

Also, to improve tune-ability, efficiency and consistency, the team utilized an electronic throttle body (ETB) in the intake system. This enhancement reduces complications of calibrating the engine, improves cold starting, and improves idle conditions over an idle air controller.

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 Rush for closed loop control of the fuel injection. 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.

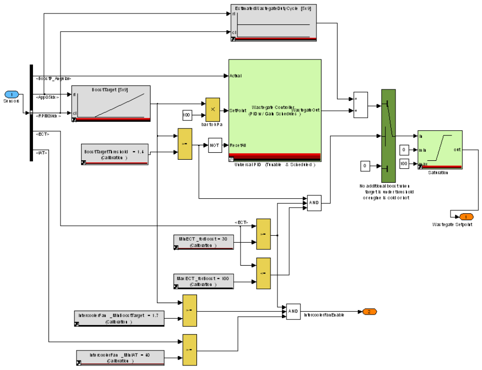

Figure 4: Image of control strategy Simulink model for electronic turbo boost control.

The Woodward engine controller coupled with the stock electronic boost controller allowed students to create their own turbo boost control strategy (Figure 4). This allowed for optimization of fuel consumption 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 (68˚ F) boost pressure is limited to 1400 mbar (20.3 psia). As temperature increase to 60˚ C (140˚ F) pressure is linearly increased to 2000 mbar (29 psia) at full power. Boost is also reduced if coolant temperature exceeds 87˚ C (188.6˚ F). These safeties protect the engine and turbo from excessive wear and damage.

To utilize the emission, noise, and fuel economy capabilities of the engine, changes in clutching and gearing were performed. Numerous dynamometer and drive tests were performed to achieve the optimal combination of cam arms and spring tension in the drive clutch. The driven clutch (secondary clutch) was tuned in conjunction with the chaincase gearing to match engine speed to a targeted range of vehicle speeds. Prior to tuning, the driven clutch was replaced with a Team Industries Tied clutch. The replacement of the manufacturer’s rotationally opening secondary clutch with an axially opening type creates quicker shifting characteristics and increased transmission efficiencies from reduced friction.

Dynamometer tests on the turbocharged engine provided results that maximum horsepower is achieved at a range of engine speeds from 5000 to 6000 rpm. At 5000 rpm maximum horsepower is generated and stays constant until 6000 rpm before dropping off. Therefore, the clutches were tuned to hold the engine speed at 5500 rpm during wide open throttle operation. Targeting this engine speed allows the vehicle to stay in an operating area of maximum horsepower throughout normal acceleration event. A significantly heavier 91g cam arm was used with an orange Polaris spring (#7041060) to minimize over-rev and increase upshifting force. These heavier cam arms are required to accommodate the lower rpms of the modified Weber engine. The drive clutch combination was chosen to increase acceleration and minimize lost efficiency through belt slippage.

Investigation of brake specific fuel consumption (BSFC) charts indicated that maximum engine efficiency was produced between 4000 and 5000 rpm. Secondary clutch adjustments were made to allow for operation within this engine speed range at low and mid-range load conditions. An increase in driven clutch spring tension raised the engines operating speed by reducing the upshift rate. A 21/40 gear-set was installed in the chaincase, providing a gear reduction of 1.91. This gear combination was chosen to improve engine efficiency at cruising speed.

Another improvement made to the powertrain to enhance efficiency was to machine the driveshaft paddles into true circles. Like most drive shafts purchased, this one came with plastic molded drive paddles that were un-machined and out-of-round. 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 for concentricity.

DRIVELINE EFFICIENCY

In an effort to further improve fuel economy the Madison team did extensive driveline efficiency testing to determine the effects of track length, studs, track weight, and bogie wheel placement. This testing was done two years ago using the 2009 BuckEV electric snowmobile. By data logging motor torque and shaft speed during testing, a very precise measure of road load for the chassis was determined at various speeds for each of the different driveline configurations. Our results are still applicable and remain the basis for all of our driveline component selection and setup.

Based on the driveline testing, the Madison team kept the stock 121 inch rear suspension that comes with the Rush Pro-R. This setup has been found to minimize amount of friction with the surface due to reduction in surface area contact and also has the lowest rotational moment of inertia of any commonly used snowmobile track size. As seen in Figure 5, changing from a 128 inch to a 121 inch track leads to a reduction in road load from 14.73 kW (19.75 hp) to 11.41 kW (15.30 hp) for a constant traveling speed of 40 km/hr (25 mph) on a packed snow surface. To ensure consistency of snow conditions, both of these tests were completed on the same pre-packed snow surface in the same night.

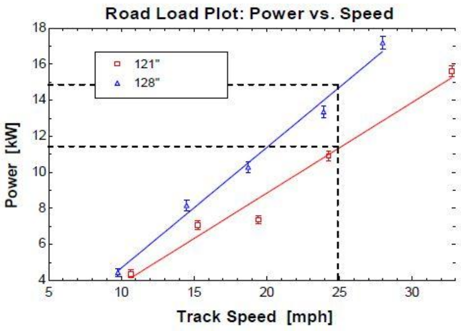

Figure 5: Graph of the road load power at various speeds for the 121’’ and 128’’ suspensions.

Additional testing was conducted to determine the effect of studding the track with respect to total road load power. As conveyed in Figure 6, adding studs changed the power required at 40 km/hr from 12.16 kW (16.31 hp) to 12.38 kW (16.60 hp). However, at low speeds the studded track leads to slightly decreased road load due to better traction.

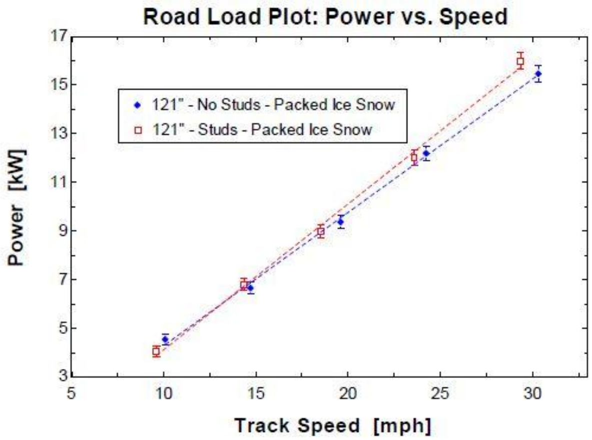

Figure 6: Plot showing the effect adding studs had on the power required at various speeds.

TRACTION

Due to consumer demand for a snowmobile with good handling, a studded track was a necessity. For 2012, 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 gets rid of the possibility of studs pulling out of the track and leaving it in a compromised condition which is a safety concern for the rider. While Wisconsin did find that studs slightly decrease the overall driveline efficiency, the increased performance and safety greatly outweigh this detriment.

FUEL SYSTEM MODIFICATIONS

In order to run on ethanol blends, 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. Ethanol fuel has lower energy per volume than gasoline, so the fuel injectors must be changed to accommodate the need for increased fuel flow. Madison identified a split-port, 6-nozzle Bosch fuel injector that was capable of delivering nearly twice the fuel delivery rate. The injector specifications are given in Table 3.

Table 3: Fuel Injector Specifications

	Gasoline Injector	**Ethanol Injector**
Bosch Part #	0 280 156 236	0 280 156 290
Body Color	Yellow	Black
60 Sec Flow	213 g	400 g
Impulse Flow	6.3 mg	11.2 mg
Impulse Time	2.5 ms	2.5 ms
Rail Pressure	300 kPa	300 kPa
Driver Stage	SEFI	SEFI

Another effect of increased fuel flow is that a larger fuel filter 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. The sensor was formally sold under the name Siemens VDO. It uses a dielectric measuring principle to detect the amount of alcohol in the fuel. The sensor also reports fuel conductivity and temperature [8]. Since air-fuel ratios are calculated on a gravimetric basis and fuel injectors are measured on a volumetric basis, the fuel temperature is measured to allow for density compensation.

These fuel properties, along with the mass air flow 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 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 air flow 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 a stoichiometric level.

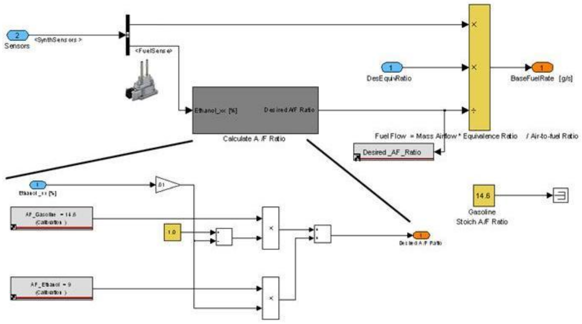

Figure 7: SimuLink block diagram for flex-fuel engine control strategy utilizes inputs from Continental flex-fuel sensor and volumetric efficiency tables to determine desired fueling rate.

CALIBRATION

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 [9]. These constraints define a window that the engine must be calibrated to operate within (Figure 8).

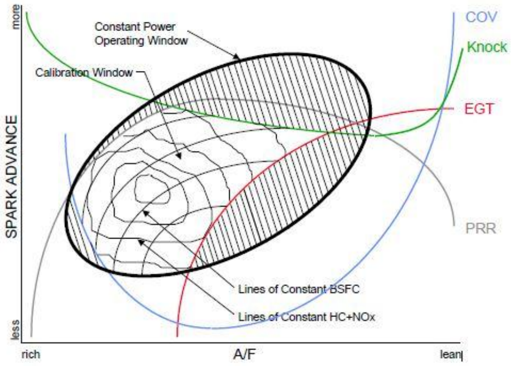

Figure 8: Graph of the typical calibration window [9].

Calibration of the 2012 Madison engine was performed using a water-brake dynamometer, a non-dispersive infrared CO meter, an Innovate wideband O_2 sensor, a chemiluminest NO_x analyzer, exhaust thermocouple probes, and of an internal combustion spark-ignition engine systematic tuning of volumetric efficiency maps. The CO meter was used to verify that both cylinders were operating at the same stoichiometric mixture in addition to verifying the O_2 sensor. The volumetric efficiency tables were then calibrated to within 0.1% of stoichiometric as indicated by the Innovate O_2 sensor. The tables included 160 points that are incremented every 500 rpm and 0.1 pressure ratio. The air-fuel mixture was adjusted to stoichiometric while the spark timing was advanced to balance engine torque and engine-out NO_x levels. Exhaust gas temperatures were also monitored with thermocouples with an end goal of reaching 925˚ C (1697˚ F) to balance power and emissions within a safe operating regime.

EMISSIONS

The first step in reducing emissions was the implementation of the custom camshaft for use with the turbocharged version of the Weber engine. In addition to providing the additional 24 kW of power, the turbo did so without negatively impacting sound or power as the turbocharger ‘muffles’ the exhaust while recapturing rejected energy in the waste stream. In order to further reduce emissions to automotive standards, the Wisconsin team’s worked with W.C. Heraeus GmbH to customize a catalyst specifically for this engine’s operating regime and also fit in the stock Polaris Rush muffler shell. Because the CSC emissions scoring is based on a combination of HC, CO and NO_x levels, a three-way, platinum-based catalyst was chosen for its ability to effectively reduce all three pollutants simultaneously. 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 reducing back pressure [10].

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/ft^3 Palladium 55.6 g/ft^3 Rhodium 8.3

To optimize 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 9, 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.

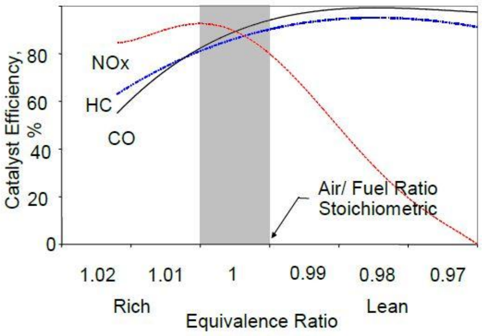

Figure 9: Figure showing the NO_x, CO, and HC conversion efficiency for a three-way catalytic converter as a function of exhaust gas air/fuel ratio operating on gasoline (Adapted from [9]).

Parameters with Mototron’s closed-loop fuel trim algorithm control the lean/rich oscillation of the engine for maximum emission reduction. Figure 10 shows the oxygen sensor value in addition to the fueling multiplier. In this area of engine operation, the base calibration is slightly rich so the emissions control algorithm has adjusted the fuel multiplier to oscillate around the stoichiometric value of 0.96. Because this engine is a two cylinder, the lean/rich parameters were adjusted for smooth engine operation which resulted in a 20 second cycle which is longer than a normal automobile engine.

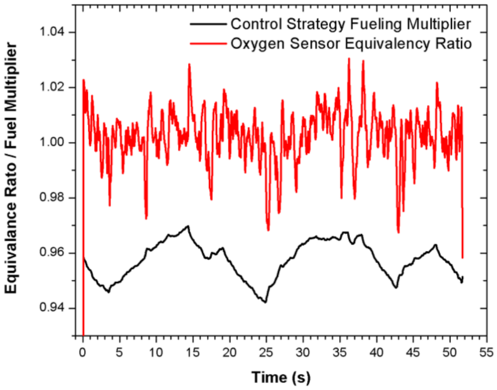

Figure 10: Figure of the engine equivalence ratio oscillating near stoichiometric as a result of closed loop control with an exhaust O_2 sensor.

During the 2011 Clean Snowmobile Competition, the Bucky CFS outperformed its competitors in the emissions event registering drastically improved emissions at all five testing modes. The operating conditions of the engine during emissions testing are listed in Table 5. The resulting e-score from five-mode testing was a 206.88 (out of a maximum possible score of 210). This corresponds to average specific mass emissions of 12.04 and 0.17 g/kW-hr for CO and HC + NO_x respectively.

Table 5: Engine operating parameters for the 2011 Bucky CFS during the five-mode emissions test

	Engine Speed (rpm)	**Torque (N-m)**	**Power (kW)**
Mode 1 (WOT)	6201.0	58.4	38.0
Mode 2 (85%)	5276.0	40.0	22.1
Mode 3 (75%)	4653.0	25.8	12.6
Mode 4 (65%)	4066.0	15.3	6.5
Mode 5 (idle)	2038.0	0.0	0.0

After manufacturing a new muffler with a new integrated three-way catalyst, Wisconsin repeated the emissions testing. Within the accuracy of Wisconsin's emission equipment, the 2012 sled is as clean as the 2011 model.

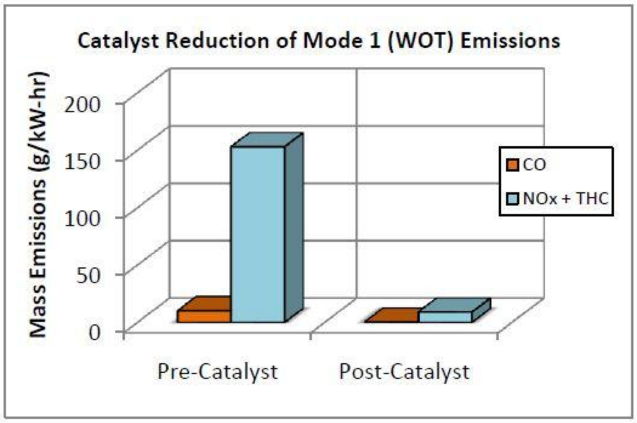

Figure 11: Figure of the catalyst system efficiency during mode 1 (100% load) operation. The catalyst yielded a 98% reduction in NO_x and THC and a 94% reduction in THC over the engine's base emissions.

Testing on the 2012 Bucky Rush for Mode 1 showed that the catalyst system and engine calibration yielded a reduction in the average specific mass emissions (HC+NO_x) from an untreated 10.1 g/kW-hr to 0.17 g/kW-hr, a 98% improvement to the Weber recreational engine as seen in Figure 11. The catalyst also reduced CO emissions by 92%, from an untreated 153 g/kW-hr to 12.04 g/kW-hr. After full optimization of the emissions reduction systems, certified emission levels for the Bucky Rush are 0.12 g/kW-hr, 0.05 g/kW-hr and 12.04 g/kW-hr for NO_x, THC and CO respectively.

NOISE

Wisconsin's primary goal for sound reduction on the Bucky Rush was to reduce A-weighted sound pass-by levels well below those of the current standard set by the International Snowmobile Manufacturers Association (ISMA), which is 78 dBa using SAE test procedure J192. A secondary goal was to reduce perceived sound levels to bystanders. Table 6 shows the A-weighted pass by levels for the stock Polaris FST LX platform which uses the same engine as the Bucky Rush. Additionally shown are the sound emissions from the average two-stroke machine.

Table 6: A comparison of noise emissions from various over-snow vehicles. Measurements are on the A-weighted dB scale and based on pass-by testing at 15.24 m (50 ft). Derived from data in [11].

	33 km/hr	58 km/hr	75 km/hr	WOT	Idle
2007 Polaris FST LX	66.1	72.2	72.6	74.3	51.4
Two-Stroke Snowmobile Average	70.7	73.9	75.3	78.7	55.4

MUFFLER DESIGN

As a starting point, redesigning the Polaris exhaust system offered the most potential for noise reduction without sacrificing muffler volume and complicating design. Because sound attenuation follows the relationship with backpressure and muffler volume as shown in equation 1, our goal was to keep muffler volume at a maximum.

$$Y = 10.977\ln(R + A) + B \quad [14] \qquad (1)$$

where Y is sound attenuation, A and B are backpressure constants, and $R = \frac{Muffler\ Volume}{Engine\ Displacement}$

Sound attenuation, Y, increases logarithmically as back pressure and muffler volume are increased so a larger volume muffler results in a quieter system but a balance of backpressure must be obtained. In addition, Wisconsin's emission strategy required the implementation of two smaller catalysts compared to one larger catalyst in previous years due to muffler size constraints in the Bucky Rush compared to the 2011 Bucky CFS. The 2012 system incorporates two catalysts in series that are each 70 mm in diameter and 74.5 mm long with loading as specified in Table 4. The Wisconsin 3-chamber catalytic muffler, which utilizes the stock Polaris Rush muffler shells and fits into the stock location, is shown in Figure 12.

Figure 12: Three-chamber catalytic muffler designed for the Bucky Rush during fabrication.

Due to fitment constraints, exhaust gases flow from the turbo through a modified turbo manifold and then to the muffler through a custom routed inlet tube. Gases then enter the catalyst through a diffusion cone to increase even gas dispersal across the catalyst. The foil design of the catalyst induces turbulence between cells which increases exhaust gas contact with the substrate. After passing through the catalyst, the exhaust gases enter the bottom chamber of the muffler. Gases are then free to flow through a series of tubes to allow gases to enter each of the three chambers and finally exit out the bottom of the snowmobile near the stock location.

Each of the three chambers have specific lengths in order to target a sound frequency created from engine exhaust. Running the snowmobile without the muffler allowed our team to acquire sound emissions data for the engine exhaust which displayed peaks in sound levels at certain frequencies. With these frequencies, we are able to determine the wavelengths of these sound waves and size the chambers accordingly to create destructive interference. With these three chambers, the first five peaks, including the peak corresponding to the fundamental firing frequency, are targeted and sound attenuation is achieved as shown in Figure 15.

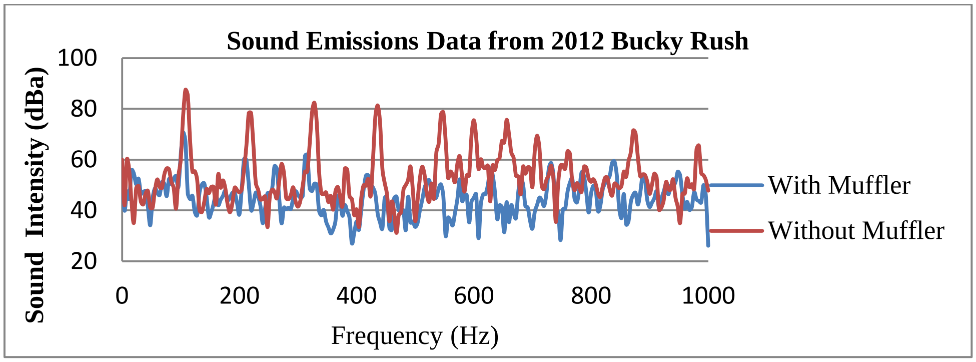

Figure 13: Sound emissions test data acquired from 2012 Bucky Rush with and without muffler

UW-Madison conducted sound testing in the same manner as SAE standard J192 in order to ensure that sound reduction is optimized. By operating at peak engine speed, we are able to determine the fundamental firing frequency (FFF) of the engine at max rpm. This FFF is seen statistically in our data as a peak occurs at 108 Hz in Figure 13. Another important part of the Wisconsin muffler design is the perforation of the exit tube and muffler packing in the center chamber. The perforation allows exhaust gases to enter the middle chamber and pass through Owens Corning "Silentex" muffler packing material to further reduce the effects of high frequency wave resonation within the exhaust system.

Mechanical Noise Reduction

With the redesigned muffler virtually 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, previous pass-by sound testing had been performed.

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 2012 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). Sound measurements were taken in a variety of snowmobile configurations (described below). 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.

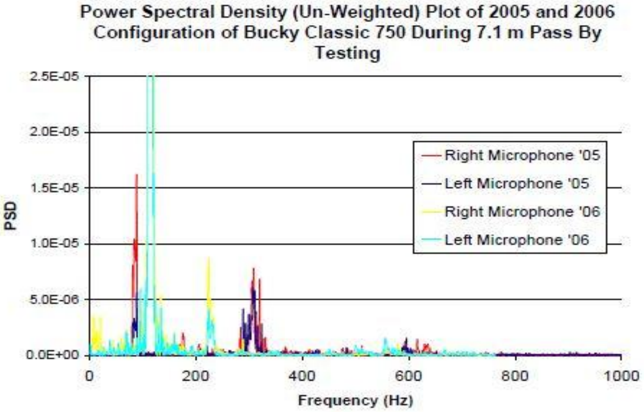

Figure 14: Spectral sound density of past UW-Madison CSC entries to determine typical sources of noise from a snowmobile.

Figure 14 shows a Power Spectral Density plot from the Bucky Rush. This plot shows the sound power emitted from the sled as a function of frequency. Three distinct peaks can be seen near 110, 220, 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 83 Hz peak is first order engine noise, the 166 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.

Drive paddle sound dampeners were installed to isolate the sound produced by the drive paddles contacting the drive lugs on the track. This contact noise on the 2010 Bucky 750 CFS was seen as a peak at 300 Hz in the 2010 test data. As the data shows (Figure 14), this 300 Hz peak is effectively reduced to zero with this modification.

Table 7: First and second order frequencies of sound emitted by three components of interest on the Rush FST.

	1st Order Frequency (Hz)	2nd Order Frequency (Hz)
Engine	83	166
2-ply Track - Paddle Interface	303	606
1-ply Track - Paddle Interface	267	534
Chain Case	1345	2690

Madison's earlier research also proved that the majority of the sound from the engine was being emitted through the exhaust tailpipe and not directly from the engine through the hood and engine bay [14]. This makes it relatively easy to reduce the level of engine noise emitted by concentrating on improving the muffler instead of focusing on insulating the engine bay which adds weight, cost, and increases engine bay temperatures. The noise coming from the track paddle interface can also be reduced through relatively simple and effective mechanisms. Madison has achieved this three separate ways: installing a Camoplast pre-studded 1-ply track in lieu of the OEM track, installing a dampener to insulate the noise from the drive paddles, and by ensuring all chassis components weren't resonating at typical operating conditions.

WEIGHT REDUCTION

One of the only ways to reduce CO_2 emissions is by decreasing fuel consumption. It is a well accepted fact that the most efficient way to improve a vehicle's fuel economy is by reducing its weight. While lightweight components are effective at meeting this goal, they are very expensive and go against the competition goals of keeping the snowmobile cost effective. The first step in reducing the overall weight of UW-Madison's CSC entry was to select a lightweight chassis--the Polaris Rush Pro-R. The main complaint that judges of the 2011 CSC had with our entry was its immense weight and that riders did not feel comfortable on the Polaris FST IQ LX chassis. A weight reduction of approximately 14.1 kg (31 lbs) was accomplished from switching from the 2007 FST IQ LX to a 2011 Polaris Rush Pro-R. Madison began working on some of these weight reductions including the elimination of the heavy mechanical reverse system. The stock lead acid battery was substituted for a lithium-ion battery made by Shorai Power resulting in a loss of 3.89 kg (8.55 lbs). An additional 3.73 kg (8.21 lbs) was shed by switching from the stock Camoplast Ripsaw track with 96 studs to the pre-studded Camoplast Ice attack. In combination, all of the changes performed this year reduced the overall weight of the machine by 34.5 kg (76.0 lbs) less than the Bucky CFS to 630 lbs.

LED HEADLIGHT ASSEMBLY

To reduce the overall electric load on the engine, the team decided to retrofit the headlight assembly by using a light emitting diode (LED) headlight. LEDs are much more energy efficient than the stock incandescent bulbs and are used primarily as daytime running lights. At night, the rider can select the high beams and use the powerful incandescent light that meet the Wisconsin Department of Natural Resources requirement for 200 foot visibility [13]. (The states of Michigan and Minnesota do not have distance requirements for snowmobile headlights.) The headlight assembly consists of one 12 volt 3 watt 18 SMT LED which are active while the low beams are selected and one 46 watt stock incandescent bulb which can be turned on by the rider by simply turning on the high beams. Therefore, using the LEDs results in a power savings of 89 watts over the stock Rush Pro-R headlights during low-beam operation.

COST ESTIMATES

Every component of the Rush FST is designed for manufacturability. In fact, many of the technologies are currently in use in other transportation applications such as the automotive camshaft, platinum based three-way catalyst, and electronic throttle body.

Furthermore, the driveline components were chosen based on actual efficiency data rather than sportiness or general perceived performance.

By using available parts to find a compromise between performance and good 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 MSRP of $12,773.92, the 2012 Bucky Rush is about $1,275 more than the 2012 Polaris IQ Turbo price of $11,499. However, if key components of the Bucky Rush such as the catalyst, ethanol sensor, and electronic throttle body became standard parts within the snowmobile industry, the base price would likely only be $400 to $500 greater than today's stock IQ Turbo configuration.

CONCLUSION

The 2012 University of Wisconsin–Madison Clean Snowmobile Challenge entry drastically improves upon the Best Available Technology in performance, fuel economy, and emissions standards for over-snow recreational vehicles. Taking into consideration consumer performance requirements for an environmentally friendly snowmobile, the team implemented a powerful turbocharged four-stroke powerplant into a revolutionary and lightweight chassis combining performance with EPA 2012 emissions compliance. The Bucky Rush's flex-fuel capability gives consumers the ability to utilize renewable fuels. Utilizing a specialized low valve overlap camshaft and a custom exhaust system equipped with a three-way catalyst, the Bucky Rush scores 206.9 on the e-score. The redesigned exhaust after treatment system ensures that Wisconsin's sled does not damage the environment it tours. Designed for manufacturability with an aesthetically pleasing package, the Bucky Rush 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 Polaris Industries, Weber AG, United Wisconsin Grain Producers LLC, and the Wisconsin Corn Promotion Board for their extensive support. Additionally, thanks go out to Polymer Technologies Inc, National Instruments, Mototron Control Solutions, W.C Heraeus, Owens Corning, Emitec, 3M, Continental Corp., Shorai Power, and Castle Racing for supporting us with the best available products and to Nelson Global Products for muffler design support. The team also wishes to thank PCB Piezotronics for the donation of sound equipment vital in the testing and reduction of sound emissions of the Bucky Rush.

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

REFERENCES

1. "Best-Selling Polaris 600 Rush wins pro class & team titles in USCC I-500 cross-country race." Polaris MN. http://www.plarisindustries.com/en-us/OurCompany/News/PressReleases/Pages/Best-Selling-Polaris-600-RUSH-Wins-Pro_Class-and-Team-Titles-in-USCC-I500-Cross-Country-Race.aspx (Website accessed 2/24/2011) "Riders' Demand Cleaner, More Efficient, Smoother Riding Snowmobiles – Polaris Delivers." SnowGoer Canada. *http://www.snowgoercanada.com/news/ news.asp?ArticleID=91* (Website accessed 8/12/2008)
2. 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.
3. 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)
4. "Pollutants/Toxics > Carcinogens." U.S. Environmental Protection Agency. *http://www.epa.gov/ebtpages/pollcarcinogens.html.* (Website accessed 2/17/2011)
5. BRP-Ski-doo. Engine Technologies-Rotax ACE 600. *http://www.ski-doo.com/technologies/engine-technologies/4-strokes.aspx*. (Website accessed 2/23/2012)
6. Bern University of Applied Sciences Engineering and Information Technology, *Bern University of Applied Sciences-Labs*. 8/4/2005. Web. 24 Feb 2012. <*http://labs.ti.bfh.ch/uploads/media/Reactions_in_a_SCR-deNOx_system_01.pdf*>.
7. Wizgall, Eberhard, Kohler, Beat. "The Multi-Purpose Engine MPE 750 from Weber Motor AG." SAE number 2004-32-0033. September 2004. Small Engine Technology Conference.
8. Continental Flex Fuel Sensor. *http://usa.vdo.com/products_solutions/cars/powertrain/sensors/powertrain/flex-fuel-sensor/* (Website accessed 2/20/2009)
9. Heywood, J.B. "Internal Combustion Engine Fundamentals." McGraw Hill, Inc 1988.
10. Emitec Innovations. *http://www.emitec.com/index.php?lang=en&mid=e4&doc=50* (Website accessed 2/20/2008)
11. Daily, John. "Supplemental Over-Snow Vehicle Sound Level Measurements." Conducted for the Winter Use Plan Supplemental Environmental Impact Statement. Prepared for State of Wyoming. February 2002.
12. "Wisconsin Snowmobile Laws." Wisconsin Department of Natural Resources. *http://dnr.wi.gov/org/es/enforcement/DOCS/snowmobile_regs.pdf* (Website accessed 2/25/2007)