Integration of Hybrid-Electric Strategy to Enhance Clean Snowmobile Performance

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ABSTRACT

The University of Wisconsin-Madison Snowmobile Team has designed and constructed a hybrid-electric snowmobile for entry in the 2005 Society of Automotive Engineers' Clean Snowmobile Challenge. Built on a 2003 cross-country touring chassis, this machine features a 784 cc fuel-injected four-stroke engine in parallel with a 48 V electric golf cart motor. The 12 kg electric motor increases powertrain torque up to 25% during acceleration and recharges the snowmobile's battery pack during steady-state operation. Air pollution from the gasoline engine is reduced to levels far below current best available technology in the snowmobile industry. The four-stroke engine's closed-loop EFI system maintains stoichiometric combustion while dual three-way catalysts reduce NO_x, HC and CO emissions by up to 94% from stock. In addition to the use of three way catalysts, the fuel injection strategy has been modified to further reduce engine emissions from the levels measured in the CSC 2004 competition. The entire hybrid drivetrain including battery pack and a two-stage muffler is packaged in a manner that maintains the snowmobile's aggressive OEM appearance.

INTRODUCTION

In 2003 alone, the sport of snowmobiling contributed over $7 billion to the United States economy. 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.

Just how important snowmobiling can be to a local economy is evidenced by recent 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 [2]. The ruling by Judge Emmet Sullivan, though recently 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 current snowmobile BAT does not do enough to prevent air pollution [3].

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

	Auto	RV	Coach	Snowmobile	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 2005 CSC will be held in Michigan's Keweenaw Peninsula from March 14-19th.

The following paper discusses how the University of Wisconsin – Madison team has engineered an entry for the 2005 CSC that fundamentally challenges conventional snowmobile powertrain design. The first section addresses performance characteristics, considerations and results achieved through the use of a parallel hybrid electric design. It also describes how the hybrid drive system components interact to achieve the performance that riders demand. The second section focuses on emissions and describes how multiple technologies employed on the sled reduce harmful exhaust pollutants. 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 2005 UW-Madison clean snowmobile design are simplicity and practicality: the design objective is to win the Clean Snowmobile Challenge with a sled that students and young adults would be willing to buy as an attractive alternative to current performance models.

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 2003, 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.

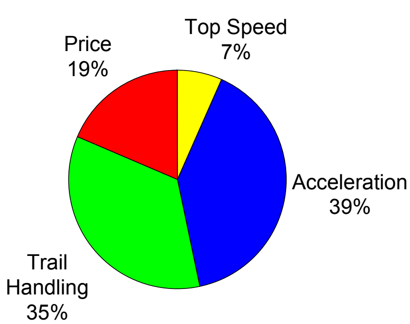

Figure 1: A survey of 75 student riders shows that acceleration and trail handling are the most important considerations when purchasing a snowmobile.

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
- Direct injection (DI) two-stroke marine engines
- Four-stroke 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, 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 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 configures achieves without compromising emissions.

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 (75+ kW) compared to the Arctic Cat 660 and Polaris Liberty four-strokes (40+ 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, the Idaho snowmobile, which utilized a four-stroke engine and catalyst system, achieved the lowest overall emissions. However, the Polaris Liberty emissions are comparable to the Idaho sled, even though the Polaris sled does not have a catalyst system.

Table 2: A comparison of emissions data from the 2002 and 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

To achieve the low CO and HC levels of the Idaho and Polaris four-strokes, the high-compression motorcycle engines 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-strokes are designed to run slightly rich of stoichiometric in order to control exhaust temperatures and maximize power output at high speeds. Forcing the engine to operate at the stoichiometric air to 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 motors excellent torque at the cost of higher emissions [10].

Given CSC core objectives, the UW-Madison team could not afford to sacrifice emissions for the added power of a high-compression motorcycle engine. Therefore, the team selected the 784 cc Polaris Liberty four-cycle engine for this year's snowmobile. While this engine does not have the power to propel the snowmobile to speeds above 97 km/hr, it achieves acceptable acceleration due to excellent torque output, which our survey confirmed to be most important to users.

ENHANCING THE POWERTRAIN - In order to increase the snowmobile's powertrain output and improve acceleration, the 2005 UW-Madison Snowmobile is employing a hybrid powertrain similar to recent automotive architectures. Five major automotive companies now market hybrid-electric cars and sport utility vehicles, achieving over-the-road fuel economy ratings in excess of 40 miles per gallon. These vehicles utilize an electric motor to *assist* the internal combustion engine during acceleration, allowing a smaller, more efficient engine to be used. The vehicle can therefore reduce fuel consumption and emissions while retaining acceptable acceleration. Hybrid electric vehicles can also take advantage of the kinetic energy normally wasted as heat when braking. This energy is converted into electricity by using the electric motor as a generator in a process called *Regenerative Braking*. Hybrid electric technology offers a cleaner, more environmentally friendly powertrain than conventional designs.

Recognizing the similarity between automotive industry's demands for clean, fuel-efficient vehicles and the objectives of the CSC, implementation of a hybrid-electric system on a snowmobile was a logical option to investigate. With the selection of an electric motor typically used in golf carts, a motor controller used in electric fork lifts, high specific-power batteries from Johnson Controls, and control hardware from marine racing applications, the University of Wisconsin's hybrid-electric snowmobile was born. Crediting the school mascot and its hybrid drive (HD) powertrain, the 2005 UW-Madison CSC entry is nicknamed the "Bucky 800 HD."

HYBRID-DRIVE PLATFORM - The Bucky 800 HD powertrain has a parallel electric motor-assist hybrid design. This means that both the IC engine and the electric motor have the ability to drive the track. The design configuration is shown in figure 2. The IC engine transmits power to the chaincase through primary and secondary clutches, just as in a conventional snowmobile. The electric motor is mounted to the chaincase. Internally, the chain is driven by two sprockets, one spun by the jackshaft coupled to the secondary clutch, and the other directly driven by the electric motor. The chain drives a third sprocket, which is coupled to the track drive shaft. Since both the engine and motor are coupled to the drive shaft, the Bucky 800 HD parallel design offers the flexibility of powering the snowmobile using engine power only, electric power only, or a combination of the two sources.

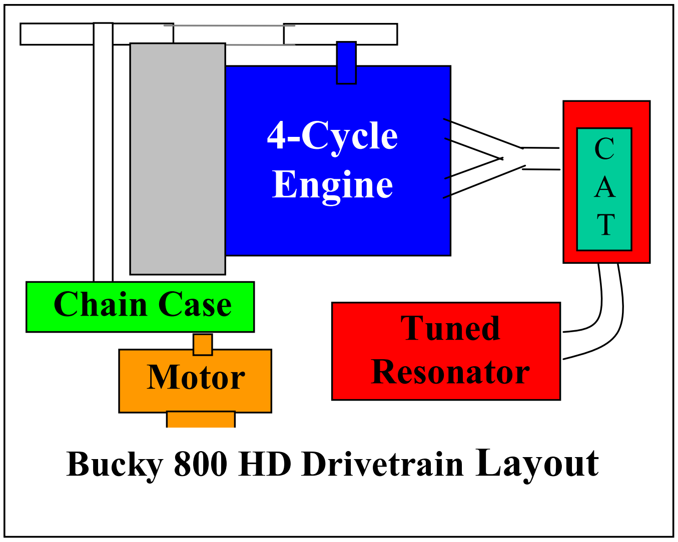

Figure 2: A schematic layout of the Bucky 800 HD parallel hybrid-electric drivetrain. The electric motor is coupled into the chaincase.

Another hybrid design that was considered is the series hybrid configuration, as is currently employed on some off-road military vehicles. In a series hybrid layout, the IC engine is directly coupled to an electric generator that charges a battery pack, capacitor bank, etc. An electric motor is then directly coupled to the wheels, with no mechanical connection between the engine and drive. This design was rejected, as the inefficiency of converting mechanical power to electrical power and then immediately back to mechanical power makes it unsuitable for vehicles that are used in mainly steady-state operation. The lower efficiency decreases fuel economy and necessitates a larger engine to achieve the same top speed. Additionally, series systems are often heavier due to the added weight of the generator.

HYBRID-DRIVE SPECIFICS - The drivetrain component that makes the parallel hybrid possible is the student designed and built chaincase. Modeled after the Polaris XC 800 chaincase, incoming torque from the secondary clutch jackshaft is transmitted through a standard Polaris 18 tooth, 19.05 mm wide silent chain drive sprocket. The output sprocket delivering power to the track is a 40 tooth standard Polaris sprocket. A custom 25-tooth sprocket was machined to integrate the electric motor into the snowmobile drivetrain. This gear ratio was selected to allow motor assist up to track speeds of 69 km/hr and allows for operation of the snowmobile up to 135 km/hr before the burst speed of the motor armature is reached. This is well above the top speed of the snowmobile, limited not only by lack of engine power, but also by the peak clutch ratio and peak engine rpm to 120 km/hr. Thus, we are able to achieve up to 25 percent more torque at the track up to 72 km/hr, making the clean burning four-stroke engine feel like a higher powered two-stroke in this speed range (figure 3).

In choosing the location to couple the electric motor to the track, three different options were considered. The electric motor could be coupled directly to the secondary jackshaft, directly coupled to the output shaft of the chaincase, or coupled to a custom gear in the chaincase. The third option was selected to allow for a choice of electric motor gear ratios, thereby optimizing the range over which the electric motor provides additional torque. Figure 3 shows the torque increases for the three electric motor placement options considered.

Figure 3 was obtained by connecting current and voltage sensors to the inputs of the electric motor. The snowmobile was then run at various speeds in the range of interest, and the motor current, voltage, and track speed were data logged. From this, the motor torque curve was found using the torque constant for this motor which will be discussed in a subsequent part of this paper.

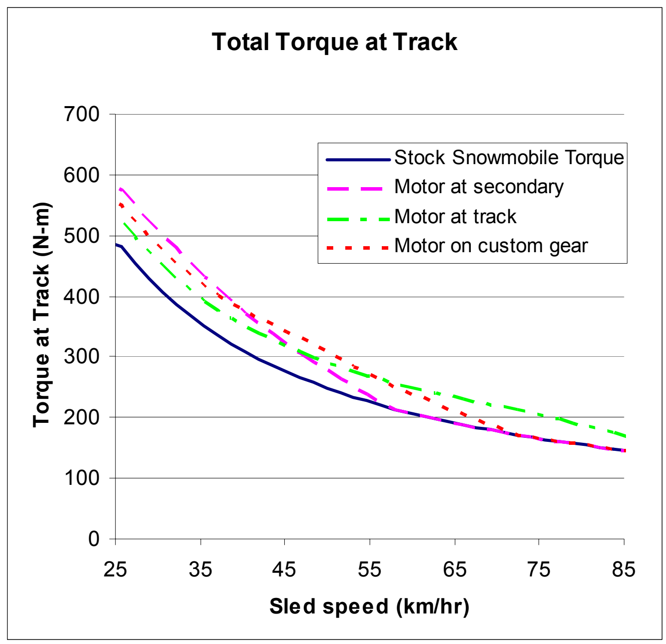

Figure 3: Measured total torque at driveshaft for a hybrid powertrain with the electric motor coupled into the chain box at three considered locations.

The chaincase in the Bucky 800 HD has been designed using standard silent chain "best design practices" regarding angle of chain wrap. Because a third gear is required to integrate the electric motor, the angle of wrap on the top sprocket is reduced. The placement of the third sprocket in the chaincase was carefully chosen to provide adequate chain wrap of 120 degrees on the top sprocket while still allowing the electric motor to fit inside the belly pan of the snowmobile. The chain tensioning system is adapted from the stock Polaris tensioning system and the chain is adjusted to the same tension. Also, the oiling system was adapted from a stock Polaris chaincase. As the hybrid chaincase adapts proven technology using standard design guidelines, it is anticipated to meet or exceed the life expectancy of an OEM chaincase.

Stock brake caliper mounting location, hole size, and thread depth were maintained in order to ensure adequate braking performance and safety. The brake rotor was cross drilled to reduce weight and drivetrain inertia. The surface area in contact with the brake pads was reduced less than 15 percent, in accordance with CSC brake modification rules.

All machining work on the custom chaincase was done in house by students on a Haas VF2 CNC machining center. 6061 T6 aluminum billet was used for both chaincase halves to ensure strength.

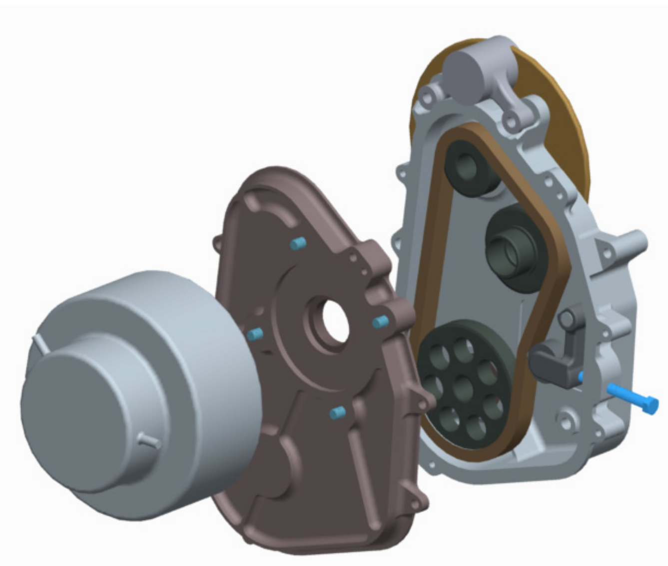

Figure 4: Exploded model of Wisconsin's student designed and built hybrid chaincase, showing the electric motor location.

ELECTRIC MOTOR - The electric motor integrated into the hybrid powertrain is an Etek DC brushed motor, manufactured by Briggs and Stratton. This motor is primarily used in golf carts and small industrial transport vehicles. As a relatively flat "pancake" style, axial flux motor, it can be mounted directly to the chaincase without extending beyond the snowmobile lower cowling. Also, the axial flux motor design provides exceptional torque, a high power-to-weight ratio, and higher efficiency than standard radial flux machines [11]. Figure 5 shows several characteristics of the motor.

The power required to spin the motor at a constant speed was measured to ensure that parasitic drag losses caused by adding the motor would not compromise sled performance during steady-state operation when hybrid assist is not utilized. At a top speed of 97 km/hr, the Etek motor introduces only 0.078 kW of drag losses. As it takes approximately 34 kW of power to propel the sled at this speed, the drag losses of the motor are insignificant.

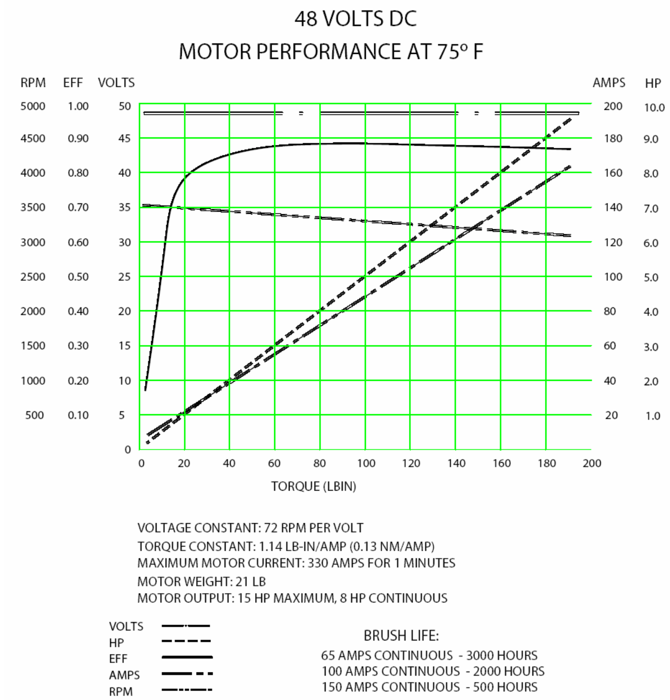

Figure 5: Torque, power, and efficiency curves for the Briggs and Stratton Etek electric motor over a range of operating conditions [11].

With a peak output of 9.0 kW and 42.9 N-m, the Etek electric motor adds significant power and torque to the Bucky 800 HD. Torque at the track is increased by up to 25 percent at higher speeds where the engine gear ratio is reduced through the CVT.

Operating at the motor's peak current of 330 A, brush life expectancy is roughly 60 hours of operation. This peak current is only achieved at wide-open throttle, and would only be seen for approximately 8 seconds at a time, depending on riding conditions. With peak current to the motor only seen for such a short time, the brushes will last for over 25,000 accelerations.

Due to the thermal limitations of the Etek electric motor, peak current of 330 amps can only be supplied for a maximum of one minute before damage to the motor will occur. To protect the motor from damage, the hybrid controller monitors the current to the electric motor and de-rates commanded torque to prevent the motor from overheating.

In addition to assisting and regenerative braking, the Etek motor can also be used as a generator to recharge the battery pack, a necessary characteristic for a parallel hybrid which you "never have to plug in." This occurs at steady state vehicle speed conditions at less than wide open throttle. However, because the motor is slowly charging the high voltage system, the power requirements are similar to that of the vehicle's alternator.

ELECTRIC MOTOR CONTROLLER - Torque commands are sent to the Etek motor through a Sevcon MillipaK motor controller designed for industrial forklift applications. The MillipaK controller is a well-suited choice for the hybrid snowmobile application, given its voltage and current rating, compact size and rugged construction. In a 48 V system with adequate cooling, the controller can accommodate up to one minute of operation at a 330 Ampere motor current, matching the motor's one-minute current rating.

The MillipaK controller measures 190 mm x 145 mm x 59 mm, which allows it to fit just above the snowmobile's right foot well. This location puts the controller in close proximity to the chaincase and motor, saving weight, cost, and resistive losses (figure 6). The controller is rated to operate while subjected to continuous 6G vibration from 40 Hz to 200 Hz and thus can be mounted directly to the chassis. [12].

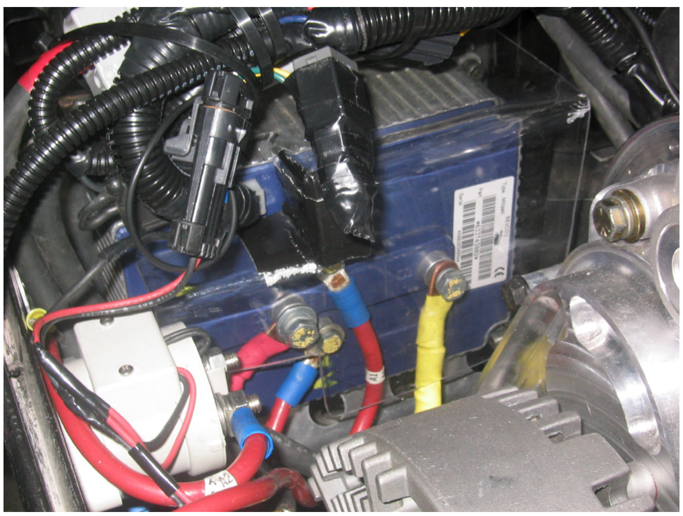

Figure 6: The MillipaK controller is mounted above the right foot well, just behind the motor and chaincase. A protective Lexan cover prevents the user from accidentally shorting battery pack terminals.

The MillipaK is a four quadrant controller, which means it is capable of providing assist and regenerative braking in both the forward and reverse directions. This allows the flexibility to perform both hybrid assist and regenerative braking.

ENERGY STORAGE - The choice of motor and controller mandates a 48 V battery pack to store electrical energy. This battery pack must be capable of delivering and accepting high current for short times while adding minimum cost and weight to the sled. A motor-assist parallel application also necessitates batteries with a high cycle life, as the batteries are cycled many times during a day of riding.

The Inspira batteries produced by Johnson Controls Incorporated satisfy these constraints. Inspira batteries use a unique patented spiral wound lead acid design that offers significantly larger plate area than traditional "flat plate" cells. Six of these spiral wound cells are assembled into a 12 V battery module that can deliver currents in excess of 2000 amps. Figure 7 shows the internal construction of an Inspira lead acid battery.

Spiral wound batteries offer many advantages over traditional lead acid batteries. They have very high power density, up to three times that of conventional lead acid batteries. Inspira batteries are sealed and maintenance free with the electrolyte contained in an Absorbent Glass Mat (AGM). The packaging of the battery is quite rugged, meeting SAE off-road vibration requirements. Installation of the Inspira battery modules is extremely simple, utilizing integral RADSOK style connections and snap-lock battery trays. In addition, these batteries allow for ease of shipment, without being subject to restrictive regulations by the US DOT or the International Air Transport Association (IATA) [13].

Currently, Inspira technology is available in 2.1 A-hr, 3.9 A-hr, and 6.3 A-hr modules. For the hybrid snowmobile application, the 6.3 A-hr package was the best choice. This battery is capable of providing 330 A for approximately 30 seconds, sufficient time to reach steady-state cruising speeds from a dead stop (figure 8). The Inspira batteries are ideally suited to high-cycle power assist applications, and are currently being considered for use in similar automotive applications.

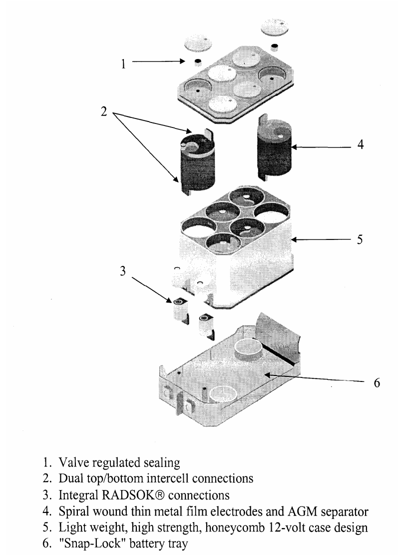

Figure 7: Internal construction of the Inspira spiral-wound lead acid battery produced by Johnson Controls Incorporated [13].

The battery pack is composed of four 6.3 A-hr Inspira 12 V modules in series and weighs just 14.2 kg. Typical parallel plate lead acid batteries can be discharged at a 10-15 C rate (the “C rate” is the nominal current at which a battery would be fully discharged in one hour), whereas the spiral wound lead acid batteries are capable of discharge rates well in excess of 50 C. A battery pack with the same capabilities built from standard lead acid batteries would weigh roughly 50 kg and require 250% more volume.

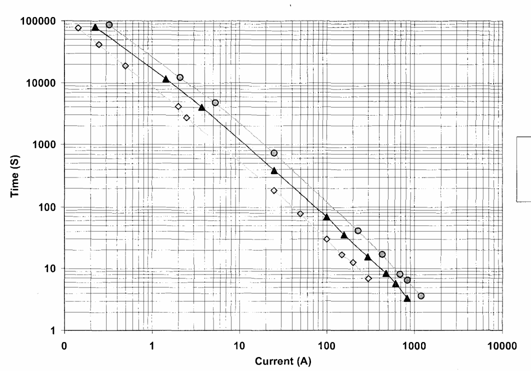

Table III – Constant Current Discharge Ratings

At 77° F (25 °C)

Duration ⇒	5 sec	10 sec	15 sec	30 sec	60 sec	1 hr	3 hr	20 hr
End Voltage ⇒	6.25 V	7.25 V	8.0 V	9.0 V	10.0 V	10.5 V	10.5 V	10.5 V
2.1-Ah	414	248	167	98	64	2.3	0.86	0.15
3.9-Ah	698	396	302	184	113	4.2	1.54	0.25
6.3-Ah	873	538	480	310	155	6.9	2.4	0.39

Figure 8: Peukert Plots for the Inspira batteries show the current that would fully discharge the battery in the specified time intervals [13].

BATTERY MANAGEMENT - In order to maximize battery life, a battery management strategy was implemented. The hybrid control computer monitors battery voltage and current draw of the batteries. By monitoring these values, the state of charge of the batteries can be calculated using discharge tables found in figure 9. The control computer derates or disables the assist torque command to the electric motor before the batteries are discharged to the point of damage.

A similar technique is used for controlling charging to avoid overcharging the batteries. The control computer monitors the current and battery voltage, appropriately derating or disabling the regenerative charging torque command. This ensures that the batteries are never over charged, under charged, or charged at too high a rate. By doing so, the hybrid control computer can maintain a specified state of charge that will maximize battery life.

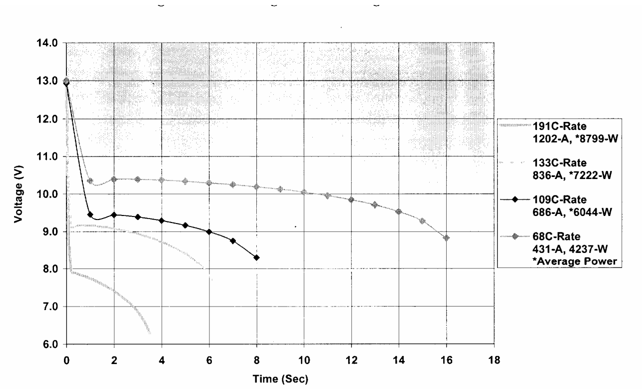

Figure 9: Discharge curves for JCI Inspira 6.3 A-hr cells. These curves were used to model the effect of discharge on terminal voltage so the hybrid control computer can accurately monitor battery state of charge and maximize battery life [13].

HYBRID DRIVE CONTROL STRATEGY - The Bucky 800 hybrid drivetrain delivers the acceleration results demanded by riders. Using a Siemens/VDO Powertrain Control Module (PCM) and control software developed by the team, the control strategy delivers electric motor torque based on throttle position, brake position, vehicle speed, and battery state of charge. For example, if the sled is traveling at 10 km/hr, the rider goes to wide open throttle (WOT), and the battery pack is at an adequate state of charge (SOC), the electric motor will deliver full assist until either: a) the rider releases the throttle; b) battery pack voltage falls to minimum allowed state of charge; c) snowmobile speeds exceeds the maximum motor assist speed (69 km/hr); or d) motor or controller thermal considerations force a reduction in torque.

Once steady state speed is reached, motor torque drops to zero. If battery state of charge is low, the controller introduces a slight regenerative braking command in order to recharge the batteries, increasing steady-state engine power demands by up to 1.7 kW. This increase in drag is barely perceptible, especially since it is ramped out whenever the rider attempts to accelerate, or if vehicle speed exceeds 75 km/hr (this avoids any reduction in top speed).

Proof of the improvement in acceleration is shown in the speed versus time curves in figure 10. The acceleration data for this chart was collected on Feb 26th, 2005 on a two-kilometer private road in Barneveld, Wisconsin. Snow conditions on this day were light powder and winds were light and variable. Data was collected using a Hall Effect type speed pickup in the chaincase with data logging software to record the track speed over time.

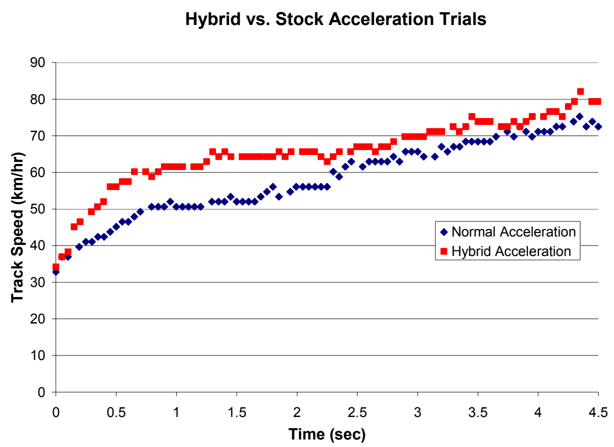

Figure 10: Acceleration comparison between the Bucky 800 HD and a stock Polaris Frontier. The 800 HD can accelerate from 30 to 65 km/hr in 1.5 seconds less than the stock configuration.

In addition to improving acceleration, a hybrid powertrain benefits fuel economy. The control strategy charges the batteries at medium-load engine conditions when the engine's efficiency is greater than it would be at WOT. This stored energy is then used to assist when the IC engine is at WOT, a low efficiency operating condition. While this fuel economy gain cannot be seen in steady-state testing, and an accurate measurement is difficult over the course of a trail ride, future development of a test cycle simulating a trail ride using a chassis dynamometer will allow for further tuning of the entire hybrid powertrain. A similar process is used by the EPA to accurately quantify the fuel economy and emissions of on-road vehicles.

While increasing fuel economy, the Bucky 800 HD's parallel gas/electric drive is poised to address one of the most significant environmental concerns in the sport of snowmobiling today: trail head emissions. The daily build up of exhaust gases from hundreds of machines starting up and warming up creates a hovering cloud of smog at the entrances to Yellowstone National Park. This smog has been cited by countless environmental groups as grounds for banning snowmobiles from the park. A 2001 study by the California EPA also shows that daily exposure to these harmful exhaust gases increases cancer risks to park employees by a factor of five [15]. In order to address these concerns, the 2004 version of the Bucky 800 HD was programmed with an electric-only mode. However, through testing of this electric-only mode, it was found that the electric motor did not have sufficient torque to propel the vehicle under non-ideal conditions. As variable excitation electric motors become available for this type of application and battery technology improves, this electric-only mode will become increasingly more feasible.

EMISSIONS

Knowing that the untreated emissions of the selected engine produces significantly higher CO, HC, and NO_x emissions than the 2002, 2003, and 2004 CSC winners, the Wisconsin team's first step in reducing emissions was the addition of catalytic after-treatment. Because the CSC emissions event score is based on a combination of HC, CO and NO_x, 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 11, the catalyst reduction efficiency for NO_x at "stoich" is just under 80% while HC and CO are reduced at near 90% efficiency. When a lean exhaust mixture goes 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 Liberty engine effectively achieves this oscillation between lean and rich operation, as there is inherent overshoot and correction when targeting stoichiometric engine operation.

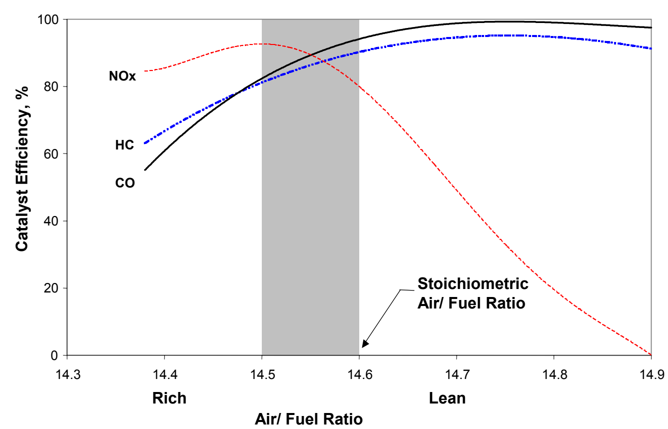

Figure 11: The NO_x, CO, and HC conversion efficiency for a three-way catalytic converter as a function of exhaust gas air/fuel ratio. (Adapted from [16])

Emissions testing during the 2004 CSC showed two problems with the fuel injection of the stock Liberty four stroke engine [20]. First, the emissions at WOT accounted for 91% of the total CO emissions, 69% of the total HC emissions, and 37% of the NO_x emissions. Second, the total emissions were not as low as desirable.

Through use of a CO gas analyzer, the team discovered that the fuel injection becomes open loop above 50%

throttle, operating up to five percent rich to obtain peak engine power. To fix this problem, the team applied an alternative fuel injection strategy to maintain closed loop control over the entire throttle range. This strategy reduced the emissions of the sled, but also slightly reduced peak power output of the engine.

Table 3: 2005 Engine operation modes when performing the five mode emissions test used for the CSC [18].

	Engine Speed (rpm)	Torque (N-m)	Power (kW)
Mode 1 (WOT)	5600	46.43175	27.229
Mode 2 (85%)	4760	22.44887	11.19
Mode 3 (75%)	4200	15.26523	6.714
Mode 4 (65%)	3600	9.102602	3.4316
Mode 5 (idle)	1100	1.041741	0.12

As a second method of emissions reduction, the Wisconsin team experimented with the addition of a second catalyst to the exhaust system to further reduce the tailpipe emissions. To ascertain whether this addition was justified, the team performed emissions testing in house in accordance with CSC testing procedures. A Dynamite engine dynamometer was attached to the engine to monitor engine torque, speed, and power. A Fourier Transform Infrared (FTIR) gas analyzer was used to measure the CO, HC, and NO_x concentrations in the engine exhaust. The engine was run at the modes listed in Table 3, and exhaust emissions were measured upstream of the catalysts, in between the two catalysts, and after both catalysts. The dual stage catalyst system was found to reduce engine pollutants up to 95%, justifying the use of the second catalyst.

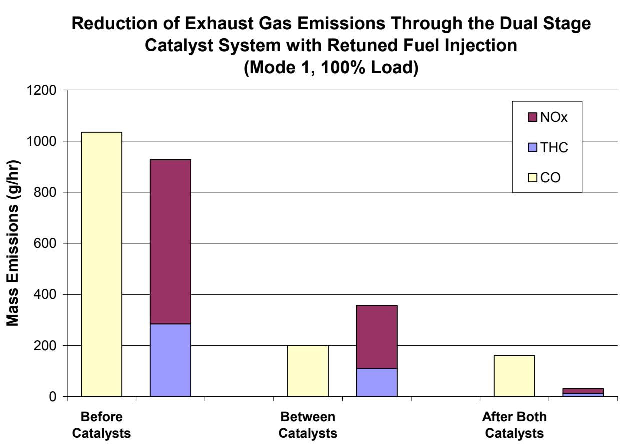

Figure 12: Up to 95% reduction of engine pollutants was achieved through the use of a dual stage catalyst system, justifying the addition of the second catalyst.

Because the fuel injection strategy for 2005 was changed from the 2004 design, a test was performed to determine the reduction in emissions from the air injection pump. This pump had been installed for the 2004 competition to reduce emissions at high load and idle, and also during cold start. Emissions tests were run at each of the five specified modes in Table 3, and the results can be seen in figure 13. As shown, with the refined fuel injection strategy used in the 2005 Bucky 800 HD, the air pump is not necessary to reduce emissions. In fact, the pump hinders the emissions reduction as it lowers the temperature of the exhaust gas below the activation temperature of the catalyst. Therefore, the air injection pump was removed from this year's snowmobile, saving both weight and cost.

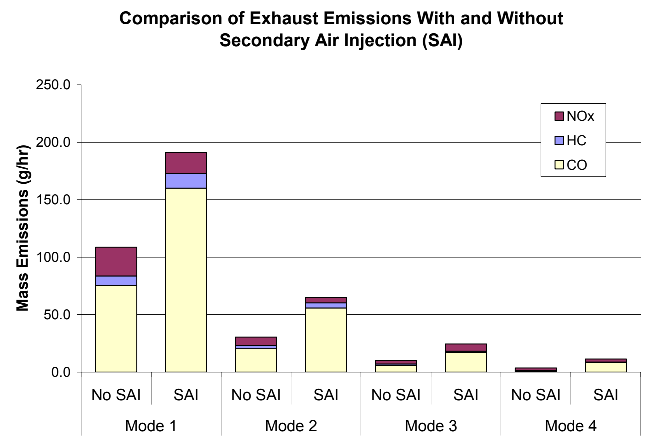

Figure 13: The Secondary Air Injection (SAI) system used in 2004 was eliminated through fuel injection changes for 2005.

Figure 14 shows the final results of the emissions testing on the Bucky 800 HD after optimization of the emissions reduction systems. Total pollutant levels have been reduced 90% from last year's entry, which scored third overall in the 2004 CSC emissions event [20].

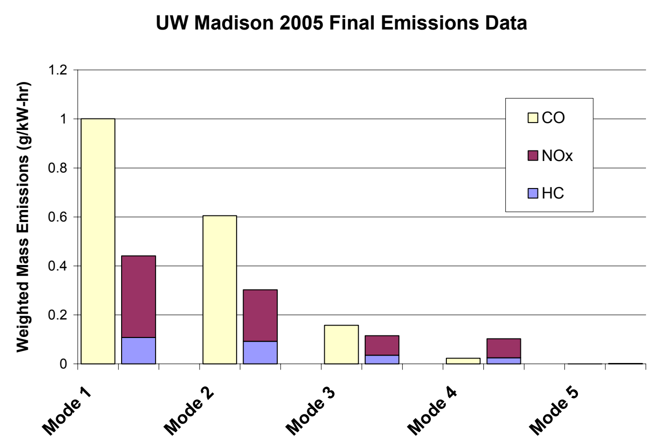

Figure 14: After optimization of the emissions systems on the Bucky 800 HD, the total pollutants were reduced 90% from last year's snowmobile.

EVAPORATIVE EMISSIONS - The Bucky 800 HD features a charcoal evaporative emissions canister 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.

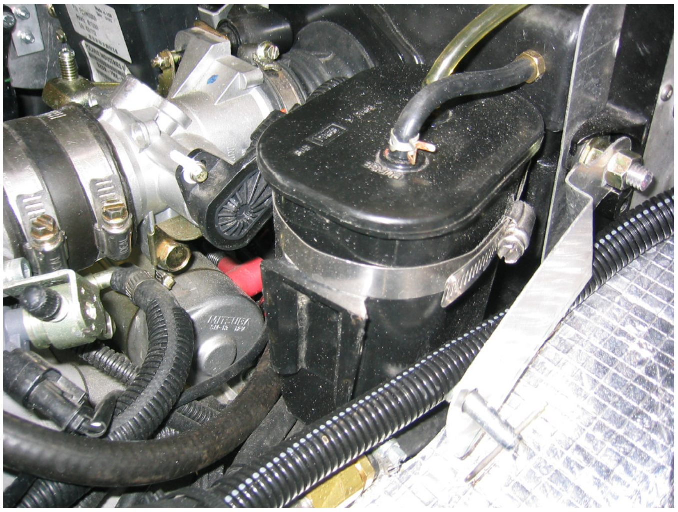

Figure 15: The evaporative emissions system on the Bucky 800 HD reduces hydrocarbon emissions due to thermal cycling of vapors in the fuel tank.

NOISE

Wisconsin's first and foremost goal for sound reduction on Bucky 800 HD was to reduce A-weighted sound pass-by-levels below those of the 2005 CSC control sled, a Ski-doo GSX Sport 600 H.O. SDI [18]. In addition, the team seeks to reduce the sound levels to increase operator comfort while riding the Bucky 800 HD. Table 4 shows the A-weighted pass by levels for the stock Polaris Frontier platform that the Bucky 800 HD is based on. Additionally, the 2004 CSC control sled and the average for two-stroke machines is shown on this table.

Table 4: 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 [19].

	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 Liberty four-stroke's exhaust system offered the most potential for noise reduction. Since Wisconsin's emission strategy required the addition of a catalyst and the electric motor 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 area directly 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.

In order to maximize muffler volume, 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 holes in the metallic core effectively reduce the ultra-high frequency components of the engine's exhaust noise.

Figure 16 shows the first of the two mufflers. 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.

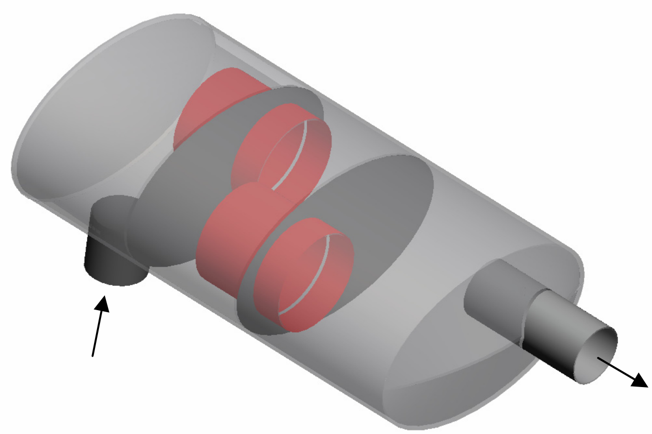

Figure 16: The first stage of the muffler system consists of the dual stage catalyst assembly.

After passing through the first muffler, the exhaust flow enters a broadband resonator designed to remove the majority of mid to high frequency noise (figure 17). After entering the muffler, 15 percent of the exhaust flow is bled out of twenty evenly spaced 3.175 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.

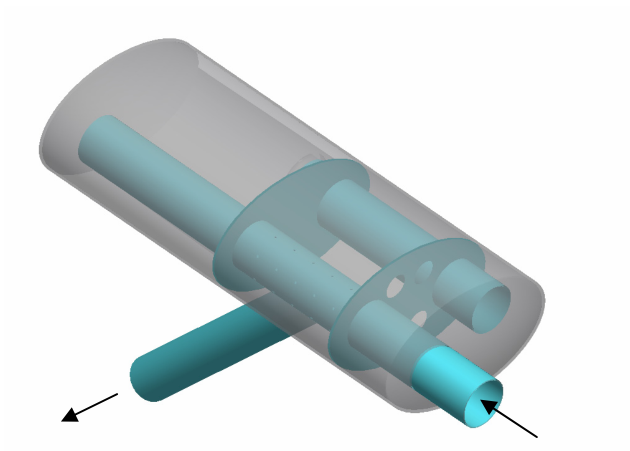

Figure 17: The second stage of the muffler system is a broadband muffler that reduces mid to high frequency sound while allowing higher flow than stock.

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 - 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.

Pass by sound tests were performed consistent with the SAE standard J2104 hemispherical sound power test used for the 2003, 2004, and 2005 CSC competitions [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 gates at the start and finish of the test section 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 at 72 km/hr between the microphones which were spaced 14 meters apart. This is the same spacing used in the 10 meter hemisphere test. The data was recorded using a Hi-Techniques HT-600 data acquisition system.

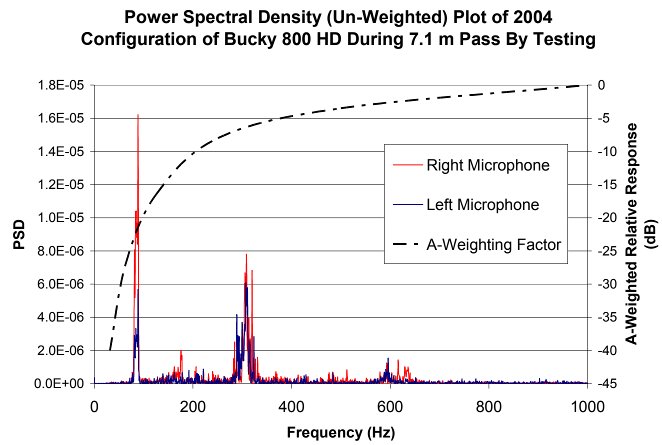

Figure 18: Three distinct sound power peaks can be seen corresponding to engine noise at 100 Hz and track noise at both 300 and 600 Hz. Testing was performed Feb 25th, 2005.

Figure 18 shows a Power Spectral Density FFT plot of the 2004 configuration of the Bucky 800 HD. This plot shows the sound power emitted from the sled as a function of frequency. Three distinct peaks can be seen near 100, 300, and 600 Hertz. By calculating the first and second order contributions of the snowmobile components at 72 km/hr (Table 5), the sources of the peaks were discovered. The 100 Hz peak is first order engine noise, while 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 peak is much higher than the left side because the exhaust outlet is on the right side of the snowmobile.

Table 5: First and second order frequencies of sound emitted by three components of interest on the Bucky 800 HD.

	1st Order Frequency (Hz)	2nd Order Frequency (Hz)
Engine	**95**	190
Track-Paddle Interface	**303**	**606**
Chain Case	1345	2690

The relative magnitudes and 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 prescribed earlier with large 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 sled.

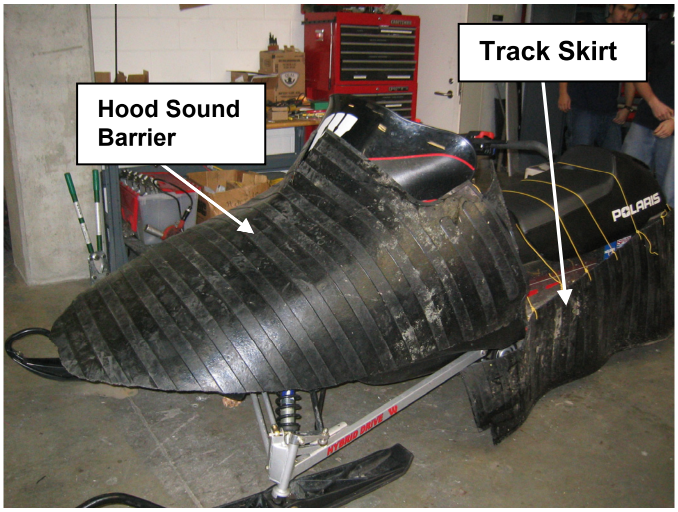

Figure 19: Rubber mats were used to isolate sound emissions from targeted components. In this way, the relative contribution of each component to the overall A-weighted sound level could be found.

From the testing performed isolating specific snowmobile components, the Wisconsin team was able to discover the relative contributions of the track and engine to sound emissions of the snowmobile. During analysis of the data, it because evident that the engine note at 100 Hz because relatively insignificant compared to the track noise at 300 and 600 Hz once the A-weighting correction was applied. Figure 20 shows the percent reduction in sound achieved through use of the engine hood cover and track skirt.

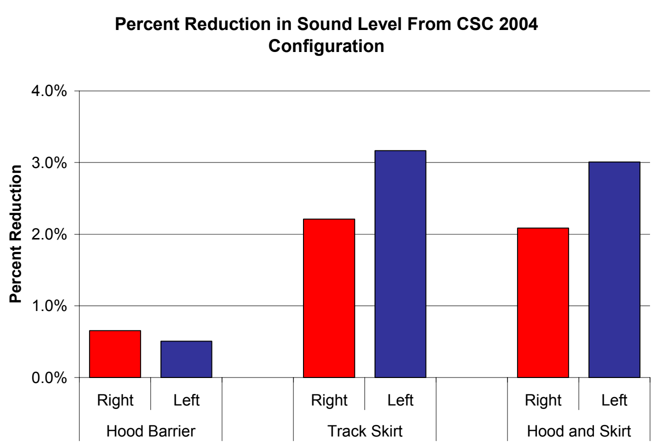

Figure 20: Graphs of pass-by sound testing results. The largest sound reduction was achieved by utilizing a track skirt.

Based upon the results of Wisconsin's pass by testing in 2005, the Bucky 800 HD is now equipped with a full track skirt which reduces sound level to 107.5 dBA sound power. This is comparable to the sound emission levels achieved by other teams at the 2004 CSC [20], and is a 2.5 dBA sound power reduction from the 2004 Bucky 800 HD.

OTHER SNOWMOBILE INFORMATION

The base chassis for the Bucky 800 HD is a 2003 Polaris EDGE sold with the Liberty 784 cc engine under the name Frontier Classic. Selected for its lightweight 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.

ELECTRONIC THROTTLE CONTROL - A major design feature of this years snowmobile is the incorporation of an electronic "drive by wire" throttle. A throttle position sensor sends a signal to the onboard computer, which in turn operates a servo to control the engine's throttle body position. This system gives the Bucky 800 HD three unique features. First, cruise control is achieved at the push of a button, lowering rider fatigue. Second, traction control during launch is programmed into the electronic throttle control. Engine throttle position is ramped in slowly during take off from a stop to achieve maximum acceleration. Thirdly, the incorporation of GPS into the Bucky 800 HD allows the potential for the creation of speed limiting zones where the snowmobile is limited in top speed through reduction of the engine throttle position. These zones could be created in national parks or in urban settings where speed, traffic, and noise are problems.

POLYCARBONATE HOOD - The Bucky 800 HD employs a lightweight polycarbonate hood shell. The un-vented shell lowers noise transmission. Polydamp Melamine foam lines both the clutch cover and the underside of the snowmobile hood. The polymer absorbs most efficiently at frequencies between 100-350 Hz, making it a good fit for engine and clutch mechanical noise at snowmobile speeds above 75 km/hr. Additionally, the Melamine foam is heat rated for temperatures up to 400°C, making it safe for use in the engine bay. The poly carbonate hood reduces noise levels from the engine, reduces vehicle weight, and increases durability when compared to the stock hood.

SUSPENSION IMPROVEMENTS - The Bucky 800 HD front suspension features shimmed Ryde FX 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 support aggressive trail riding desired by customers (figure 1).

The rear suspension is a modified M-10, featured on multiple Polaris models. In efforts to decrease rolling resistance and improve fuel economy, an additional set of idler wheels was added along the slide rails.

STARTER BATTERY - A single JCI Inspira battery (described in detail in the energy storage section) supplies power to the snowmobile's 12 V system. This system, independent of the hybrid energy storage system, provides power for electric start, engine controls, headlamps and dashboard information displays. The Inspira battery, while mounted in the stock location, is 6 kg lighter than the stock Polaris battery.

TOTAL SNOWMOBILE WEIGHT - The stock Polaris Frontier Classic weighs 298 kg without fuel. The Bucky 800 HD with complete hybrid system has a mass of 286 kg without fuel. Despite adding 12 kg for the electric motor and controller along with 15 kg for the battery pack, Wisconsin's overall weight is 12 kg lighter.

Many individual components contributed to the weight reduction. Most notably, the use of lightweight materials in the new muffler significantly cut overall mass. However, small changes such as the 6 kg savings from the JCI battery substitution, a 2 kg savings through use of a lightweight composite hood and switching to a 3.175 cm lugged track add up to significant weight savings. Through efficient design and professional packaging, the UW-Madison team effectively decreased the snowmobile weight, while adding technology to make the sled cleaner and faster.

COST ESTIMATES

Every component of the Bucky 800 HD is designed for manufacturability. Many technologies such as the electric motor are already in production in other transportation applications. This allows for cost effective implementation into the snowmobile. The values listed in the cost summary of Table 6 are based on the assumption that parts are manufactured in production quantities of at least 5,000, or 60% of prototype cost per 2005 CSC rules. Review of Table 6 clearly shows that a hybrid-electric drive-train is a cost effective way to improve performance of clean snowmobiles without increasing engine power output.

Table 6: Projected Cost of the Bucky 800 HD

Item	UW-Madison Bucky 800 HD	2003 Polaris Frontier Classic
Base sled cost with 784 cc Liberty Four-Stroke	$5,899	$5,899
Sled Modifications	$60	None
Electric Motor and Controller	$283	None
Hybrid Battery and wiring	$151	None
Catalyst	$40	None
Total:	**$6,433**	**$5,899**

CONCLUSION

The 2005 University of Wisconsin – Madison Clean Snowmobile Challenge entry redefines performance and emissions standards for over-snow recreational vehicles. Understanding consumer performance requirements for an environmentally friendly snowmobile, the team engineered an innovative hybrid-electric powertrain that improves acceleration nearly 30%. A custom exhaust with dual three-way catalysts reduces air pollutants to levels well ahead of current EPA requirements. A redesigned powertrain and a multi-chambered muffler ensures that Wisconsin's sled does not disrupt the environment it tours. Designed for manufacturability and aesthetic packaging, the Bucky 800 HD is a cost effective alternative for performance-orientated riders seeking a cleaner, quieter sled than any marketed to date.

ACKNOWLEDGMENTS

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The team would also like to thank their advisor, Dr. Glenn R. Bower. Without his machining expertise, commitment of time, enthusiasm and willingness to teach, this project would not have been possible.

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APPENDIX

2004 CSC Competition Results

The 2004 CSC was held at the Keweenaw Research facility near Houghton Michigan on the week of March 16th. Fifteen teams from schools around the United States and Canada competed. This section summarizes the results of last year's competition where the 2004 version of the Bucky 800 HD was entered.

The 2004 Bucky 800 HD completed every event without any failures or problems. The endurance event involved 161 km of riding at a nominal speed of 72 km/hr, 40% on an oval track on KRC grounds and 60% on groomed trails to Copper Harbor. On this event, the 2004 Bucky 800 HD achieved fuel economy of 7.57 km/L, a 17% increase over the control sled, an Arctic Cat 660 four-stroke touring sled.

The team took 4th place in the braking event, stopping in 39.3 meters from a speed of 64.4 km/hr.

The acceleration event in the competition consisted of a timed run from a standing start over a 152.4 m straight-line course. The 2004 Bucky 800 HD had the 5th-best acceleration time in the competition, achieving an acceleration time 8% better than that of the control sled despite having lower measured peak power.

During the emissions portion of the competition, UW Madison finished third place, achieving a 43% reduction in CO, an 82% reduction in HC, and an 83% reduction in NOx emissions compared to the control sled. The overall emissions levels were measured at 57.2 g/kW-hr of CO, 2.02 g/kW-hr of HC, and 3.89 g/kW-hr of NOx.

UW Madison's unique hybrid design fared very well against a field of several well designed snowmobiles. The team finished first place in CSC 2004, and also won the Best Design Award presented by SAE International.