Development of the Bucky Classic 750: A Cleaner and Quieter Snowmobile

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ABSTRACT

The University of Wisconsin-Madison Snowmobile Team has designed and constructed a clean, quiet, high performance snowmobile, the Bucky Classic 750, for entry in the 2006 Society of Automotive Engineers' Clean Snowmobile Challenge. This year, UW-Madison has developed a totally new powertrain after developing and optimizing the world's first hybrid snowmobile powertrain over the last two years. Built on a 2003 cross-country touring chassis, this machine features a 750 cc fuel-injected closed-loop four-stroke engine. Improving on the engine's EPA Best Available Technology certification, a dual three-way catalyst further reduces NOx, HC and CO emissions by up to 90%. The powertrain, catalyst and muffler are packaged in a manner that maintains the snowmobile's aggressive OEM appearance.

INTRODUCTION

In 2004 alone, the sport of snowmobiling contributed over $20 billion to the economies of the United States Canada. With more than 500,000 snowmobiles registered in Wisconsin and Michigan, snowmobilers in these two states alone spend nearly $2 billion annually on the sport [1]. Clearly, snowmobiling plays a vital role in northern states' winter economies and ensures financial stability for communities with tourism-based economies.

The importance of snowmobiling to local economies is historically evident by business closings and bankruptcies in the town of West Yellowstone, Montana, resulting from a two-month court injunction severely limiting snowmobile access to Yellowstone National Park in 2003 [2]. The ruling by Judge Emmet Sullivan, though overturned, cited that the park's winter use policy did not adequately address the environmental impact of snowmobiles. The impact of snowmobiling on air quality, as seen in Table 1, raises justifiable concern. Though smaller and used for only a few months each year, snowmobiles can account for more air pollution in national parks than all other mobile sources combined.

Prior to the ruling, the Yellowstone winter use policy allowed snowmobile access with the stipulation that a specific percentage of the snowmobiles entering the park were the industry's Best Available Technology (BAT). However, the district court judge ruled that even the current snowmobile BAT at that time did not do enough to prevent air pollution [3].

Table 1: Annual emissions from mobile sources in Yellowstone National Park [4].

	Auto	RV	Coach	Snow-mobile	Bus	Total
HC	93	19	3	780	4	899
CO	1335	337	25	939	15	2652

Estimated average annual emissions in tons based on 1999 Denver University study

Given this negative publicity and the recent scrutiny on National Park recreational vehicle policies, the need for cleaner, quieter snowmobiles has become absolutely clear. The life of the sport and the survival of winter tourism economies are dependent on new technologies which must drastically reduce environmental impact while maintaining the performance that riders demand.

Recognizing the difficulty of this challenge, the Society of Automotive Engineers (SAE) developed the "Clean Snowmobile Challenge" (CSC) as an engineering design competition among colleges and universities which is geared toward the research and development of environmentally friendly snowmobiles. 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. Successful CSC entries must also demonstrate reliability, efficiency, and cost effectiveness. The 2006 CSC will be held in Michigan's Keweenaw Peninsula from March 13-18.

The following paper discusses how the University of Wisconsin – Madison team has engineered an entry for the 2006 CSC that improves upon the industry's best available emissions technology, while maintaining exceptional riding characteristics. The first section addresses the engine selection process. The second section describes modifications to the snowmobile's drivetrain and chassis while 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 2006 UW-Madison clean snowmobile design are simplicity and practicality: the design objective is to develop 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 this group, the team first determined the characteristics which are important to riders in that demographic sector. In fall of 2005, the team surveyed 75 UW-Madison students, each of whom had previous snowmobile riding experience. The subjects were asked to rank the importance of the following characteristics: top speed, acceleration, trail handling, and price. The results, as seen in Figure 1, show that acceleration and trail handling influence a buyer significantly more than top speed, with price being the third most persuading factor.

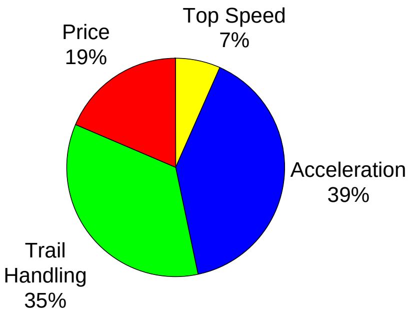

Figure 1: A survey of 75 student riders shows that acceleration and trail handling are the most important considerations when purchasing a snowmobile.

These results were verified and confirmed by checking them against industry-wide sales information. For example, in 2001, the world's top selling snowmobile had a 600 cc engine integrated into a cross-country race chassis [5]. Though this engine was not the largest displacement available, a lightweight chassis and aggressive suspension gave the sled solid acceleration and trail performance. Also consistent with survey results, the 600 cc snowmobile sold as a higher end model, but still cost 15% to 20% less than the largest displacement sport models or premium touring sleds [5].

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 [6]. 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 [7]. While SDI engines are a significant improvement compared to conventional two-stokes, they cannot attain current four-stroke emission levels. Aside from the three pollutants measured for competition scoring, two-stroke spark ignition engines are known emitters of benzene, 1,3-butadiene and gas-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) [8].

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 limits four-stroke displacement to 960 cc and current marine engines 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.

Final Engine Selection

Given the heavy weighting on emissions in CSC competition scoring, the team determined that a commercially available 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 (90+ kW). To compare the effect of the choices on emissions, the UW team examined the University of Idaho's emissions results at the 2003 CSC as well as their test results as part of the 2002 SwRI study. As seen in Table 2, four-stroke engines emit slightly higher NOx emissions relative to a two-stroke engine but significantly reduce hydrocarbon and carbon monoxide emissions.

Table 2: A comparison of emissions data from a SWRI, 2003 CSC and current commercial four-stroke snowmobile engines (Adapted from [6, 9]).

	HC g/kW-hr	CO g/kW-hr	NO_x g/kW-hr
Two-stroke average (SwRI 2002)	189	517	0.72
Idaho four-stroke (CSC 2003)	2.1	23.8	5.5
Idaho four-stroke (SwRI 2002)	3.5	152.9	0.19
Arctic Cat 660 (4s) (SwRI 2002)	6.2	79.9	10.6
Polaris Liberty (4s) (SwRI 2002)	3.2	79.1	7.0

High compression four-stroke engines are designed to run slightly rich 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 [10]. Coupled with the difficulties of implementing a CVT onto a motorcycle engine, this option was eliminated.

High-performance turbocharged snowmobile engines such as the Polaris FST and Arctic Cat 660T provide much more power than the equivalent non-turbocharged engines, but at a penalty of increased emissions and cost. While the non-turbocharged FS engine is EPA 2012 emissions certified, the FST is not [11]. Therefore, the team decided that, while turbo-charging would provide increased power, the increased emissions would be unacceptable.

Given the core objectives of the CSC, the added power of a high-compression motorcycle engine or turbocharged snowmobile engine is not justified by their increased emissions. Therefore, the team selected the 750 cc Polaris FS non-turbocharged four-stroke engine for this year's snowmobile (Table 3). In its stock configuration, this engine is EPA 2012 certified and produces nearly 50 kW of power, comparable to a 500 cc two-stroke engine [12]. This combination provides enough power to satisfy the performance demands of the snowmobile enthusiast, while maintaining low emissions required by law.

Table 3: FS engine specifications [13].

Engine Type/ Cooling	Four Stroke / Liquid
Cylinders	2
Displacement	750 cc
Bore	85 mm
Stroke	66 mm
Ignition	Bosch – Closed Loop
Exhaust	Single
Carburetion	EFI
Tested Power	46.6 kW
Tested Torque	54.9 Nm

Enhancing the Powertrain

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 Pro/Engineer 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.

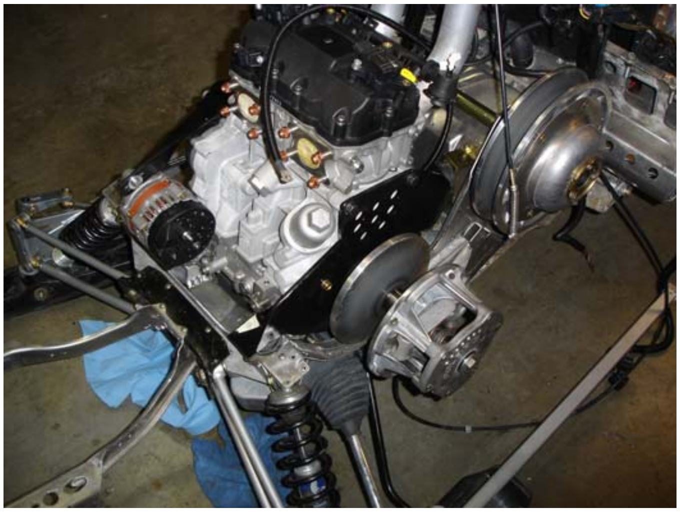

Figure 2: Image of the Clutch-side engine mounting bracket during the fabrication phase.

Due to differences in steering column and jackshaft location between our chassis and the original FS 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.

Figure 3: Image of custom air induction system used to integrate the stock throttle bodies.

The new intake system was fabricated 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 4: Image of the custom air box mounted over the engine.

The air box was constructed from aluminum and was shaped to maximize airflow and minimize size, allowing the use of an unmodified hood. The air box pulls air through a filter located above the clutch assembly. The intake location was optimized to minimize induced air temperature based on data logged during actual riding conditions. The air box was covered with a sound-dampening rubber compound to reduce resonant vibration and intake noise.

Figure 5: Image of the oil reservoir mounted in the Bucky Classic 750.

The FS engine employs a dry sump oiling system which requires a separate oil reservoir. The team used the stock FS reservoir to ensure correct flow and reserve volume and mounted it in a location near the chaincase. 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. 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.

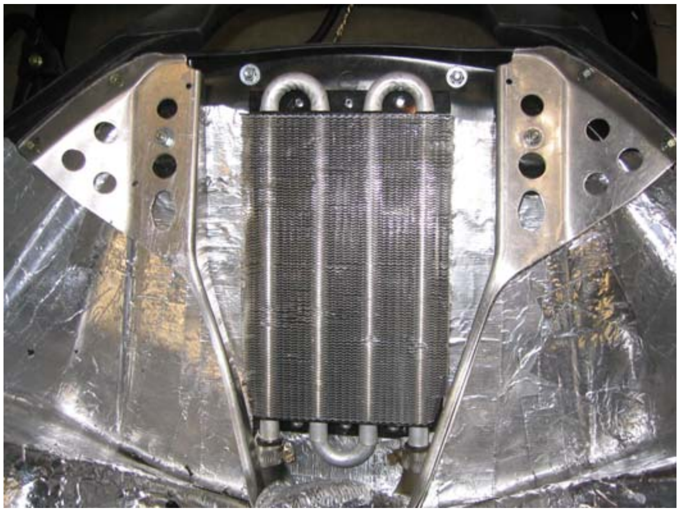

Figure 6: Image of the oil cooler mounted in the front, lower cowling of the Bucky Classic 750.

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. The original FS chaincase utilizes a 21/46 gear-set (2.19 reduction), but does not fit in the Edge chassis. Therefore, a 18/39 gear-set was used instead, providing a reduction of 2.17 for optimal performance.

EMISSIONS

Knowing that the untreated emissions of the FS engine are significantly higher than the CO, HC, and NO_x levels 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.

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 7, 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. The closed-loop fuel injection system used on the FS engine actively monitors and corrects the fuel/air mixture to minimize engine emissions.

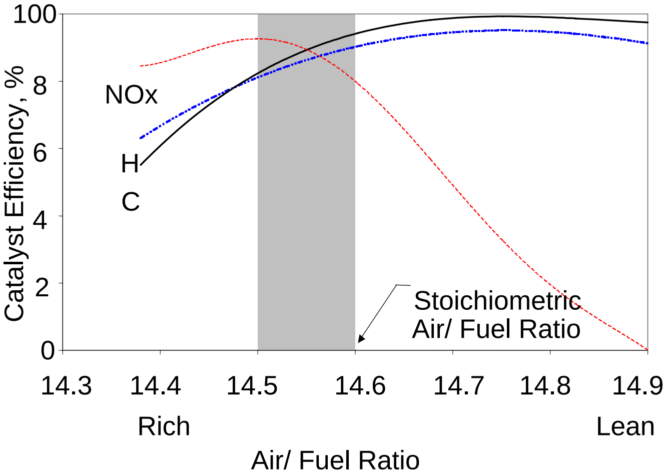

Figure 7: The NOx, CO, and HC conversion efficiency for a three-way catalytic converter as a function of exhaust gas air/fuel ratio (Adapted from [14]).

The Liberty engine used in the 2004 and 2005 sled switched to open-loop control at high loads, necessitating complex modifications to the fuel-injection system to minimize emissions. Extensive testing using a Fourier Transform Infrared (FTIR) gas analyzer and a Dynomite dynamometer showed that the FS engine chosen this year utilizes closed-loop control across its entire range of operation, providing good emissions in all tested regimes.

Table 4: Polaris FS operating conditions for the five-mode emissions test used for the CSC [15].

	Engine Speed (rpm)	**Torque (N-m)**	**Power (kW)**
Mode 1 (WOT)	8000	54.9	46.0
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

Testing on the 2005 sled showed that using two catalysts in series offers significantly reduced emissions over a single catalyst system. Though the FS engine offers better base emissions than the Liberty engine used in 2005, the weight of a second catalyst is so minimal (under 1 kg) that the team chose to use it in an effort to attain maximum emissions reduction. The dual-catalyst system yielded a reduction in the average specific mass emission (HC+NO_x) from an untreated 8.80 g/kW-hr to 0.89 g/kW-hr, a 90% improvement.

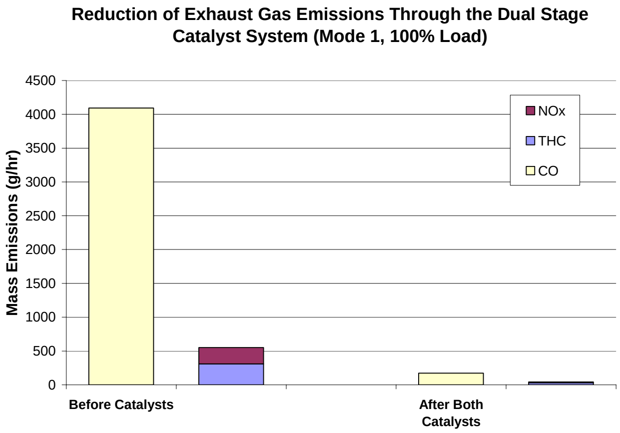

Figure 8: The dual-catalyst system yielded a 95% reduction in CO and NO_x and a 90% reduction in THC over the FS engine's base emissions at 100% load.

Figure 9 shows the final results of the emissions testing on the Bucky Classic 750 after full optimization of the emissions reduction systems. Total pollutant levels (specific HC+NO_x) have been reduced 25% from last year's entry, which scored first overall in the 2005 CSC emissions event [16].

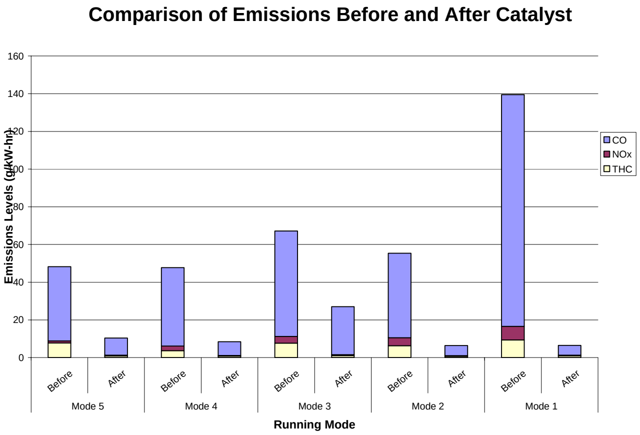

Figure 9: This year's design offers excellent emissions across all ranges of riding condition. The high bar for idle CO emissions is primarily due to the low power output at idle and has little effect on the composite score due to the 5% idle weighting.

Evaporative Emissions

The Bucky Classic 750 features a charcoal evaporative emissions canister (shown in Figure 10) to reduce hydrocarbon emissions due to thermal cycling of the fuel tank. This canister captures harmful vapors released from the tank when the snowmobile is not in use and releases them into the air box during engine operation where they are combusted. These canisters have been used on vehicles since the late 1960s and have been required on all on-road vehicles manufactured since 1971.

Figure 10: The evaporative emissions system on the Bucky Classic 750 reduces hydrocarbon emissions due to thermal cycling of vapors in the fuel tank, a major source of unburned hydrocarbon emissions.

NOISE

Wisconsin's primary goal for sound reduction on the Bucky Classic 750 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 the SAE test procedure J192. A secondary goal was to reduce perceived sound levels to bystanders. Table 5 shows the A-weighted pass-by levels for the stock Polaris Frontier platform that the Bucky Classic 750 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 5: 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 [17].

	33 km/hr	50 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
Snow Coaches / Conversion Vans	69.6	74.0	---	---	---	46.4

Muffler Design

As a starting point, redesigning the FS exhaust system offered the most potential for noise reduction. Since

Wisconsin's emission strategy required the addition of a catalyst and the oil reservoir occupies the stock muffler location, the new exhaust system faced a number of design constraints.

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. Flow tested with the help of Nelson Industries, Wisconsin's two-stage muffler increases exhaust volume by 30% over stock, while maintaining identical exhaust back pressure for efficient engine operation.

To maximize catalyst temperature, the two catalysts are mounted inside the first muffler, locating them only 30-40 cm downstream of the engine exhaust manifold. In addition to emissions reduction, the catalyst acts as the muffler's first passage. The small pass-through channels in the catalyst's metallic core effectively reduce the ultra-high frequency components of the engine's exhaust noise.

Figure 11 shows a schematic drawing of the first muffler. Exhaust flow from the engine headers enters into the first chamber of the muffler where it is allowed to expand and mix achieving even flow of gasses into the catalyst. After passing through the catalyst, the exhaust flows into a second chamber where it is again allowed to mix before passing through the second catalyst. The exhaust then flows into a third chamber before passing into the second stage of the exhaust system.

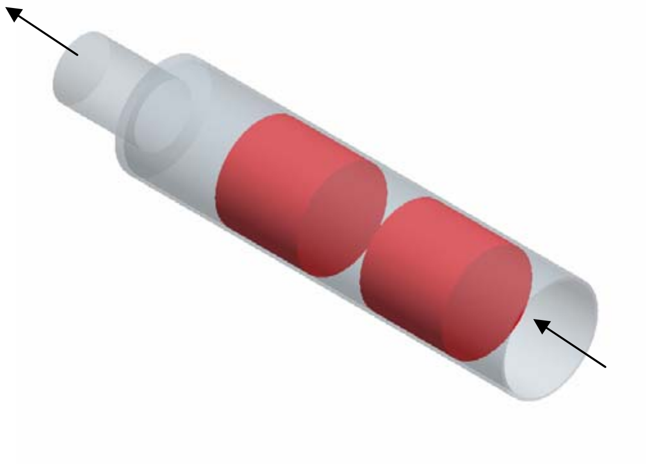

Figure 11: The first stage of the muffler system consists of the dual stage catalyst assembly.

After passing through the first muffler, the exhaust flow enters a broadband resonator (Figure 12) designed to remove the majority of mid to high frequency noise. After entering the muffler, 15 percent of the exhaust flow is bled out of twenty evenly spaced 3.2 mm diameter holes drilled in the inlet pipe. The remaining flow exits the pipe into the large chamber of the muffler. The flange of this chamber is packed with fiberglass insulation to prevent sound reflection. The flow then enters the second pipe through an ideal entry and is carried to the smallest chamber where another insulated flange further reduces sound. Finally, the flow enters the third mid-sized chamber where it is allowed to recombine with the bled flow. Due to the path length difference between the main flow and bled flow, there is a phase shift in the sound, allowing for noise cancellation upon flow recombination.

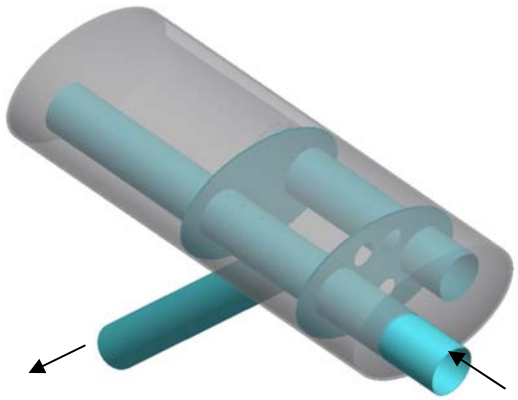

Figure 12: The second stage of the muffler system is a broadband muffler that reduces mid to high frequency sound while allowing higher flow than stock.

Fabricated from aluminized steel, the muffler can be cost-effectively manufactured in high volume using a press seal method to ensure weldability. To protect engine bay components from exhaust heat, portions of each muffler are wrapped in a layer of needled fiberglass insulation. As in a conventional sled, portions of the hood and lower cowling are lined with reflective tape to reduce radiated heat transfer.

Mechanical Noise Reduction

In order to identify the main contributors of the sound from the snowmobile, pass by sound tests were performed consistent with the SAE standard J2104 sound power test used for the 2006 CSC competition [18]. This test uses six microphones positioned on the surface of a 10 meter hemisphere. The snowmobile is ridden at constant speed through the hemisphere, and optical gates at the start and finish of the test section to start and stop data acquisition. This data is then A-weighted and reported as a sound power level emitted from the snowmobile as it passed through the hemisphere.

Because the Wisconsin team only had two PCB Piezotronics ICP® style microphones available, the KRC hemispherical method had to be modified. The snowmobile was ridden along a 45 m track at a constant speed of 72 km/hr between the pair of microphones, each positioned 7.5 m from the centerline. The sound data was recorded using a Hi-Techniques HT-600 data acquisition system that automatically processed sound data.

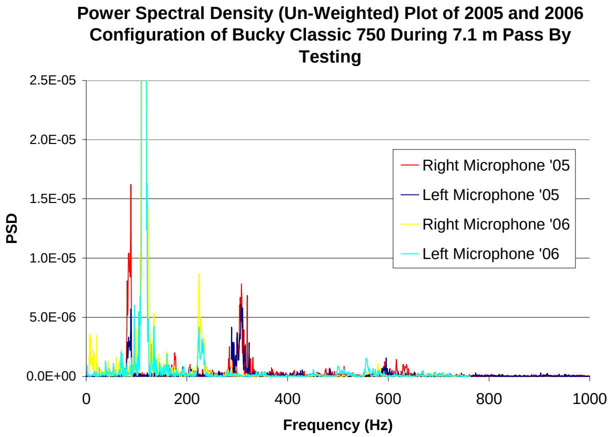

Figure 13: Spectral sound density of UW-Madison 2005 and 2006 CSC entries. Testing was performed Feb 25, 2005 and March 1, 2006.

Figure 13 shows a power spectral density plot of the 2005 and 2006 configuration of the Bucky Classic 750. 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 6), the sources of the peaks were discovered. The 100 Hz peak is first order engine noise, the 225 Hz peak is second order engine noise, and the 300 and 600 Hz peaks are first and second order noise produced where the track paddles interface the track. The right side 100 Hz and 225 Hz peak is much higher than the left side because the exhaust outlet is on the right side of the snowmobile. The 2006 data shows extremely large peaks at the 100 Hz and 225 Hz engine noise frequency because of an exhaust leak that developed during testing (this is not representative of the actual sound power produced by the FS engine).

Table 6: First and second order frequencies of sound emitted by three components of interest on the Bucky Classic 750.

	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 2006 Bucky Classic 750 were 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 14: Arctic Cat Silent Track installed in the Bucky Classic 750.

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 Classic 750 is the drive paddle noise dampener located on the front arm of the rear suspension (shown in Figure 15).

Figure 15: 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 13), this 300 Hz peak has been reduced to nearly zero.

In addition to analyzing the sound spectra, J192 pass-by sound tests were performed to determine overall noise levels. These tests were used to evaluate possible techniques for increasing noise reductions. Thick rubber mats were 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 16 shows these sound barriers installed on the snowmobile. Figure 17 shows the results of the testing. Variables tested include isolating the hood, isolating the track, isolating both the hood and track, and the removal of the front bogie wheels.

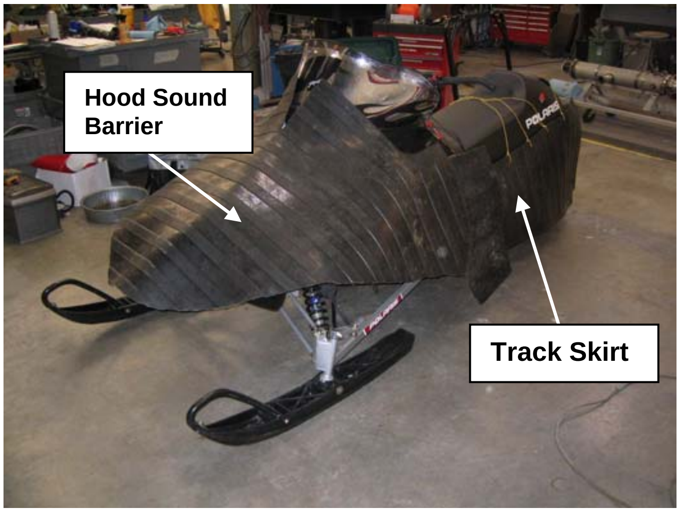

Figure 16: Rubber mats were used to isolate sound emissions from targeted components. In this way, the relative contribution of each component to the overall A-weighted sound level could be found.

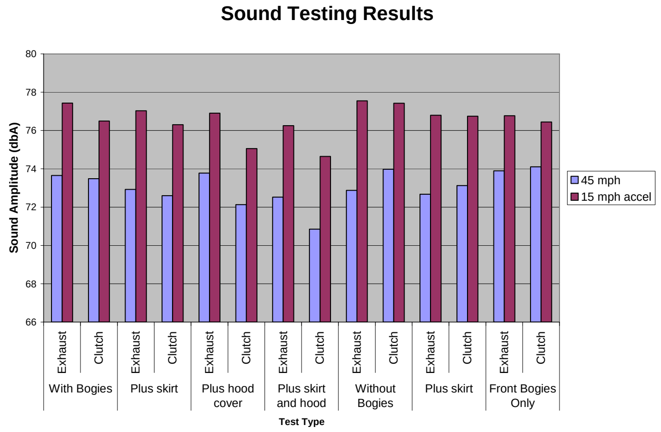

Figure 17: Graphs of pass-by sound testing results. Running with bogie wheels installed yielded consistently lower sound levels.

Based upon the results of Wisconsin's pass-by testing in 2006, the Bucky Classic 750 is equipped with bogie wheels on the front and rear. Running with front and rears bogies achieved consistently lower sound levels than running with only the rear bogies. Bogie wheels on the front of the suspension rail provide a tensioning force that keeps the front of the track from vibrating at speed, reducing noise. The use of front bogie wheels yielded a 6% reduction in total sound power at 72 km/hr.

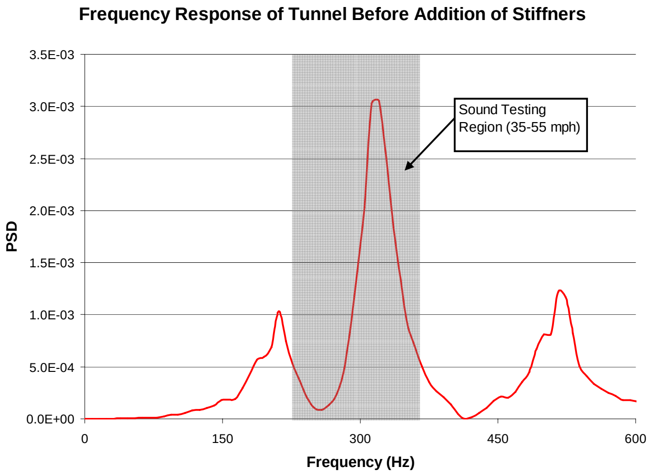

Figure 18: Frequency response of tunnel before adding tunnel stiffeners.

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 18). 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 19).

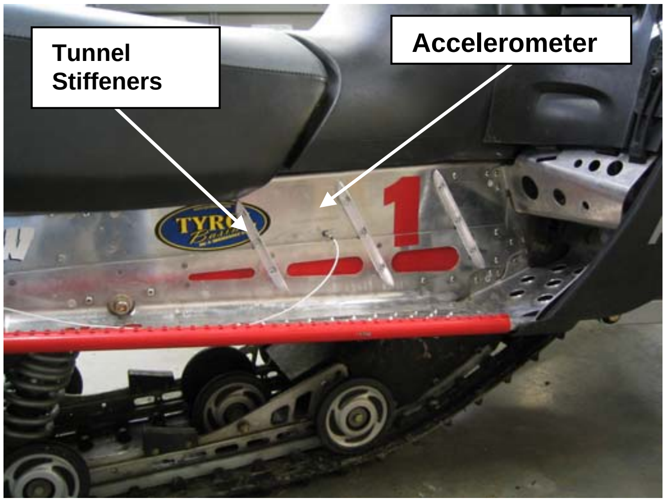

Figure 19: Tunnel stiffening angle brackets with accelerometer attached.

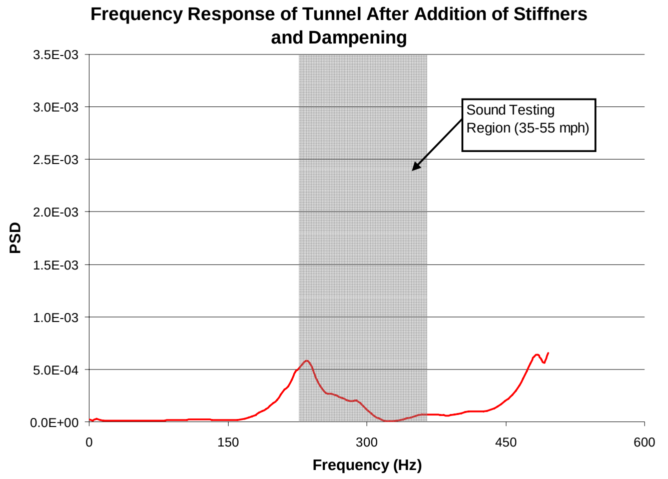

Figure 20: Frequency response of the tunnel after adding tunnel stiffeners.

The frequency response graph in Figure 20 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 (Table 6) through the resonating tunnel, greatly reducing perceived track noise.

Although our data showed a substantial reduction in overall snowmobile sound over our 2005 CSC entry, the team decided to further verify the reduction by measuring perceived noise levels to bystanders. On February 26, 2006, the team conducted a perceived noise test on Lake Winnebago in northeast Wisconsin. The Bucky Classic 750 was driven at an approximate speed of 75 km/hr past a group of observers at a distance of 25 m. The 20 observers were then asked to evaluate perceived sound intensity level and subjective sound quality (annoyance level) compared to a Polaris Indy 500 two-stroke control snowmobile. The observers were instructed to evaluate quality on the basis of "which snowmobile would [they] rather hear passing by their house all day."

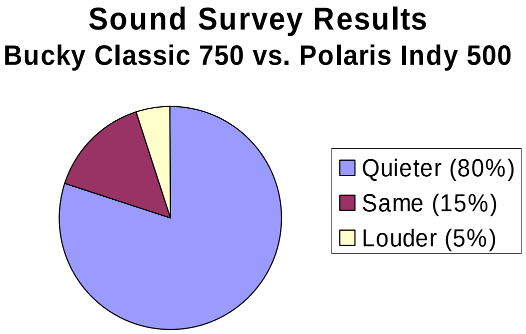

Figure 21: Survey results of perceived sound quality taken on 2 / 26 / 2006.

An overwhelming majority of the group, 80%, thought that the Bucky Classic 750 had better or equal sound quality than the comparable two-stroke snowmobile. These results show that the 2006 UW-Madison CSC entry not only emits a low sound power, but produces a sound quality that is acceptable to a majority of the public.

OTHER SNOWMOBILE INFORMATION

The base chassis for the Bucky Classic 750 is a 2003 Polaris EDGE sold 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 hybrid powertrain.

Polycarbonate Hood

The Bucky Classic 750 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.

Suspension Improvements

The Bucky Classic 750 front suspension features shimmed RydeFX gas shocks, tuned to instant dampening despite the added mass of the four-stroke engine. Stiffer coil springs are preloaded to supplement the tuned shocks. The overall stiffer front suspension is set up to provide responsive steering and excellent control at trail speeds, which is one major purchase consideration (Figure 1). The rear suspension is a modified M-10, featured on multiple Polaris models.

STARTER BATTERY

The 12V system is powered using a single JCI Inspira battery. This system provides power for electric start, engine controls, headlamps and dashboard information displays. Inspira batteries use a unique patented spiral wound lead acid design that offers significantly larger plate area than traditional "flat plate" cells. Figure 22 shows the internal construction of an Inspira lead acid battery. The Inspira battery is mounted in the stock location, is sealed and leak proof, and is 6 kg lighter than the stock Polaris battery.

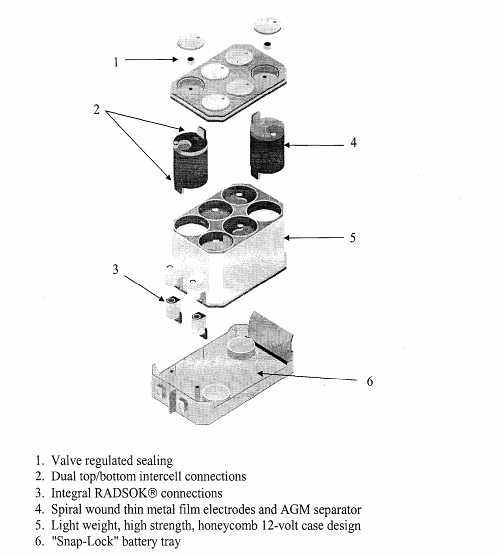

Figure 22: Internal construction of the Inspira spiral-wound lead acid battery produced by Johnson Controls Incorporated [19].

COST ESTIMATES

Every component of the Bucky Classic 750 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 7 are based on the assumption that parts are either manufactured in production quantities of at least 5000, or are priced at 60% of prototype cost (per 2006 CSC rules).

Table 7: Projected cost of the Bucky Classic 750

Item	**UW-Madison Bucky Classic 750**	**2003 Polaris Frontier Classic**
Base sled cost (with 784 cc Liberty Four-Stroke)	$5,899	$5,899
FS Engine Upgrade	$199	None
Inspira Starter Battery	$26	None
Dual Stage Catalyst	$69	None
Premium Muffler	$20	None
Total	**$6,213**	**$5,899**

CONCLUSION

The 2006 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 certified emissions. A custom exhaust with dual three-way catalysts reduces 2012 BAT emission levels by up to 90%. The redesigned drivetrain and exhaust after-treatment system ensure that Wisconsin's sled does not damage the environment it tours. Designed for manufacturability and aesthetic packaging, the Bucky Classic 750 is a cost-effective solution for performance-oriented riders seeking a cleaner, quieter snowmobile.

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