Improving Upon Best Available Technology: A Clean Flex Fuel Snowmobile

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ABSTRACT

The University of Wisconsin-Madison Snowmobile Team has designed and constructed a clean, quiet, high performance snowmobile for entry in the 2008 Society of Automotive Engineers' Clean Snowmobile Challenge. Built on a 2003 cross-country touring chassis, this machine features a 750 cc fuel-injected four-stroke engine equipped with a fuel sensor which allows operation ranging from regular gasoline to an 85% blend of ethanol and gasoline (E85). The engine has been customized with a Mototron control system which allows for full engine optimization using a range of fuels from E10 to E85. Utilizing a heated oxygen sensor and a 3-way catalyst customized for this engine by W.C. Heraeus-GmbH, this sled reduces NOx, HC and CO emissions by up to 89% to an average specific mass of 0.484, 0.154, 4.94 g/kW-hr respectively. Finally, the Mototron system also allowed Wisconsin to extract another 4 kW from the Weber 750cc engine; producing 45 kW and 65 Nm of torque. A two stage muffler system along with sound absorbing material under the hood combines to reduce the sound levels to 71 dbA using SAE test procedure J192. The entire engine and two-stage muffler system is packaged in a manner that maintains the snowmobile's aggressive OEM appearance.

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 futuristic 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 2008 CSC will be held in Michigan's Keweenaw Peninsula from March 10-15th.

The following paper discusses how the University of Wisconsin – Madison team has engineered an entry for the 2008 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 fuel choice. The second section describes modifications to the snowmobile's drivetrain. 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.

PERFORMANCE

The guiding principles for the 2008 UW-Madison clean snowmobile design are simplicity and practicality: 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 to current snowmobile consumers, the team first determined the characteristics which are important in this demographic sector. In 2008, the team attended the World Championship Snowmobile Derby in Eagle River, Wisconsin. While exhibiting the 2008 CSC entry, the team surveyed 115 attendees 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 the following list: acceleration, handling, price, fuel economy, and emissions. The results, as seen in Figure 1, show that acceleration, trail handling, and price influence a buyer significantly more than fuel economy or emissions.

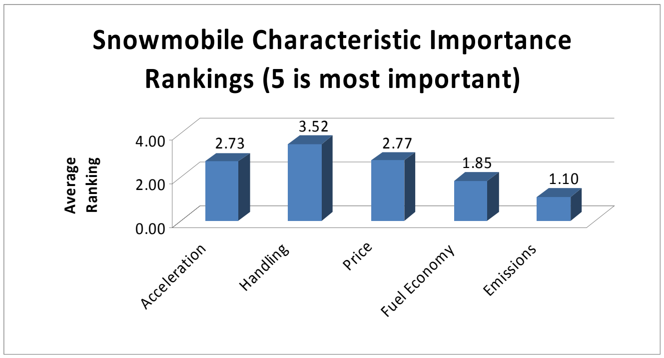

Figure 1: A survey of 115 snowmobilers taken at the 2008 Eagle River Ice Derby shows that acceleration, price, and handling are the most important considerations when purchasing a snowmobile.

The survey results confirm the guiding principles of the Wisconsin 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 sales numbers for the 2006 model year. The manufacturer with the highest market share, Bombardier Recreational Product's Ski-Doo line, exclusively builds lightweight high performance two strokes that demonstrate excellent acceleration and handling characteristics. Also, the best selling single model from 2006, Polaris' 600 HO I.Q., 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. Engines were considered on a basis of hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxide (NO_x) emissions, power-to-weight ratio, cost, and ease of implementation. To match the design to CSC competition objectives, emissions and power-to-weight ratios were equally weighted, followed sequentially by ease of implementation and cost. 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 marine engines
- Four-stroke personal watercraft (marine) engines
- Compression ignition (CI) engines
- High-compression motorcycle four-stroke engines
- V-twin motorcycle four-stroke engines

The choice between current snowmobile engine technologies is fairly straightforward. Conventional and SDI two-strokes have significantly higher power-to-weight ratios than current snowmobile four-strokes. However, snowmobile emissions testing conducted by Southwest Research Institute (SwRI) clearly states that commercially available four–strokes "…emit 98-95 percent less HC, 85 percent less CO, and 90-96 percent less PM" than conventional two-stroke snowmobile engines [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 SDI two-stroke technology, current publications from Bombardier Recreational Products, the developer of SDI technology, suggests that the system improves emissions only 50% over conventional two-strokes [3]. While SDI engines are a significant improvement compared to conventional two-stokes, they cannot attain current four-stroke emission levels and the SDI injectors have not been designed 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. Similarly, the marine engine options were eliminated because of their low power to displacement ratios. CSC rules restrict four-stroke displacement to 960 cc and current marine outputs in this range produce only 40-50 hp. At these power levels, four-stroke engines designed for snowmobiles and ATVs offer far easier implementations. The difficulty of adapting a four-stroke motorcycle V-twin engine to a snowmobile CVT eliminated this option, though the team recognized the excellent low-end torque this engine configuration achieves without compromising emissions.

To aid in our engine selection, the Eagle River survey also had volunteers choose the powertrain option they would most likely buy between a semi-direct injection two-stroke, a port-injected four stroke, or a zero emissions electric. As seen in Figure 2, almost 50 percent of the volunteers claimed they would choose a four stroke engine to power their snowmobile.

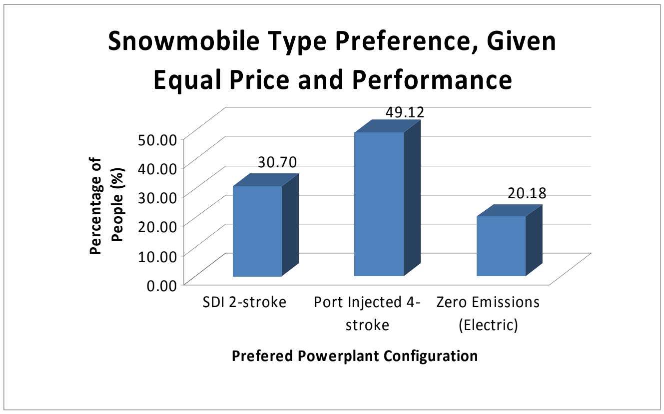

Figure 2: Results from the 2008 Eagle River survey showing people would prefer a four stroke engine in their snowmobile.

Final Engine Selection

Given the heavy weighting on emissions in CSC competition scoring, the team determined that a commercially available snowmobile or high-compression motorcycle four-stoke engine offered the most potential. High-compression motorcycle four-stokes such as the Kawasaki ZX9R and Yamaha RX engines have substantially higher power output (130+ kW) compared to the Arctic Cat 660 and Polaris FS four-stroke engines (each 40+ kW). Commercially available turbocharged versions of the FS and 660 are capable of power output close to that of motorcycle engines (100+ kW). To compare the emissions of different engines, the UW team examined a SwRI study which compared conventional two-stroke snowmobile emissions to that of the Arctic Cat 660 and the Polaris Liberty. As seen in Table 1, the un-catalyzed four-stroke engines slightly increase NO_x emissions while significantly reducing HC and CO emissions.

Table 1: Emissions Data from a SwRI Study [2].

	HC g/kW-hr	CO g/kW-hr	NO_x g/kW-hr
Two-stroke average	189	517	0.72
Arctic Cat 660 (4s)	6.2	79.9	10.6
Polaris Liberty (4s)	3.2	79.1	7.0

To achieve the low CO and HC levels of the Arctic Cat and Polaris four-strokes, a high-compression motorcycle engine would need to employ catalytic after-treatment. Integrating a three-way catalyst into the Kawasaki ZX9R proved particularly difficult for UW-Madison in 2003. High compression four-stroke engines are designed to run slightly rich of stoichiometric in order to control exhaust temperatures and maximize high-speed power output. Forcing the engine to operate at the stoichiometric air-fuel ratios necessary for efficient three-way catalyst operation causes excessive exhaust temperatures. Kevin Cameron of SnowTech concurs, noting that valve overlap (the crank angle duration that both the intake and exhaust valves are open) gives these engines excellent torque at the cost of higher emissions [5].

High-performance turbocharged snowmobile engines such as the Polaris FST and Arctic Cat 660T almost double the power output of the base engine but at a penalty of increased emissions, fuel economy and cost. While the non-turbocharged FS engine is EPA 2012 emissions certified, the FST is not [6]. Studying the CSC competition results from 2006 and 2007, the naturally aspirated FS engine consistently achieves a 9% increase in fuel economy when compared to the Polaris FST engine. Therefore, the team decided that, while turbo-charging would provide increased power, the increased emissions would not be acceptable.

Given the CSC core objectives of clean and quiet, the added power of a high-compression motorcycle engine or turbocharged snowmobile engine because of their increased emissions. Therefore, the team selected the 750 cc Polaris FS four-stroke engine for this year’s snowmobile (Table 2). In its stock configuration, this engine is EPA 2012 certified and produces 45 kW of power, comparable to a 500 cc two-stroke engine [7]. The engine had significant cam development leading to 9 mm and 9.5 mm of exhaust and intake valve lift respectively along with short overlap. This combination provides enough 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 [16].

Table 2: Polaris FS Engine Specifications [8]

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	11.5:1

Fuel Choice

As fuel prices increase and consumers become more concerned with the source of their fuel, domestically produced ethanol has been proposed as a possible solution. Although the energy density of ethanol is not as high as standard gasoline, ethanol has the advantages of being an environmentally friendly renewable resource. E85 is an alcohol fuel mixture that normally contains a mixture of 85% denatured ethanol and 15% gasoline by volume. To ensure cold-startability, the ethanol component may be dropped to 70% during the winter months so that blending with a standard winter gasoline will produce an acceptable vapor pressure: a higher vapor pressure will produce faster fuel evaporation necessary for cold weather engine starting. Otherwise, special, more volatile hydrocarbons can be mixed with the ethanol to maintain the 85% mixer while supplying an appropriate winter vapor pressure (~100 kPa): Gage Fuels supplies this type of E85 for the SAE Clean Snowmobile Challenge. Thorough testing and appropriate cold start tuning were employed to ensure that the Wisconsin sled will start at temperature down to -24ºC

Since E85 will also be the only fuel choice available for spark ignited engines at the 2008 CSC competition the Wisconsin entry will utilize E85 blended fuel. However, consumers indicated in our Eagle River survey that they would want flex fuel capability on their next snowmobile. As seen in Figure 3, over 75 percent of the volunteers would be more willing to purchase a new snowmobile if it had a flex fuel option. To make the snowmobile more widely accepted and practical for the public, it will be flex fuel capable. Flex fuel capability allows the user to run the engine on gasoline that is blended with anywhere from 10% to 85% ethanol. This capability will ensure the user is able to purchase fuel wherever they are. It also gives them the option to not use E85 on days that difficult cold starting would be unacceptable.

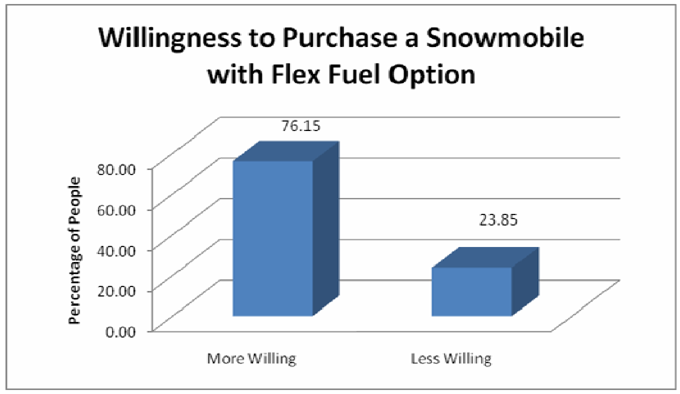

Figure 3: A survey of consumers show that they would be more likely to buy a snowmobile if it was flex fuel capable.

POWERTRAIN ENHANCEMENT

Once the team chose the Polaris FS snowmobile engine, the next step was to integrate it into our existing chassis. This required fabrication of engine mounts, engine intake, new clutching, and chaincase gearing. Per our stated design goals, this all had to be packaged while maintaining the stock appearance of the snowmobile.

The first step in installing the FS engine was to fabricate new aluminum engine mounts. The engine was positioned to maintain optimal center-to-center clutch distance and engine angle. The team then designed and constructed new engine mounting brackets using Solidworks software, using the stock Polaris Frontier and FS engine mounting locations as a template. In an effort to optimize the longevity of the mounts and reduce vibration transmitted into the chassis, the team utilized rubber vibration isolation mounts in non-parallel planes. Finally, the mounts were powder-coated black to improve the under-hood appearance.

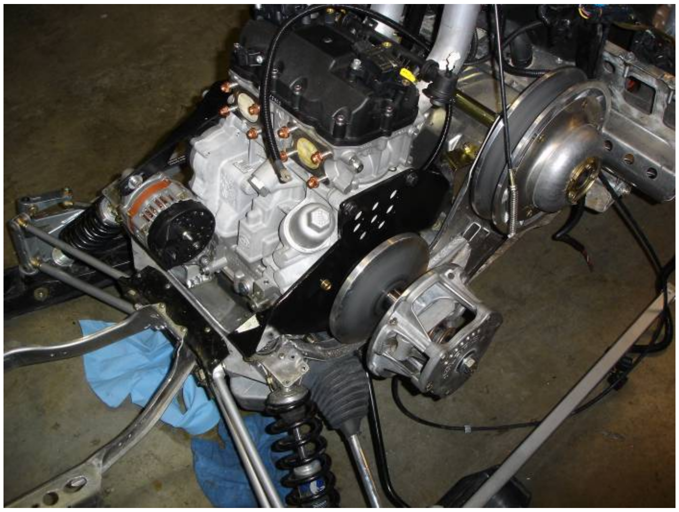

Figure 4: Picture of the clutch-side engine mounting bracket during fabrication phase.

Due to differences in steering column and jackshaft location between the EDGE chassis and the original IQ chassis, a new design for the throttle bodies and induction system was required. To simplify final calibration of the engine and improve reliability, the team integrated the stock throttle bodies into a custom intake system. The new intake system was assembled from aluminum tube. After welding, the interior passages were polished to optimize airflow and increase efficiency. The longer intake passages also helped improve the engine's low-end torque.

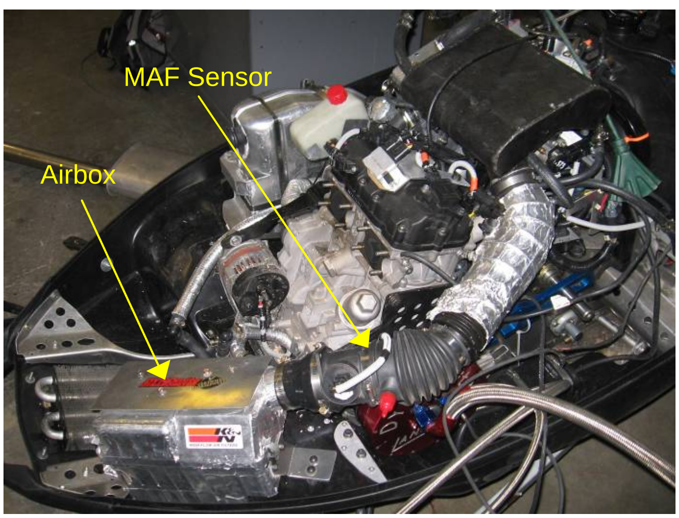

Figure 5: Air box construction and location. Note the mass air flow sensor used for engine calibration.

The air box of the UW snowmobile features a large two stage air box system that features an upper and lower box assembly. The large overall size of the dual air box assembly reduces the air velocity in the system, which thereby reduces intake noise. The upper portion air box was constructed from aluminum and shaped to maximize airflow and minimize size, allowing the use of an unmodified hood. The aluminum upper air box was covered with a sound-dampening rubber compound to reduce resonant vibration and intake noise. The upper air box pulls air through an adapted automotive air intake system from the lower air box. The lower air box intake location was optimized to minimize inducted air temperature based on data logged during actual riding conditions.

The FS engine uses a dry sump design to allow a lower mounting point, improving handling by lowering the center of gravity. The dry sump design requires a separate oil reservoir. The team used the stock FS reservoir to ensure correct flow and reserve volume and remounted it in a central location near the airbox. This location allows for more room in the engine bay for mufflers and sound dampening. The reservoir was coated with reflective material to minimize heat absorbed from the nearby muffler. Oil lines running near hot exhaust components are covered in reflective insulation to prevent heat damage.

To improve cooling efficiency, the team utilized an oil cooler mounted near the front of the lower cowl as seen in figure 6. Oil is circulated from the engine's crankcase, through the heat exchanger, and back into the reservoir. Vents were cut into the lower cowl to maximize airflow through the oil cooler and provide additional under-hood cooling.

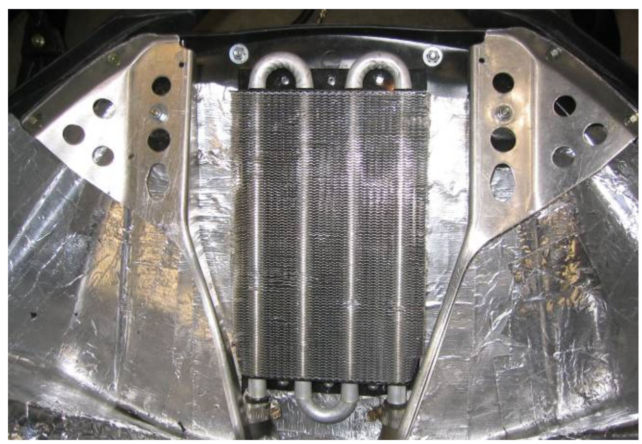

Figure 6: Picture of the oil cooler mounting system designed to efficiently cool the FS engine.

To optimize the gearing, we replaced the stock primary clutch weights and secondary helix with appropriately chosen parts. In addition, the team added a Team Industries roller secondary clutch, improving transient performance. The roller secondary clutch provides increased transmission efficiencies through decreased friction, and much quicker up and back shifting than the stock slider clutch. A 19/39 gear-set was installed in the chaincase, providing a gear reduction of 2.05. This gear combination was chosen to improve acceleration and engine efficiency at cruising speed versus the 2.19 ratio used in the stock FS chaincase.

Another improvement made to the powertrain to enhance efficiency was to machine the driveshaft paddles into true circles. The team purchased a hollow, light weight driveshaft to reduce weight. Like most drive shafts purchased, this one came with plastic molded drive paddles that were un-machined. The molding process of these drive paddles do not create a very uniform shape, which can cause a snowmobile's track to change tension while moving. This effect of relaxing and tensioning of the track can make the snowmobile less efficient as well as increase snowmobile noise and wear. To reduce these effects, the driveshaft was machined on a lathe so that both drive paddles were symmetrical in shape.

Control Hardware

Since Bosch would not supply the tools to reprogram the stock FS engine controller to operate on E85, Wisconsin is utilizing a Motorola MPC555 Powertrain Control Module (PCM) embedded system that is specifically designed for automotive applications. The PCM, which utilizes an operating system developed by MotoTron, 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.

Figure 7: Picture of the Motorola MPC555 powertrain control module.

The base control strategy was supplied by Mototron 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 so that switching from gasoline to ethanol is seamless.

Fuel System Modifications

In order to run E85, 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. Wisconsin 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: 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 inline 35 micron sintered bronze fuel filter capable of delivering fuel at five gallons per minute. 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 names Siemens VDO. It uses a dielectric measuring principle to detect the amount of alcohol in the fuel. Continental flex fuel sensor also reports fuel conductivity and temperature [14].

Figure 8: Picture of Continental Flex Fuel Sensor.

These fuel properties are supplied to the Mototron controller. The engine management system is based on the physics of combustion 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. 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 oxygen sensor is activated and is responsible for fine tuning the air-fuel ratio to a stochiometric level. Using the input from the flex fuel sensor, algorithms have been added for adjusting the fuel density and the target air-fuel ratio for andy commercially available ethanol blend. The heated oxygen sensor is than utilized to trim the fuel quantity to stoichmetric values: optimizing the catalyst reductions while ensuring efficient and clean flex-fuel power.

Calibration

Using a water-brake dynamometer, a non-dispersive infrared CO meter, a HEGO O_2 sensor, a chemiluminest NOx analyzer and exhaust thermocouple probes, Wisconsin systematically optimized the engine. 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 fuel mixture was adjusted to stoichiometric while the spark timing was advanced to balance engine torque and engine-out NO_x levels.

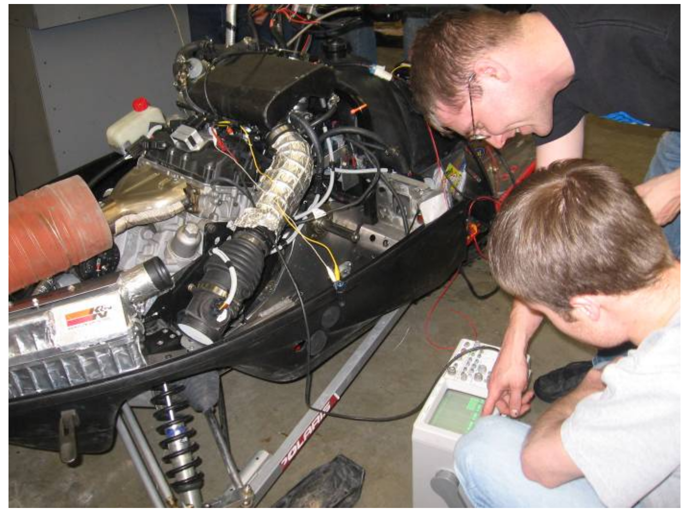

Figure 9: Picture of the students huddling around an oscilloscope calibrating the new E85 injectors.

EMISSIONS

Knowing that the untreated emissions of the FS engine are significantly higher than the CO, HC, and NO_x figures of past CSC winners, the Wisconsin team's first step in reducing emissions was the addition of catalytic after-treatment. 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. W.C. Heraeus GmbH supplied a custom 3-way catalyst (Table 4) for this engine's operating conditions. The Hearsus catalyst features 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 allowing for the use of smaller volume catalysts and/or reducing back pressure [15].

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 10, 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 reacts with the HC and CO to form N_2 and CO_2 and/or H_2O. Mototron's closed-loop fuel trim algorithm incorporates this oscillation between lean and rich operation for maximum emission reduction.

Table 4: Catalyst Specifications.

Manufacturer	W.C Heraeus GmbH
Diameter	105mm
Length	140mm
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 g/ft^3

To create a less restrictive exhaust flow and increase contact time between catalysts and exhaust gases, one larger diameter catalyst was used in lieu of the quad catalysts system used in the past. The single catalyst has a cross sectional flow area of 8659 mm^2, 30% larger than the previous quad design decreasing flow velocity and thus increasing exhaust contact time with the precious metals maximizing emission reduction. The new catalyst density is increased by 50% to 600 cells per square inch and the substrate loading is increased from 50 to 75 g/ft^3 in a 4/20/3 ratio of platinum, palladium and rhodium respectively. Extensive emissions testing using a traditional California Analytical emissions bench was used to determine emission levels and catalyst efficiencies. The operating conditions of the engine during emissions testing are listed in Table 5.

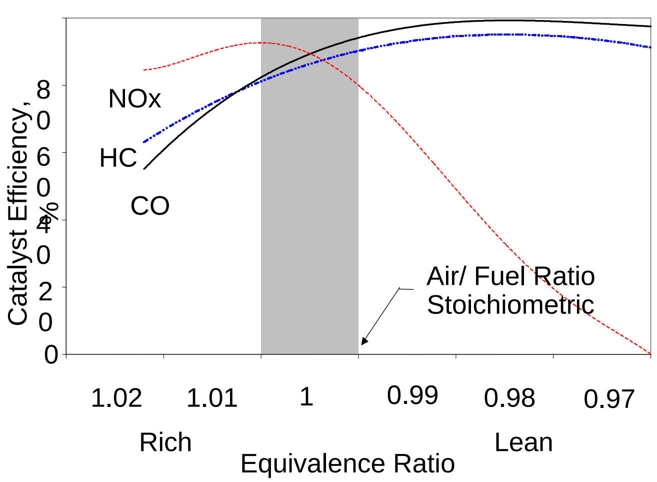

Figure 10: The NOx, CO, and HC conversion efficiency for a three-way catalytic converter as a function of exhaust gas air/fuel ratio operating on gasoline (Adapted from [10]).

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Table 5: Engine operating characteristics when performing the five-mode emissions test used for the 2008 Bucky 750 FX [11].

	Engine Speed (rpm)	**Torque (N-m)**	**Power (kW)**
Mode 1 (WOT)	8000	54.9	45.0
Mode 2 (85%)	6800	28.0	19.9
Mode 3 (75%)	6000	18.1	11.4
Mode 4 (65%)	5200	10.7	5.8
Mode 5 (idle)	1700	1.4	0.2

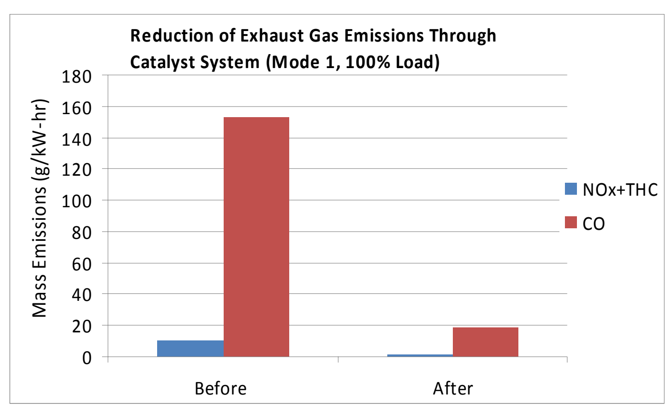

Figure 11: The catalyst system yielded a 88% reduction in CO and NOx and a 89% reduction in THC over the FS engine's base emissions at 100% load.

Testing on the sled for Mode 1 showed that the catalyst system yielded a reduction in the average specific mass emissions (HC+NO_x) from an untreated 10.1 g/kW-hr to

1.123 g/kW-hr, an 89% improvement. The catalyst also reduced CO emissions by 88%, from an untreated 153 g/kW-hr to 18.4 g/kW-hr Figure 12 shows the final results of the emissions testing on the Bucky 750 FX after full optimization of the emissions reduction systems.

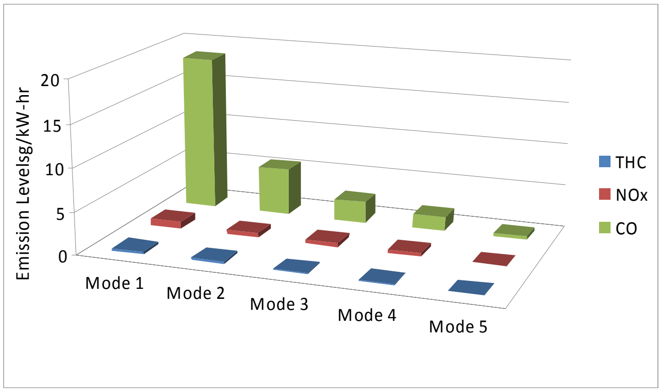

Figure 12: Post catalyst emission levels for the FS engine operating on E85 fuel.

NOISE

Wisconsin's primary goal for sound reduction on the Bucky 750 FX was to reduce A-weighted sound pass-by levels below those of the current standard set by the International Snowmobile Manufacturers Association (ISMA), which is 78 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 Frontier platform that the Bucky 750 FX is based on. Additionally shown are the sound emissions from a 2002 Arctic Cat 660 four-stroke and the average for two-stroke machines.

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 [12].

	33 km/hr	58 km/hr	75 km/hr	WOT	Idle
2002 Arctic Cat 660	65.8	72.0	72.3	71.6	42.1
2002 Polaris Frontier	65.6	71.2	72.6	74.0	51.4
Two-Stroke Snowmobile Average	70.7	73.9	75.3	78.7	55.4

Muffler Design

As a starting point, redesigning the FS exhaust system offered the most potential for noise reduction. In addition, Wisconsin's emission strategy required the implementation of several catalysts.

Using the space still limited by packaging constraints on the right side of the snowmobile, students designed a two-stage exhaust system that takes advantage of the open space in front the engine. The 2008 system incorporates a single catalyst that is 105 mm in diameter and 140 mm long. The 2008 Wisconsin CSC catalyst system improves upon the 2007 system by removing the dual catalysts which occupied extra space under the hood and created a sharp bend in the system due to the length of two sets of catalysts. Back pressure on the engine was reduced by avoiding sharp bends and unneeded splits in the exhaust system. To maximize catalyst temperature, the catalyst is mounted as part of the exhaust system, locating them only 30-40 cm downstream of the engine exhaust manifold

Figure 13 shows a schematic drawing of the catalyst chamber. Exhaust flow from the engine headers enters the catalyst through a cone diffusion cone to minimize pressure drop. The foil design of the catalyst induces turbulence between cells increasing exhaust gas contact with the substrate.

Figure 13: Soildworks model of a catalyst expansion chamber.

After passing through the catalyst chamber, the exhaust flow enters a high frequency diffuser designed to remove the majority of mid to high frequency noise. The diffuser reduced noise levels noticeably from 75.1 to 73.3 dB when calculated at a 50 foot equivalent sound level. The diffuser helped most when operating at mid range engine speeds, which are most typical during average operation. Figure 14 shows sound levels at different frequencies that were eliminated by adding the high frequency diffuser to the exhaust system.

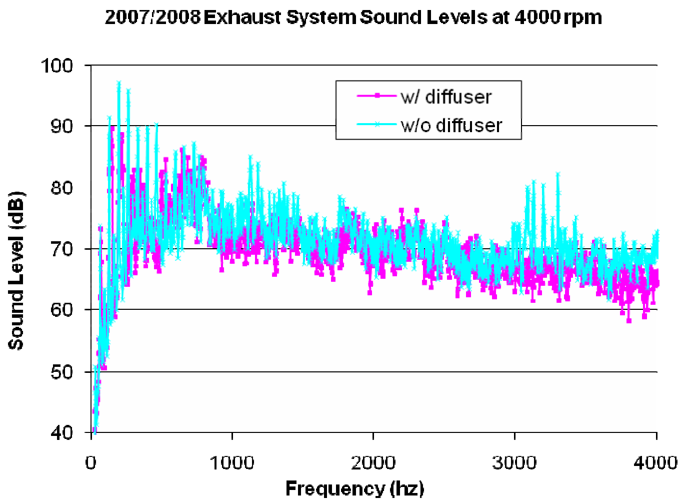

Figure 14: Graph of the 2007/2008 exhaust system spectral sound spectrum measured at a distance of 10 ft with and without high frequency diffuser installed in system (April 25, 2007).

After passing through the catalyst chamber, the exhaust flow enters a high frequency diffuser (Figure 15) designed to remove the majority of mid to high frequency noise. After exiting this chamber, the exhaust is directed into a stock Arctic Cat 660 four stroke muffler. The Arctic Cat muffler was selected after extensive testing on several different muffler designs, including the stock FS muffler and Wisconsin's previous muffler designs. The Arctic Cat muffler was found to provide the best sound attenuation while also reducing weight by 3.5 Kg over the stock FS exhaust.

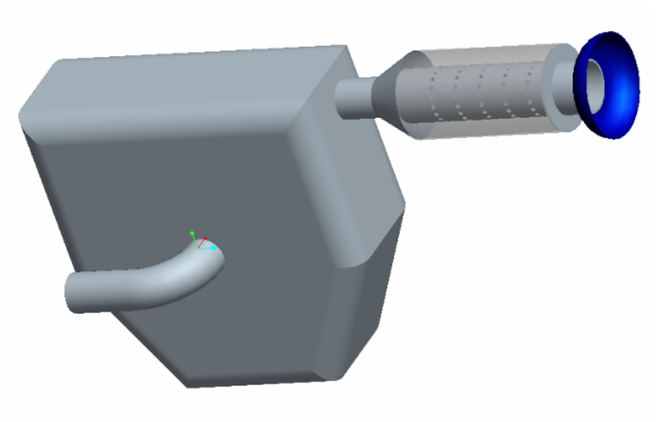

Figure 15: Solidworks model of the second stage of the muffler system is consists of a high frequency diffuser in-line with an Arctic Cat box muffler.

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, pass-by sound testing was performed.

To quantify noise levels, Wisconsin performed various different sound tests including drive-bys at constant speed and during WOT acceleration. 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.

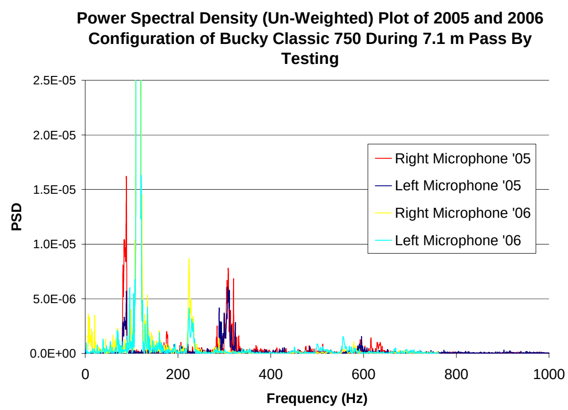

Figure 16: Spectral sound density of past UW-Madison CSC entries. Testing was performed Feb 25, 2005 and March 1, 2006.

Figure 16 shows a Power Spectral Density plot from the Bucky 750 FX for the previous two years. 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 (Table 7), 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.

Table 7: First and second order frequencies of sound emitted by three components of interest on the Bucky 750 FX

	1st Order Frequency (Hz)	2nd Order Frequency (Hz)
Engine	100	225
Track-Paddle Interface	303	606
Chain Case	1345	2690

The 300 Hz and 600 Hz track sound power for the 2008 Bucky 750 FX are nearly negligible compared to the sound power produced by the 2005 snowmobile. This reduction is due to the incorporation of an Arctic Cat silent track in place of the stock Polaris track, and the installation of a drive paddle sound dampening device on the front suspension arm.

Figure 17: Picture of the Arctic Cat Silent Track installed in the Bucky 750 FX.

The Arctic Cat silent track has small opposing ramps placed on the inner surface near the outside edge of the track. These ramps compensate for flex in the track due to the lug spacing, creating an even radius of curvature as the track bends. This allows the track to move smoothly over the front and rear idlers, reducing track friction, vibration and noise.

Another addition to the sound dampening package on the Bucky 750 FX is the drive paddle noise dampener located on the front arm of the rear suspension (Figure 18).

Figure 18: Picture of the drive paddle sound dampener installed on front suspension arm.

The drive paddle sound dampener isolates the sound produced by the drive paddles contacting the drive lugs on the track. This contact noise was seen as a peak at 300 Hz in the 2005 test data. As the 2006 data shows (Figure 17), this 300 Hz peak has been reduced to nearly zero.

The relative contributions of the engine and track noise are difficult to ascertain from this graph because the data is not A-weighted. Therefore, more pass-by tests were performed to determine the relative contributions of the engine and track noise.

Pass-by tests were performed in the same manner described earlier with thick rubber mats placed over portions of the snowmobile to isolate that area's sound emissions. A rubber cover was made for the hood and a rubber skirt was made for the track. Figure 19 shows these sound barriers installed on the snowmobile.

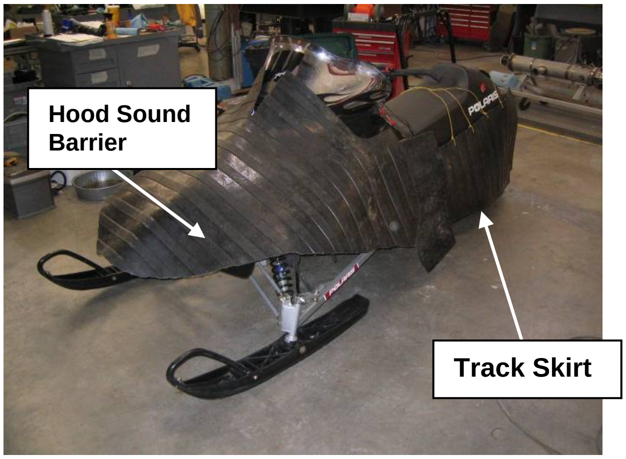

Figure 19: Picture of the rubber mats used to isolate sound emissions from targeted components. In this way, the relative contribution of each component to the overall A-weighted sound level could be found.

The rubber covers allowed the isolation of specific snowmobile components, and the team was able to discover the relative contributions of the track and engine to overall sound emissions of the snowmobile. Figure 20 shows the results of the testing. Variables tested include isolating the hood, isolating the track, isolating both the hood and track, and comparison of the 2006 exhaust with the 2008 exhaust.

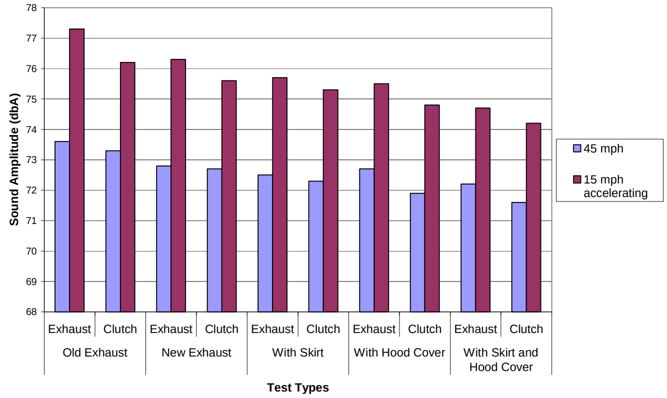

Figure 20: Graphs of pass-by sound testing results. The 2008 exhaust is about 1 db quieter than 2006.

Based upon the results of Wisconsin's pass-by testing in 2007, the Bucky 750 FX's exhaust is significantly quieter than the 2006 exhaust system. Isolating individual components of the snowmobile, such as the track or the engine bay, also reduced sound levels. The reductions that were achieved by using the rubber mats could not be fully realized on the final design, as the amount of added weight would have been unacceptable.

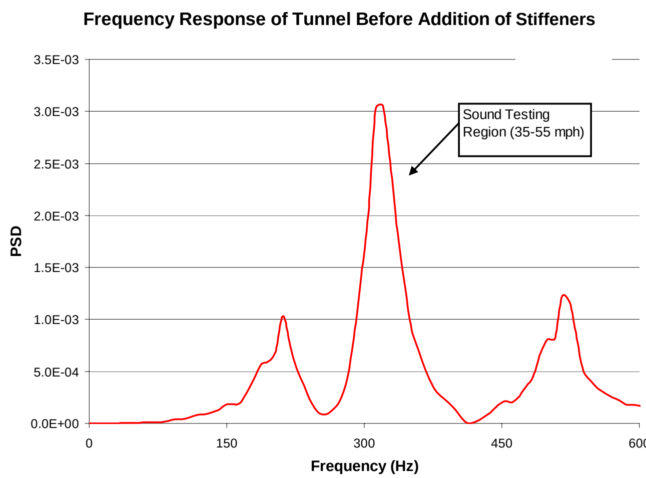

Figure 21: Frequency response of tunnel before adding tunnel stiffeners.

In addition to the mechanical sound reducing enhancements outlined above, the UW-Madison team decided to investigate the resonant frequency of the tunnel, looking for a possible track-tunnel sound amplification. Using a Hi-Techniques data acquisition system and PCB Piezoelectric accelerometer, the team discovered that the tunnel had a resonant frequency that matched the 300 Hz track vibration (Figure 21). This meant that any vibration from the track was being amplified by the tunnel, greatly increasing noise.

In an effort to change the resonance frequency of the tunnel, the team decided to add tunnel-stiffening angle brackets to the sides of the tunnel near the foot wells (Figure 23).

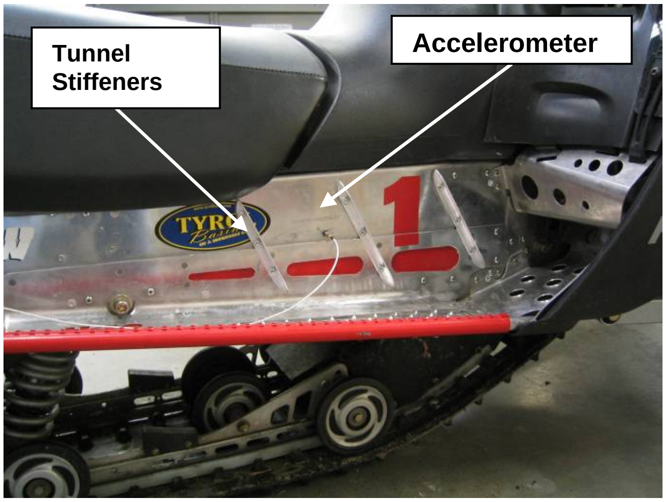

Figure 22: Picture of the tunnel stiffening angle brackets with accelerometer attached.

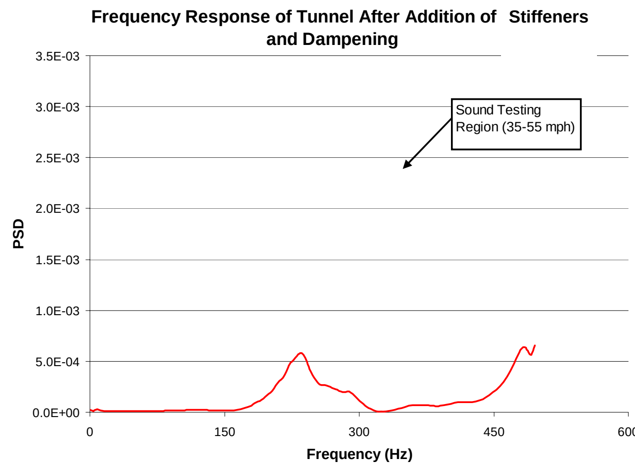

Figure 23: Frequency response of the tunnel after adding tunnel stiffeners.

The frequency response graph in Figure 23 clearly shows the elimination of the 300 Hz natural frequency of the tunnel through the use of the tunnel stiffeners. This change in the natural frequency effectively removed any amplification of track noise through the resonating tunnel, greatly reducing perceived track noise. This modification helped the team reduce sound power produced by the track and suspension in the Bucky 750 FX over 69% compared to earlier Wisconsin CSC entries.

OTHER SNOWMOBILE INFORMATION

The base chassis for the Bucky 750 FX is a 2003 Polaris EDGE sold with a Liberty 784 cc engine under the name Frontier Classic. Selected for its versatility, the EDGE chassis offers a variety of suspension and ride adjustments for different performance needs. The EDGE chassis provided a cost-effective base from which Wisconsin could implement a modified powertrain.

LED Headlight Assembly

Figure 24: Pictures of the dual LED headlight assembly before installation.

To reduce the overall electric load on the engine, the team decided to design and install light emitting diode (LED) headlights. LEDs are much more energy efficient than the stock incandescent bulbs while maintaining the required 200 foot visibility limit as required by the Wisconsin Department of Natural Resources [13]. The states of Michigan and Minnesota do not have distance visibility requirements for snowmobile headlights. The headlight assembly consists of two 6 volt, 3 watt LEDs connected in series combination to the wiring harness, making a total electrical load of 6 watts with the same luminescence. The stock incandescent bulbs use 97 watts of power at low beam. Therefore, using the LEDs results in a power savings of 91 watts.

Polycarbonate Hood

The Bucky 750 FX employs a lightweight polycarbonate hood shell. This un-vented shell lowers noise transmission, reduced vehicle weight, and increases durability compared to a stock hood. The clutch cover and underside of the hood have been lined with Polydamp Melamine for noise reduction. This polymer was selected for its sound absorption peak at frequencies between 100-350 Hz, maximizing the reduction of engine and clutch mechanical noise and speeds above 75 km/hr. The foam is rated for temperatures up to 400°C, making it safe for use in the engine bay.

Starter Battery

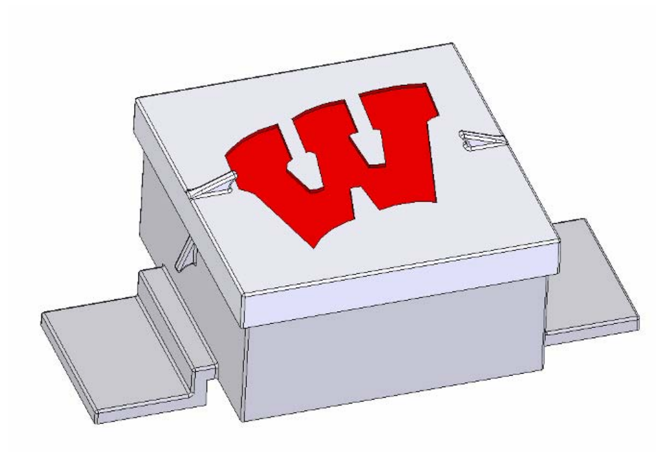

Figure 25: Image of the Solidworks model of battery box assembly.

In order to increase the amount of space under the hood, the team decided to move the battery box under the seat. The battery box was designed and modeled in Solidworks, and constructed of ABS plastic utilizing a rapid prototyping process. The box is designed to fit the stock Polaris battery.

Suspension Improvements

The rear suspension is a modified M-10, featured on multiple Polaris models. This suspension provides optimum rider comfort and performance that is sought by consumers.

Figure 26: Picture of the lightweight front suspension being utilized by Wisconsin.

The team decided to modify the front suspension of the 2008 CSC entry in order to reduce weight as much as possible. Consideration was given to a student designed and built suspension, but safety concerns led the team to install a professionally designed and built lightweight front end kit manufactured by Timbersled products. The front end kit reduces the suspension weight by 12 pounds, much of which is unsprung weight. This reduction in unsprung weight allows the suspension to be more responsive to rough terrain. The stock steel radius rods are replaced with aluminum, and the spindle is greatly redesigned with reducing weight as a priority. The suspension allows for a 10 degree sharper steering angle while maintaining a near stock ski stance and sway bar for optimal stability while cornering.

COST ESTIMATES

To help the Wisconsin team determine an acceptable manufacturer's suggested retail price (MSRP), 115 snowmobilers were surveyed at the 2008 World Championship Snowmobile Derby in Eagle River, WI. The individuals indicated the maximum surcharge that they would be willing to pay for a snowmobile utilizing clean and quiet technologies was between $300 and $600. The results are given in Figure 27.

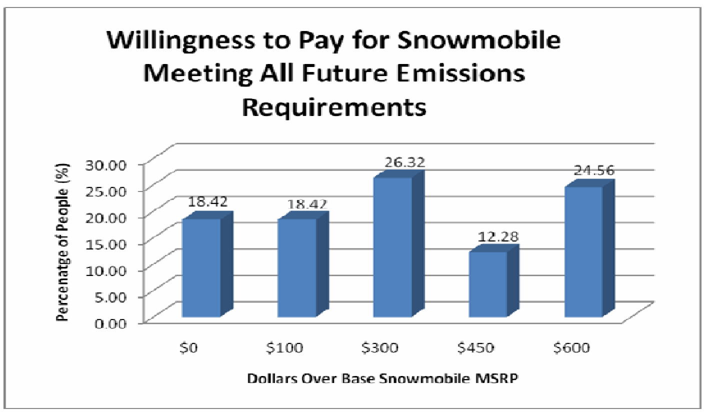

Figure 27: A survey of 115 snowmobilers shows that an added cost of $600 for clean and quiet technologies will be acceptable to many consumers.

Every component of the Bucky 750 FX is designed for manufacturability. Many of the technologies are currently in use in other transportation applications. The values listed in the cost summary of Table 8 are based on the assumption that parts are either manufactured in production quantities of at least 5000, plus 50% (Per 2008 CSC Rules).

Table 8: Projected MSRP of the Bucky 750 FX

Item	2008 UW-Madison 750 FX	2003 Polaris Frontier Classic
2003 Frontier Classic	N/A	$5,899
2008 Yamaha Phazer	$6,599.00	N/A
Sled Modifications	$650.00	None
Catalysts (1)	$310.00	None
Total	**$7,559**	**$5,899**

CONCLUSION

The 2008 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 engineered and installed a new, powerful four-stroke powerplant that combined satisfying performance with EPA 2012 emissions. The Bucky 750FX's flex fuel capability gives consumers the ability to utilize renewable fuels. A custom exhaust with a three-way catalyst reduces air pollutants to levels well below EPA's 2012 emission requirements. The redesigned drivetrain and exhaust after-treatment system ensures that Wisconsin's sled does not damage the environment it tours. Designed for manufacturability and aesthetically pleasing packaging, the Bucky 750FX is a cost-effective solution for performance-oriented riders seeking a cleaner, quieter snowmobile.

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