Fuel Efficiency and Emissions Optimization of a Quiet, Turbocharged Four Stroke Flex Fuel Snowmobile

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ABSTRACT

The University of Wisconsin-Madison Snowmobile Team has designed and constructed a clean and quiet, high performance snowmobile for entry in the 2010 Society of Automotive Engineers' Clean Snowmobile Challenge. Built on a 2007 Polaris FST LX trail chassis, this machine features a 750 cc port fuel-injected turbocharged 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 E0 to E85. An electronic throttle body and tunable volumetric efficiency maps allow for accurate calibrations for all gasoline/ethanol blended fuels. 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 98% to an average specific mass of 0.15, 0.06, 4.88 g/kW-hr respectively. Utilizing 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 maintains the snowmobile's aggressive OEM appearance. In addition to engine tuning, extensive driveline efficiency testing was completed in order to minimize road load power and maximize fuel efficiency. By replacing the stock 128 inch suspension with a Polaris IQ 121 inch suspension, and utilizing a 121 inch. 2.86 track with 2 additional bogie wheels resulted in an overall drag reduction of 23.63%, correlating to a further 16.69% increase in fuel economy.

INTRODUCTION

The Society of Automotive Engineers (SAE) developed the "Clean Snowmobile Challenge" (CSC) in 2000 when snowmobiles were banned from National Parks. It is an engineering design competition among colleges and universities that demonstrates clean, quiet and practical alternatives to the conventional two-stroke snowmobile. Competition entries are redesigned versions of original equipment manufacturer (OEM) snowmobiles and are expected to significantly reduce unburned hydrocarbons, carbon monoxide, nitrous oxide, and noise emissions while maintaining a consumer acceptable level of performance. Successful CSC entries must also demonstrate reliability, efficiency, and cost effectiveness. The 2010 CSC will be held in Michigan's Keweenaw Peninsula from March 15-20th.

The following paper discusses how the University of Wisconsin – Madison team has engineered an entry for the 2010 CSC that improves upon the industry's best available emissions and sound technology, while maintaining exceptional riding characteristics. The first section addresses the engine selection process and modifications to the snowmobile's drivetrain. The second section describes the fuel system modifications necessary for flex fuel capability. The third section focuses on emissions and emissions reduction techniques. The next section discusses specific design enhancements that reduce overall snowmobile noise. Finally, the paper addresses general snowmobile modifications employed to enhance the previously mentioned technologies. In addition, the paper summarizes the implementation costs compared to a comparable production snowmobile.

MARKET SURVEY

The guiding principles for the 2010 UW-Madison clean snowmobile design are simplicity, efficiency, 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 a product 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.

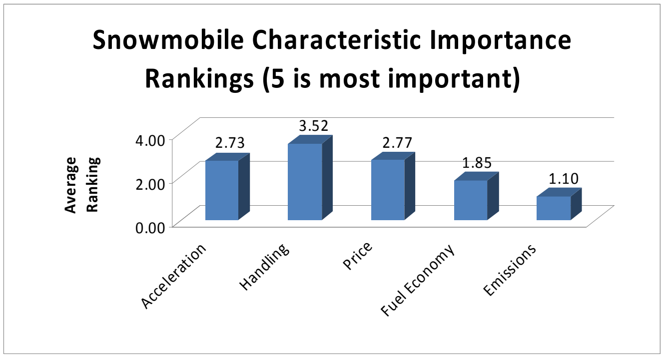

Figure 1: A survey of 115 snowmobilers taken at the 2008 Eagle River Ice Derby shows that acceleration, price, and handling are the most important considerations when purchasing a snowmobile.

The survey results confirm the guiding principles of the 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 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

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 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. Similarly, the marine engine options were eliminated because of their low power to displacement ratios. CSC rules restrict peak horsepower to 130 horsepower and 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.

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 voters claimed they would choose a four stroke engine to power their snowmobile.

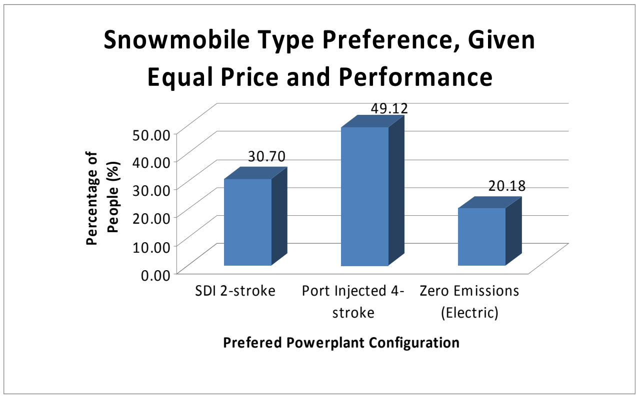

Figure 2: Results from the 2008 Eagle River survey showing people would prefer a four stroke engine in their snowmobile.

FINAL ENGINE SELECTION

Given the heavy weighting on emissions in CSC competition scoring, the team determined that a commercially available snowmobile engine offered the best starting point. Commercially available turbocharged versions of the FS and 660 are capable of power output of 97 kW (130 hp). 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

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. 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. However, new technologies are making it easier to create a clean, fuel efficient and yet powerful turbocharged engine.

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 NOx 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 which is 24 kW higher than the high-speed naturally aspirated engine. 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 NOx emissions by reducing combustion temperatures and allowing continued reactions in the manifold and turbine [6]. 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 [6].

Table 2: Polaris FST Engine Specifications [6]

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 Bosch would not supply the tools to reprogram the stock FST 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℃ to 130℃, 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 3: Picture of the Motorola MPC555 powertrain control module which is used as the engine control module in the Bucky CFS.

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 ECONOMY IMPROVEMENT

The competition objectives are to develop a clean, quiet, and fuel efficient design with moderate performance. Building off of the 2009 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: engine calibrations, engine modifications, and improving driveline efficiency.

Competition objectives for 2010 allowed for more precise calibration of the engine to improve upon last year's fuel economy. Knowing the specific narrow 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 dyno to optimize these two parameters for fuels ranging from E20-E29 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 overall friction 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 motor (Figure 4) is a highly tuned and well developed engine made to be sporty and practical. While Weber didn't leave much room to improve this engine, the Madison team found some places to improve efficiency, power, and fuel economy.

Figure 4: Model of the PWC 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 5 [6].

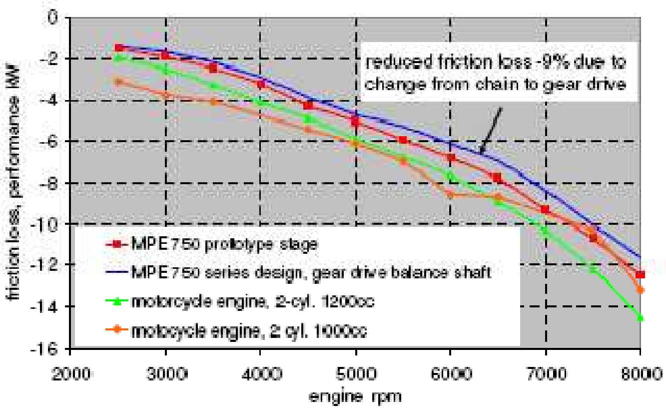

Figure 5: Results from friction loss testing on several engines conducted by Weber AG [6].

Also, to improve tune ability, efficiency and consistency, the team utilized an electronic throttle body (ETB) in the intake system (Figure 6). The electronic throttle body replaces the two stock mechanical throttle bodies with the Bosch ETB found in the PWC version of the MPE 750 engine. This enhancement reduces complications of calibrating the engine, makes cold start possible, and improves idle conditions over an idle air controller.

Figure 6: Picture of the Bosch electronic throttle body utilized on Polaris MSX personal watercrafts.

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 O2 sensor was utilized in Bucky CFS 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.

The Mototron engine controller coupled with the stock electronic boost controller allowed students to create their own turbo boost control strategy (Figure 7). 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.

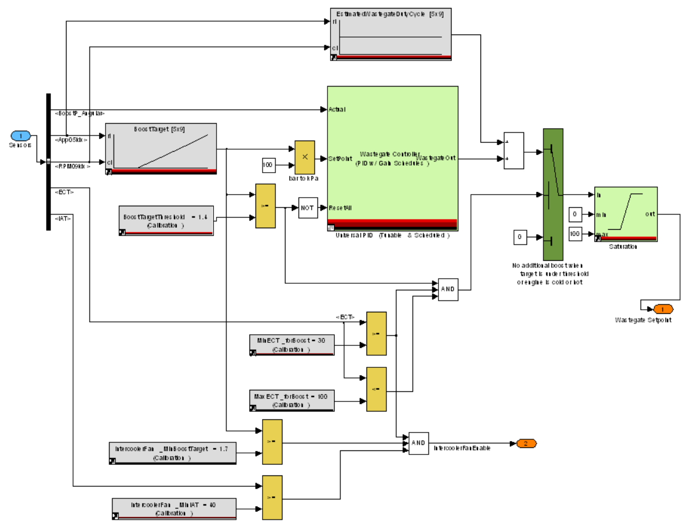

Figure 7: Image of control strategy Simulink model for electronic turbo boost control.

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. Upon tuning of 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 roller secondary. The replacement of the manufacturer's friction type secondary clutch with a roller type creates quicker shifting characteristics and increased transmission efficiencies from reduced friction.

Dynamometer tests on the turbo charged 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 90g cam arm was used with a orange Polaris spring 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. Furthermore, since major changes were made to the suspension and driveline components this year, the secondary clutching also had to be optimized for the reduction in chassis resistance.

Investigation of BSFC charts indicated that maximum engine efficiency was produced between 4000 and 5000rpm. 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 23/44 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. 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 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 so that both drive paddles were round.

DRIVELINE EFFICIENCY

In an effort to further improve fuel economy the UW-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 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.

Based on the driveline testing the largest potential for reduction in road load was to replace the stock 128 inch suspension on the Bucky CFS with the 121 inch model from a Polaris Shift Chassis. This change not only reduces the amount of friction with the surface due to reduction in surface area contact but also reduces the rotational moment of inertia due to the lighter 121 inch track. As seen in,figure 8, this combination 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.

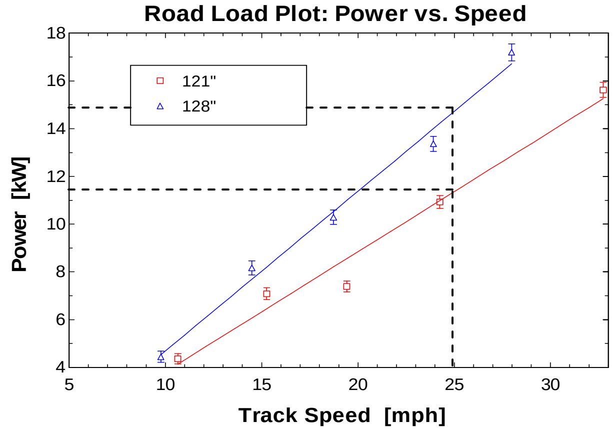

Figure 8: Graph of the road load power at various speeds for the 121'' and 128'' suspensions.

The drag reduction is relatively independent of sled speed. Switching to the 121 inch suspension would translate to a 22.5 percent decrease in the power required by the Bucky CFS. Based on the dyno data collected during the emissions portion of the competition last year, this would result in a 15.69 percent increase in fuel economy.

Additional testing was conducted to determine the effect of studding the track with respect to total road load power. As conveyed in Figure 9 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.

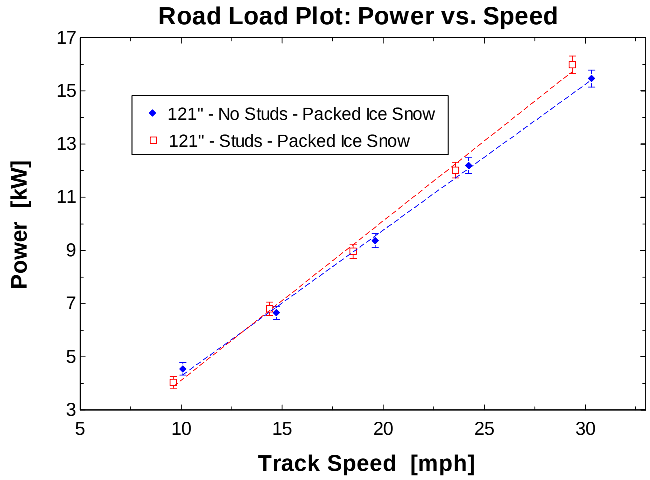

Figure 9: Plot showing the effect adding studs had on the power required at various speeds.

UW-Madison's final set of testing focused on 2.86 pitch, 1-ply tracks versus 2.52 pitch, 2-ply tracks and varying numbers of bogie wheels. The snowmobile industry is moving towards 1-ply tracks due to their ease of manufacturing and lightweight characteristics. The 1-ply track which UW-Madison tested was 5 pounds lighter than the equivalent 2-ply version. To accommodate the different pitch of the 1-ply track a non-stock, a 2.86 pitch driveshaft had to be used. The stock suspension came with 2 bogie wheels per side in addition to the rear idler, however, a total of 4 bogie wheels can reasonably fit on each side.

Three different track and bogie wheel configurations were able to be tested before snow conditions drastically changed. Figure 10 shows the road load power at the five tested speeds for these varying configurations.

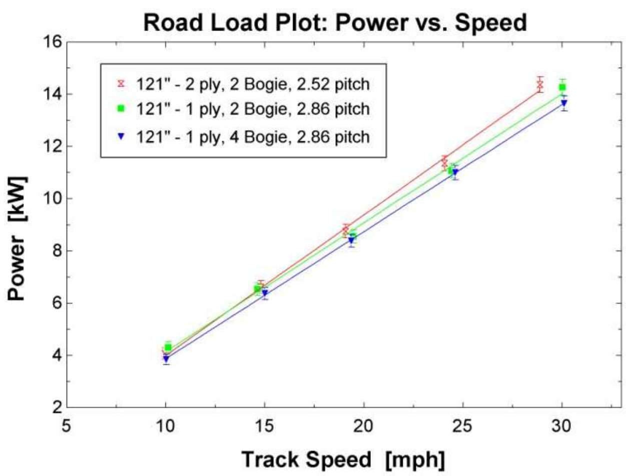

Figure 10: Influence of changing track ply and number of bogie wheels on road load power.

The results indicate that the larger pitched drive sprocket with the 1-ply track reduced drag by 5.31% compared to the convention 2.52 pitch 2-ply track. Additional bogie wheels in the suspension further reduced drag by 3.02%. With the ideal setup of a 2.86 track and a 121 inch suspension, a total driveline efficiency improvement of 23.63% was achieved compared to the stock 128" suspension. In summation, changes to the stock driveline configuration produced a 16.69% decrease fuel consumption.

TRACTION

At the 2008 competition, several judges during the subjective handling event commented that handling and braking capabilities of the sled would be vastly improved with increased traction through the use of studs. Since one of the goals of this competition is to maintain performance and consumer acceptability of the snowmobile, Madison listened to the judges' comments and added 84 studs in a centerline pattern to help increase traction during acceleration, cornering and braking while minimizing the effects of studs pulling out of the track. While this does slightly reduce the overall efficiency of the driveline at higher speeds, the increased performance and safety greatly outweigh this detriment.

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. 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 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 name 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 [7]. Since air fuel ratios are calculated on a gravimetric basis and fuel injectors are measured on a volumetric basis, the fuel temperature is measured to allow for density compensation.

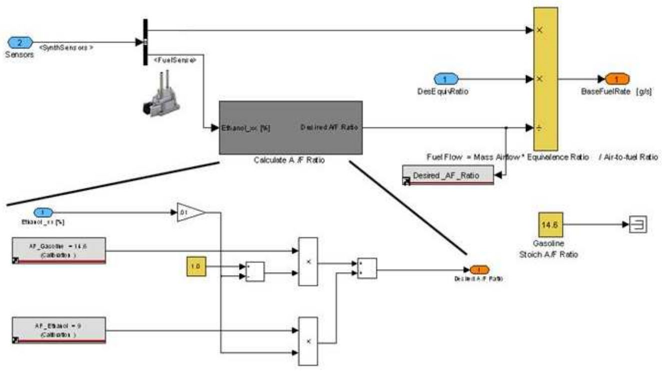

Figure 11: SimuLink block diagram for flex fuel engine control strategy, utilizes inputs from Continental flex fuel sensor and volumetric efficiency tables to determine desired fueling rate.

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 11). 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.

COLD STARTABILITY

One disadvantage of ethanol based fuels is its inability to effectively vaporize as the temperature decreases. As seen in figure 12, the volume of fuel needed to start an engine increases dramatically as either temperature decreases or ethanol concentration increases. [8]

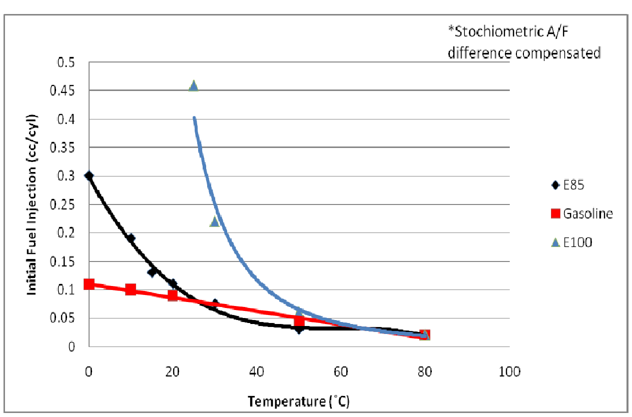

Figure 12: Graph of initial fuel injection volume vs. fuel temperature at different ethanol concentrations [8].

In a study on the effect of ethanol on spark ignition engine cold startability, Toyota Motor Corporation states that one of the most practical methods of boosting the vaporization of ethanol is to heat it up by either directly heating the fuel or the intake air with a heater [8]. Therefore, Madison decided to install a Philips and Temro intake grid heater, just before the throttle body. At 1.1 kW, this grid heater will heat up at a rate of 50˚ C (122˚ C) per second. While cranking at approximately 700 rpm, it takes about 1.15 seconds for the full volume of the hot air in the intake system to be inducted into the engine (figure 13). This is sufficient to heat the fuel enough to make reliable cold start possible.

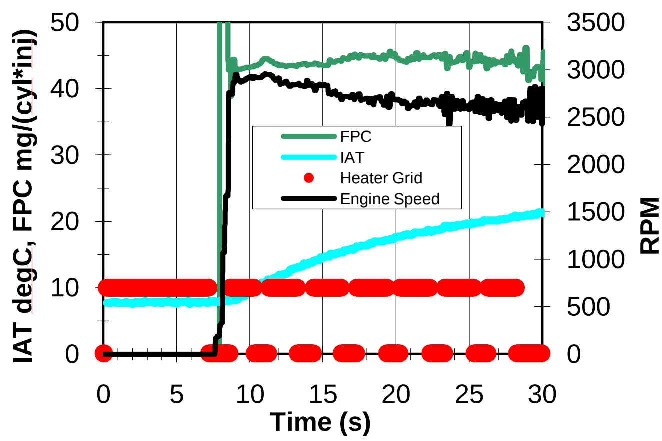

Figure 13: Plot of intake air temperature during startup with grid heater cycling.

CALIBRATION

Typically, when calibrating an engine, there are two main goals to adhere to. The first is to minimize BSFC under part-throttle operation and the second is 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 14).

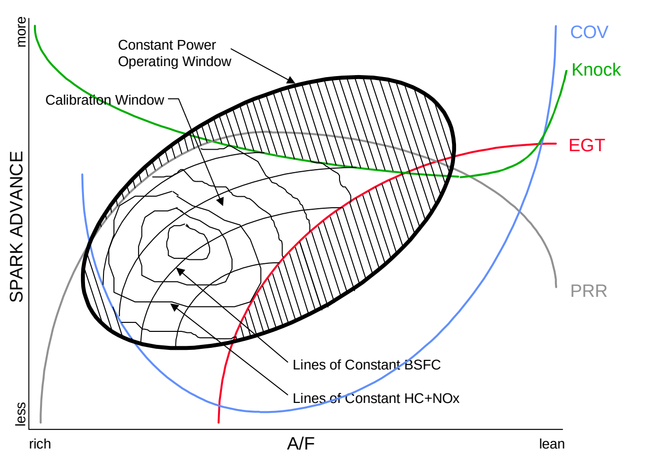

Figure 14: Graph of the typical calibration window of an internal combustion spark-ignition engine [9].

Calibration of the 2010 Madison engine was performed using a water-brake dynamometer, a non-dispersive infrared CO meter, an Innovate wideband O_2 sensor, a chemiluminest NOx analyzer, exhaust thermocouple probes, and 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 O2 sensor. The tables included 160 points that 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.

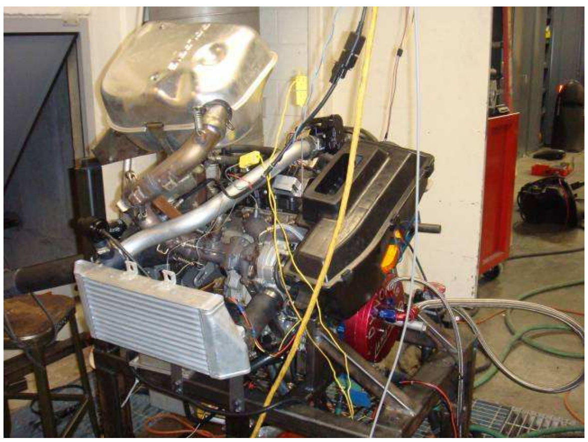

Figure 15: Picture of the Weber MPE 750 equipped with the custom camshaft operating on Madison dynamometer stand.

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, it did so without negatively impacting sound or power as the turbo charger '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 GmgH to customize a catalyst specifically for this engine's operating regime. 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 Hearsus 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 catalysts and/or reducing back pressure [10].

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 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 16, 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.

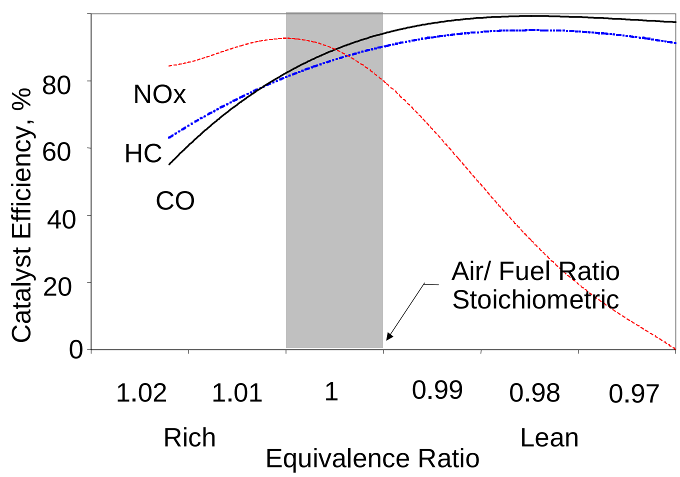

Figure 16: Figure showing the NOx, CO, and HC conversion efficiency for a three-way catalytic converter as a function of exhaust gas air/fuel ratio operating on gasoline (Adapted from [11]).

Parameters with Mototron's closed-loop fuel trim algorithm control the lean/rich oscillation of the engine for maximum emission reduction. Figure 17 shows the oxygen sensor value in addition to the fueling multiplier. In this area of engine operation, the base calibration is slightly rich and so the emissions control algorithm has adjusted the fuel multiplier to oscillate around the stoichiometric value of 0.96. 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.

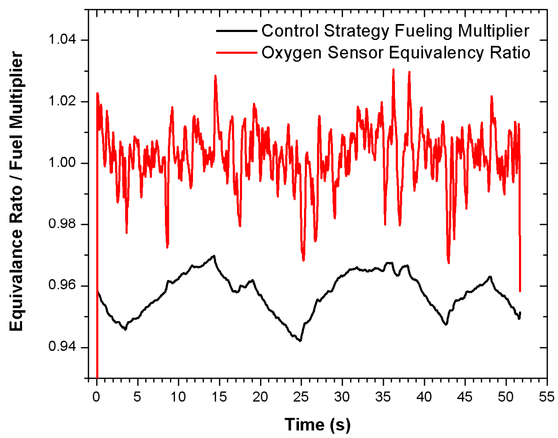

Figure 17: Figure of the Engine equivalence ratio oscillating near stoichiometric as a result of closed loop control with an exhaust O2 sensor.

During the 2009 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 208.6 (out of a maximum possible score of 210). This corresponds to average specific mass emissions of 0.06, 4.88, and 0.15 g/kW-hr for HC, CO, and NOx respectively. Due to the inverse nature of the e-score calculation for competition, even a substantial reduction in our emissions this year would not lead to a significant improvement in our e-score.

Table 5: Engine operating parameters for the 2009 Bucky CFS during the five-mode emissions test [12].

	Engine Speed (rpm)	Torque (N-m)	Power (kW)
Mode 1 (WOT)	6380	96.6	64.5
Mode 2 (85%)	5421	58.0	32.9
Mode 3 (75%)	4787	34.8	17.4
Mode 4 (65%)	4125	23.6	10.2
Mode 5 (idle)	1676	0.0	0.0

After manufacturing a new muffler with integrated three way catalyst, Wisconsin repeated the emissions testing. Within the accuracy of Wisconsin's emission equipment, the 2010 sled is as 'clean' or 'cleaner' than the 2009 model.

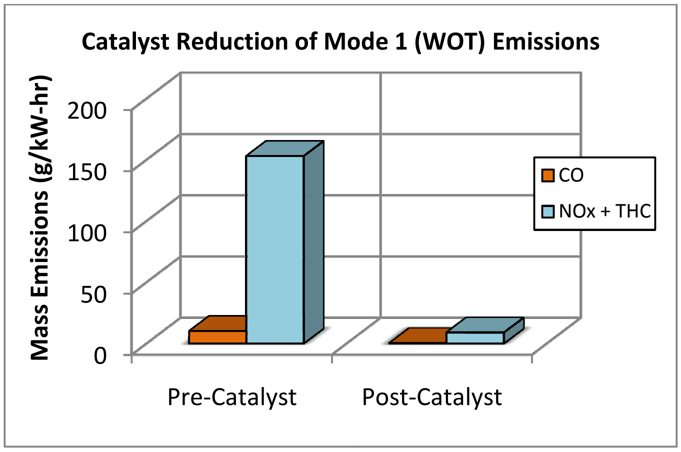

Figure 18: Figure of the catalyst system efficiency during mode 1 (100% load) operation. The catalyst yielded a 98% reduction in NOx and THC and a 94% reduction in THC over the engine's base emissions.

Testing on the 2010 Bucky CFS sled 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 0.21 g/kW-hr, a 98% improvement to the stock FST. The catalyst also reduced CO emissions by 94%, from an untreated 153 g/kW-hr to 8.96 g/kW-hr. Figure 19 shows the final results of the emissions testing on the Bucky CFS after full optimization of the emissions reduction systems. The certified emission levels for the Bucky CFS 750 are 0.15 g/kW-hr, 0.06 g/kW-hr and 4.88 g/kW-hr for NOx, THC and CO respectively.

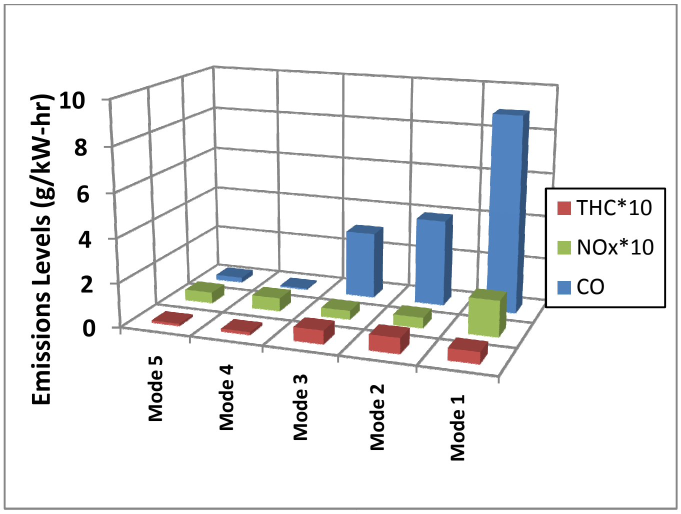

Figure 19: Figure of the post catalyst emission levels for the Bucky CFS engine operating on E85 fuel.

NOISE

Wisconsin's primary goal for sound reduction on the Bucky CFS 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 FST LX platform that the Bucky CFS 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 [13].

	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
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 FST exhaust system offered the most potential for noise reduction in the space available. In addition, Wisconsin's emission strategy required the implementation of a single large catalyst.

Using the space still limited by packaging constraints on the right side of the snowmobile, students designed a four chamber catalytic muffler that fits in the same space and housing used by the stock muffler. The 2010 system incorporates a single catalyst that is 105 mm in diameter and 140 mm long. The 2010 Wisconsin CSC catalyst system improves upon the 2009 system by keeping the exhaust manifold and exhaust pipes stock which helps lower exhaust backpressure. The catalyst is mounted inside of the muffler directly after the inlet. Keeping the exhaust tubing length to a minimum helps ensure proper catalyst temperatures. The muffler itself is insulated with 3M Interam 1101 material surrounded by an aluminum heat shield housing. These features will help maintain sufficient catalyst temperatures while minimizing under hood temperatures.

Figure 20 shows a schematic drawing of the catalytic muffler. Exhaust flow from the engine flows through the stock pipes into the muffler inlet. It then enters the catalyst through a diffusion cone to minimize pressure drop. The foil design of the catalyst induces turbulence between cells increasing exhaust gas contact with the substrate.

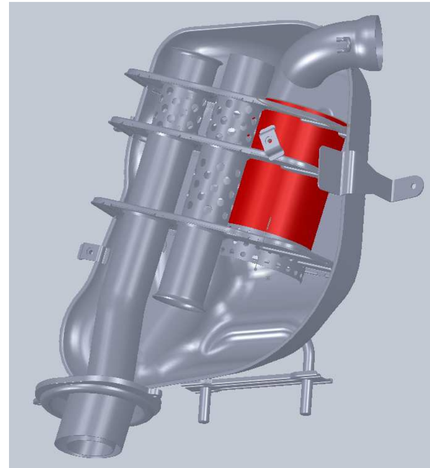

Figure 20: CAD Model of the four chamber catalytic muffler cutaway designed for the Bucky CFS.

After passing through the catalyst chamber, the exhaust flow enters the first chamber of the muffler. The flow is then free to flow through a series of corrugated pipes to reduce high frequency sound and chambers to cancel the engine's low, fundamental frequencies. Additionally Owens Corning "Silentex" muffler packing material was added in the second chamber to further reduce the effects of high frequency wave resonation within the exhaust system. Because the Bucky CFS operates at 5000 rpm instead of 7000 rpm, the fundamental engine frequency is lowered from 116 Hz to 83 Hz respectively. This gives the Bucky CFS a deeper 'rumble' and subsequently lowers its A-weighted sound level.

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 2010 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.

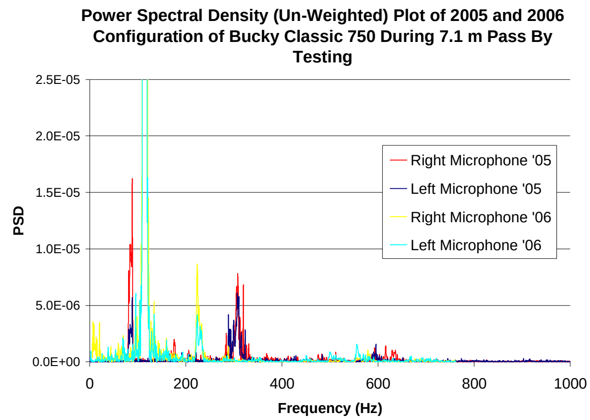

Figure 21: Spectral sound density of past UW-Madison CSC entries to determine typical sources of noise from a snowmobile (recreated from [14]).

Figure 21 shows a Power Spectral Density plot from the Bucky 750 FX. This plot shows the sound power emitted from the sled as a function of frequency. Three distinct peaks can be seen near 100, 225, 300, and 600 Hertz. By calculating the first and second order contributions of the snowmobile components at 72 km/hr, the sources of the peaks were discovered. The 100 Hz peak is first order engine noise, the 225 Hz peak is second order engine noise, and the 300 and 600 Hz peaks are first and second order noise produced where the track paddles interface the track. The right side 100 Hz and 225 Hz peak is much higher than the left side because the exhaust outlet is on the right side of the snowmobile.

Figure 22: 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 on the Bucky 750 FX was seen as a peak at 300 Hz in the 2005 test data. As the 2006 data shows (Figure 21), 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 Bucky 750 FX.

	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 1-ply track in lieu of the OEM track, fabricating a dampener to insulate the noise from the drive paddles (Figure 22), and by ensuring all chassis components weren't resonating at typical operating conditions.

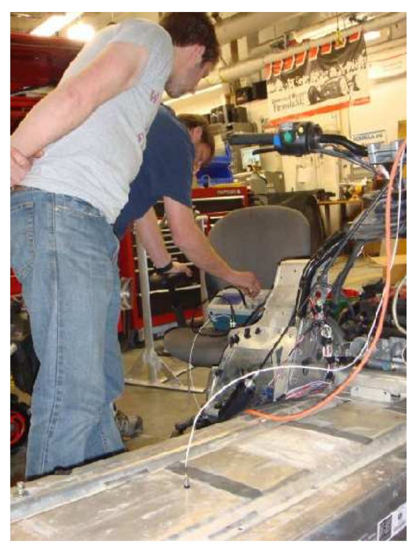

Figure 23: UW-Madison students obtaining frequency response of a snowmobile chassis with an accelerometer.

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 (Figure 23). Using a Hi-Techniques data acquisition system and PCB Piezoelectric accelerometer, the team discovered that the tunnel had a very similar construction as previous years with a resonant frequency close to the 300 Hz track vibration (Figure 24). This meant that any vibration from the track was being amplified by the tunnel, greatly increasing noise.

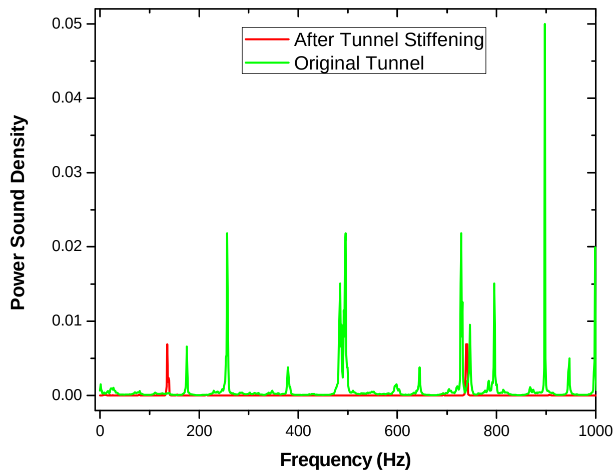

Figure 24: Figure of the Polaris IQ chassis frequency spectrum before and after tunnel stiffeners were added.

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 25).

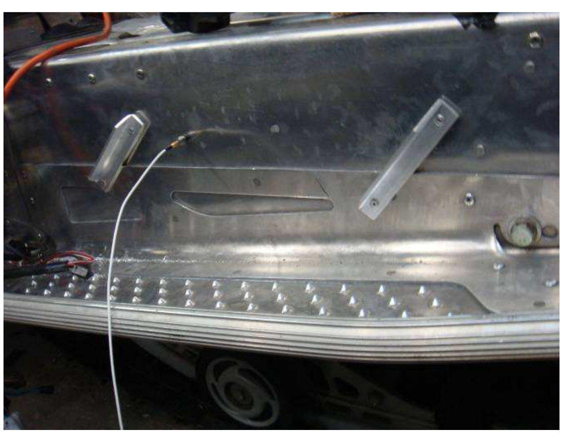

Figure 25: Picture of tunnel resonance being tested with tunnel stiffening ribs installed.

The frequency response graph in figure 25 clearly shows the elimination of the natural frequency near 300 Hz of the tunnel through the use of the tunnel stiffeners. Besides eliminating the majority of the natural frequencies, the two major remaining modes were reduced in amplitude by factor of 1.5. Finally, switching to a 1-ply track also lowers the track's fundamental frequency due to its larger pitch drive.

WEIGHT REDUCTION

One of the only ways to reduce CO2 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 will go against the competition goals of keeping the snowmobile cost effective. However, there are certain components that can be modified or changed that will also reduce the overall weight. Madison began working on some of these weight reductions including exchanging the very heavy and complex stock reverse gearbox of the FST with a much lighter and simple design incorporated on the new 2009 Polaris Shift chassis's. Additional weight was shed by switching from a 128 inch suspension with a stock track to a 121 inch model with a 1-ply Camoplast track. In combination, all of these changes reduced the overall weight of the machine by 13 kg (28.6 lbs).

COST ESTIMATES

Every component of the Bucky CFS is designed for manufacturability. In fact, many of the technologies are currently in use in other transportation applications such as the automotive camshaft, platinum 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. Actually, the retail price of many of the components that replaced stock parts were 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. Thus, the MSRP of the 2010 Bucky CFS is about $2,300 more than the Polaris IQ Turbo Dragon price of $10,999. However, if key components of the Bucky CFS such as the catalyst and ethanol sensor became standard parts within the snowmobile industry, the base price would likely only be $200 to $300 greater than today's stock Turbo Dragon configuration.

CONCLUSION

The 2010 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 engineered and installed a new, powerful turbocharged four-stroke powerplant that combined satisfying performance with EPA 2012 emissions compliance. The Bucky CFS's flex fuel capability gives consumers the ability to utilize renewable fuels. Utilizing a specialized low valve overlap camshaft and a custom exhaust equipped with a three-way catalyst, the Bucky CFS scores 208.6 on the e-score. An extensive track drag study utilizing Wisconsin's BuckEV clearly defines the optimal track, track tension, drive pitch, and bogie wheel combination. Overall, the 2010 entry is projected to be 23.63% more efficient. The redesigned drivetrain and exhaust after-treatment system ensures that Wisconsin's sled does not damage the environment it tours. Designed for manufacturability and an aesthetically pleasing packaging, the 65 kW, studded Bucky CFS is a cost-effective solution for performance-oriented riders seeking a cleaner, quieter snowmobile.

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