University of Idaho's Flex-Fuel Two-Stroke Snowmobile

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ABSTRACT

The University of Idaho's entry into the 2009 SAE Clean Snowmobile Challenge (CSC) was a semi-direct-injection (SDI) two-stroke powered REV-XP snowmobile modified to use flex fuel. The flex fuel engine produces stock engine power on any blend of ethanol and gasoline from E10 to E85. The emissions output was reduced using an oxidation catalyst located after the exhaust silencer. Noise from the engine compartment was reduced by custom-carbon fiber hood and side panels, which allowed placement of extra sound absorbing materials. Pre-competition testing had the snowmobile entering the 2009 SAE CSC competition producing 108 hp (80.5 kW), weighing 524 lbs (238 kg) wet, achieving 13.3 mpg (5.65 km/L) running on E85 ethanol fuel, and a J-192 sound magnitude score of 80 dBA.

INTRODUCTION

Snowmobiling offers a great opportunity for winter recreation and exploration. Snowmobiles have traditionally been loud, with high levels of toxic exhaust emissions and poor fuel economy. Snowmobiles are often ridden in environmentally sensitive areas such as Yellowstone National Park where the adverse effects of snowmobiles can be substantial. The snowmobile's negative impact and comments by industry and others prompted the snowmobile community and conservationists to partner and challenge college students to design a cleaner, quieter snowmobile. SAE, the Environmental Protection Agency (EPA), National Park Service (NPS), the Department of Energy (DoE), and others supported the effort to begin the CSC in 2000.

The 2009 Clean Snowmobile Challenge continued to encourage snowmobile development by mandating the use of flex fuel, which can be any blend of ethanol and gasoline fuel from 10% ethanol to 85% ethanol. The blend of fuel was unknown to the competitors during the CSC. Therefore, the snowmobiles had to detect and alter calibrations based on the fuel blend with no user input. Ethanol is a renewable fuel that has a lower energy content per volume than gasoline. Blended ethanol fuels hazardous exhaust emissions also differ from those of gasoline, with lower unburned hydrocarbons (UHC) and carbon monoxide (CO) quantities but elevated acetaldehydes and formaldehyde emissions [1]. The corrosive properties of ethanol also require revised design strategies.

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DESIGN GOALS – The first goal for the competition was to reduce exhaust emissions while running on blended ethanol fuel. The primary emphasis is on reducing CO and UHC without increasing the already low emission of oxides of nitrogen (NO_x) of traditional two-stroke snowmobile engines. Scoring was based on both the 2012 EPA snowmobile standards using the weighted five-mode testing procedure as published by SwRI and an in-service emission measurement [2, 3]. The SwRI five-mode test weights emissions of CO and $UHC+NO_x$ at engine speed and load points indicative of snowmobile operation [3]. Table 1 shows the loads, speeds, and weighting factors for the five-mode test.

Table 1: The five modes used for snowmobile testing for the EPA and NPS.

Mode Point	Speed [% of Rated]	Torque [% of Rated]	Weighting [%]
1	100	100	12
2	85	51	27
3	75	33	25
4	65	19	31
5	Idle	0	5

The results of the five-mode test are used in Equation (1) to determine the EPA snowmobile emission number E

[4]. The EPA states that a minimum E score of 100 is required for the corporate average for the 2012 snowmobile emission standards. In addition to the minimum score, the average weighted emissions for ($UHC+NO_x$) and CO cannot exceed 90 g/kW-hr and 275 g/kW-hr respectively. Points were given to teams that achieved the minimum composite score with additional points being awarded for scores greater than 100. Snowmobiles that passed the event received 100 points, with additional points given based on how the engine performed compared to the rest of the competition.

$$E = \left[1 - \frac{(HC + NO_x) - 15}{150}\right] * 100 + \left[1 - \frac{CO}{400}\right] * 100 \qquad (1)$$

While the EPA will require a standard of 100, the NPS has stricter standards for snowmobiles that are allowed into National Parks. Any snowmobile entering the Parks must be considered best available technology (BAT) with a minimum EPA score of 170, with $UHC+NO_x$ and CO emissions not to exceed 15 g/kW-hr and 120 g/kW-hr respectively [5].

The in-service emission event was new for the 2009 CSC. The in-service emission test consisted of emission collection from the snowmobile during trail conditions. A competition organizer drove each snowmobile over approximately 3 miles while an emission measurement trailer collected the HC, CO, CO2, and NOx produced. Teams were scored from 0 to 50 points based on how their total grams of emissions compare to the cleanest and dirtiest competitors [2].

Reducing noise emissions from the snowmobile was also a large priority for the competition. At the competition, there were both an objective and subjective noise test. The objective noise test was based on the SAE J-192 pass-by sound pressure testing procedure [6]. It is a pass/fail test where the snowmobiles cannot produce more than 78 dBA, the standard set by the International Snowmobile Manufacturers Association. If the snowmobile passed the J-192 test, the team received 75 points and was then eligible to receive more points based on how far below the 78 dBA mark they are, along with points from a separate subjective noise test. The subjective test used the recordings of the J-192 test and played them back to a jury of CSC attendees. The team that received the most favorable subjective evaluation was awarded an additional 150 points while the team with the least favorable rating received zero additional points.

Another goal was to improve fuel efficiency beyond that of conventional touring snowmobiles. The target range for the competition endurance event was 100 mi (161 km). Each snowmobile had to complete the endurance event while following a trail judge [2]. If the snowmobile was unable to complete the event or if the trail judge determined the snowmobile could not keep pace, it was disqualified. The fuel consumption was recorded and each team that finished received 100 points. Additional points were awarded based on how fuel-efficient the snowmobile was compared to the rest of the competitors.

To quantify performance and handling characteristics, the snowmobiles also competed in an acceleration event and two handling events. The acceleration event was based on the time it took to travel 500 ft (152 m) from rest. To pass the event, the snowmobiles needed to complete the course in less than 12 seconds. Each snowmobile competed twice, with the lowest time used for scoring. The fastest team received 100 points. The other teams received points based on their relative performance to the fastest and slowest snowmobiles. The first handling test was subjective. Professional riders scored the snowmobiles based on specific handling and drivability criteria [2]. The winner of the subjective handling event received 50 points with the other teams receiving points based on their relative scores. The second handling event was used to evaluate the agility and maneuverability of each snowmobile. A member of the team rode the snowmobile twice through an obstacle course. The fastest team through the course received 75 points, and the other teams received points based on their relative performance.

The snowmobiles were also subjected to a cold start test. The snowmobiles were cold soaked overnight and then had to start within 20 seconds without the use of starting fluids and travel 100 feet within 120 seconds. Each snowmobile that passed the event received 50 points. Snowmobiles were also weighed with a full fuel tank. The lightest snowmobile received 100 points, with other teams receiving points based on a comparison with the lightest and heaviest competitors [2].

Students submitted a technical design paper describing the approach taken and the challenges met during the design and building of the snowmobiles. The teams also gave an oral design presentation and presented a static display. These presentations focused on how the teams' snowmobiles accomplished the goals of the competition while trying to "sell" the product to potential buyers. With these design goals in mind, the 2009 University of Idaho Clean Snowmobile Challenge (UICSC) Team began designing a clean and quiet snowmobile.

UICSC SNOWMOBILE DESIGN

CHASSIS SELECTION – The 2009 UICSC team chose to use a 2008 Ski-Doo MXZ Rev XP Chassis. It is a industry leading lightweight chassis with good handling characteristics and comfortable rider positioning. The chassis also came from the manufacturer with the selected engine.

ENGINE SELECTION – In 2007, the CSC competition was won by a direct injection (DI) two-stroke snowmobile [12]. In 2008, a DI two-stroke running on E85 placed second [13]. The 2007 competition was the first time in recent history that a two-stroke engine beat out "clean" four-stroke engines. In the past, it has been proven that four-stroke engines can be used in snowmobile designs to produce fuel-efficient, clean, and quiet snowmobiles [7, 8, 9, 10, and 11]. However, due to the preferred power-to-weight ratio of two-stroke powered snowmobiles, demand for this type of engine is still high, and new technology is beginning to emerge.

With use of semi-direct fuel injection (SDI), two-stroke powered snowmobiles are now capable of fuel economy similar to, or better than, four-stroke snowmobiles and have remained lighter weight [10]. However, the SDI two-stroke engines still have poor emissions compared to four-stroke engines. Results from the control snowmobile used at several past CSC competitions as shown in Table 2 clearly illustrate the difference in exhaust emissions and fuel economy between typical carbureted two-stroke, SDI two-stroke, and EFI four-stroke snowmobile engines.

Table 2: Five-mode emissions and fuel economy of two and four-stroke control snowmobiles at CSC [8, 9, and 10].

CSC Year Engine Type	CO [g/kW-hr]	UHC [g/kW-hr]	NOx [g/kW-hr]	Fuel Econ. [MPG]
'03 2-Stroke Carbureted	319.94	125.50	0.73	8.7
'04 4-Stroke EFI	99.84	11.48	23.33	15.3
'05 2-Stroke SDI	215.38	63.53	2.39	19.1

Both the SDI two-stroke and EFI four-stroke in Table 2 meet the 2012 EPA emissions standard with scores of 112 and 162 respectively [9,10]. However, they do not meet the NPS BAT standards. Significant improvement can and should be made to further reduce emissions and increase fuel economy.

Two-stroke engines are less mechanically complex than their four-stroke counterparts. High specific output allows two-stroke engines to have better performance characteristics than many four-strokes. Table 3 compares vehicle weight, engine size, and power output of several different snowmobiles [13].

Table 3: Comparison between competition two-stroke and four-stroke snowmobile engine displacement, power, and weight. [12]

University and Engine Type	Engine size [cc]	Engine power [hp,kW]	Vehicle weight [lb,kg]	Power-to-weight [hp/lb,kW/kg]
2009 Idaho 2-Stroke SDI	593	108/80.5	524/238	0.21/0.34
2008 Idaho 2-Stroke DI (E85)	593	94.4/70	609/276	0.16/0.25
2008 MTU 4-Stroke EFI Turbo (E85)	750	81/60.7	703/319	0.12/0.19
2008 U. Wisconsin Madison EFI 4-Stroke (E85)	750	55/41	632/287	0.09/0.14
2008 U. Maine EFI 4-Stroke (E85)	500	36/26.8	663/301	0.05/0.09

It is clear that two-stroke snowmobiles have better power-to-weight ratios. Two-stoke engines also have torque curves well suited for the belt-type continuously variable transmissions (CVT) that are used in snowmobiles [3].

After considering the above information and the large potential for improvement of emissions over current two-stroke engines, it was decided to build a clean and quiet two-stroke powered snowmobile without sacrificing the high-power output. A major design constraint was that any method used to increase fuel economy and reduce emissions could not significantly increase engine complexity or weight in order to maintain the low cost and high power-to-weight advantage over four-stroke engines.

The engine chosen by the UICSC team was a semi-direct injected, reed valve, and loop scavenged Rotax 593cc engine with a variable exhaust system, and a tuned pipe, similar to the engine shown in Figure 1 [14]. This engine was chosen for several reasons. The engine falls within the guidelines of the competition, it had the typical performance characteristics for two-stroke trail snowmobiles, and parts are readily available.

TWO STROKE ENGINES – The characteristics that make two-stroke engines mechanically simple also cause them to have poor thermal efficiency, poor low load operation, and high exhaust emissions. These are caused by the way the air/fuel mixture is introduced into the combustion chamber. During the scavenging process, the intake and exhaust ports are open at the same time, and a portion of the fresh air/fuel charge is lost out the exhaust pipe, or "short-circuited." Towards the end of the scavenging process, there can be a backflow of fresh charge and exhaust gas residuals into the combustion chamber due to the ramming effect of the tuned exhaust pipe [15].

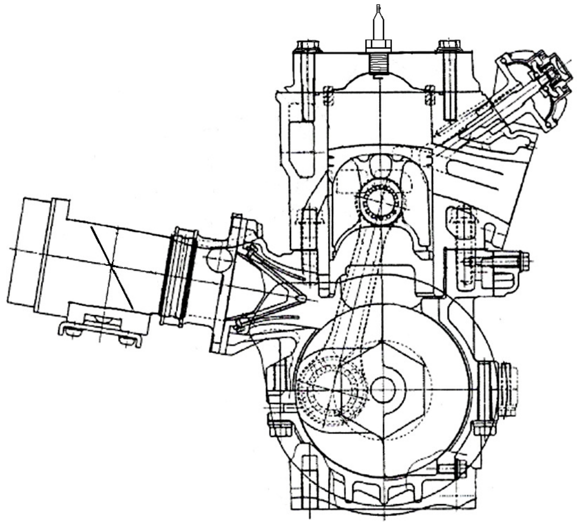

Figure 1: Cross section of a two-stroke engine similar to the one used for the UICSC engine [14].

Stone [16] identifies two very undesirable side effects of two-stroke operation: the short-circuiting of the fresh charge and the mixing of the fresh fuel/air mixture with the exhaust gas residuals. Short-circuited fuel can account for a loss of as much as 50% of the supplied fuel, especially during off-design speeds and loads. However, the CVT used for snowmobiles keeps the engine operating conditions close to the designed engine speeds and loads, limiting the short-circuited fuel to around 10-30% [17, 18, and 19].

The largest amount of the UHC emissions, on a mass/power basis, occurs at wide-open throttle (WOT) and at low engine speeds and loads. The UHC emissions at low engine speeds and loads are due to incomplete combustion, low scavenging efficiency, misfire, and fuel short-circuiting [18]. The poor combustion and misfire are attributed to air-intake throttling, which reduces the scavenging efficiency and leaves excessive residual exhaust gases in the cylinder. This leads to incomplete combustion and high emissions. As engine speed increases, the scavenging process becomes more efficient, less residual exhaust gases are present, and combustion is more complete.

The UHC emissions at WOT are due to fuel short-circuiting and rich air/fuel ratios. The engine is typically operated fuel rich to produce maximum power and to cool the piston to prevent seizure [18]. Reducing the WOT UHC emissions, improving idle quality and light load operation, and reducing the short-circuited fuel across the entire speed and load range would have a large positive effect on fuel efficiency and UHC emissions.

Table 2 showed that typical two-stroke engines also produce more CO emissions than four-stroke engines. The formation process for CO in two-stroke engines is the same as that for other engines [15]. It is a result of operating an engine fuel-rich. The lack of oxygen in the combustion chamber prevents the carbon from fully oxidizing to carbon dioxide and CO forms. To reduce the two-stroke CO emissions the engines will have to be operated with leaner air/fuel ratios.

Nitrogen oxide emissions, NO_x, are a combination of NO and NO_2 that are formed from the high temperatures and pressures that occur during combustion. The formation of NO_x is based on the dissociation of N_2 and O_2 molecules following the flame boundary, and a lack of time available for chemical equilibrium to be reached [18]. Nitrogen oxide formation depends on two basic factors: (1) peak temperatures reached during combustion, and (2) oxygen content in the trapped mixture [18]. Typical two-stroke engines have inherently low NO_x emissions because they have low effective compression ratios, they are operated fuel-rich, and have high residual exhaust gases (EGR), all of which contribute to lower peak cylinder temperatures and less trapped oxygen, leading to less NO_x formation [20]. One goal for new two-stroke technologies is to maintain the low NO_x emissions.

FUEL SYSTEM – There are three different fuel delivery strategies for two-stroke engines. The most common system uses carburetion or throttle body fuel injection to introduce air-fuel mixture into the crankcase of the engine. This method leads to excessive amounts of short-circuiting, poor fuel economy, and high UHC emissions. The second system, semi-direct injection, scavenges air into the crankcase and injects fuel into the engine's boost ports. This system reduces short-circuiting an offers improved air fuel ratio control. SDI systems still introduce fuel into the crankcase and this allows short-circuiting at WOT and low engine speeds and loads. SDI systems offer improved fuel economy and lower emissions than the first fuel system discussed. The third fuel system, direct injection, offers the best emissions, engine efficiency, and fuel economy. In a DI two-stroke, fuel is injected directly into the cylinder at an optimal time for complete mixing and combustion. Air-assisted or high-pressure fuel injectors are used to ensure the fuel enters the combustion chamber in small droplets so the fuel can atomize quickly and mix with the freshly scavenged air. It lessens the effects of charge and exhaust-gas mixing, significantly reduces short-circuiting, and offers precise air/fuel ratio control. The direct injected two-stroke engine platform has been proven at CSC to have better fuel economy and similar emission production to four-stroke snowmobiles [12, 13].

The 2009 CSC rules mandate the use of flex fuel, which requires continuous ethanol content feedback to the engine controller. This feedback alters the engine's calibration strategy to efficiently combust the blend of ethanol fuel in the system. While direct injection is very clean and efficient, it also requires a complex electronic control system for proper operation. UICSC's 2008 DI control unit would not accommodate in-service fuel changes. Due to time and resource constraints, it was determined that a DI system with ethanol content feedback was not feasible for the 2009 competition. Instead, the UICSC team decided to use an SDI platform, which uses a standard fuel injection controller.

An SDI two-stroke maintains a high power-to-weight ratio and offers improved emissions and fuel economy over carbureted and throttle body injected two-stroke engines.

UICSC Flex Fuel System – The fuel requirement for CSC 2009 is gasoline/ethanol flex fuel. A flex fuel engine must be able to efficiently burn any blend of gasoline and ethanol from 10% ethanol to 85% ethanol. The properties of ethanol are significantly different from gasoline and require different calibration strategies. Therefore, a true flex fuel system requires active feedback of the fuel's ethanol content to the engine controller.

Ethanol fuel has lower energy content and higher heat of vaporization. The flame speed and knock resistance of ethanol also varies from that of gasoline. Due to ethanol's lower energy content, more of it must be combusted to produce the same amount of power. The higher heat of vaporization significantly affects the cold start ability of the engine. Both the flame speed and knock resistance affect the compression ratio and spark timing of the engine [21]. All of these facts must be taken into account when a flex fuel engine is built.

To create an ideal flex fuel engine, the compression ratio would have to vary with the ethanol content of the fuel. High blends of ethanol require a high compression ratio to create power efficiently, while low ethanol blends must have a lower compression ratio to avoid detonation. Engines with variable compression are very complex and would require years of development. For these reasons, the UICSC team decided to create a flex fuel system using only ethanol content feedback and calibration changes.

Ethanol content feedback was accomplished using a Continental flex fuel sensor that continuously measures the ethanol content of the fuel. A custom circuit was built to relay the information from the flex fuel sensor to the engine control unit (ECU) and display the ethanol content to the rider using an LED display.

The engine control unit (ECU) was provided to the team by Walbro, Inc. The Walbro ECU is a state-of-the-art total engine fuel injection and ignition control unit. The ECU was programmed to receive the ethanol content information and alter the injection amount and ignition timing to consume the fuel as efficiently as possible. The Walbro ECU is shown in figure 2.

Figure 2: Walbro Engine Control Unit.

Inductive Ignition System – For 2009, the UICSC team chose again to use an inductive ignition system. An inductive ignition discharges energy continuously into the fuel-air mixture as opposed to the multiple strike strategy of a capacitive discharge system. This design was chosen due to the added energy requirements for the combustion of ethanol and the added flexibility in engine calibrations it allows for.

Oil control and engine lubrication – Traditional two-stroke snowmobile engines use a total-loss oiling system. Either the oil is premixed with the fuel or the oil is pumped into the inlet-air stream where it mixes with the incoming fuel. As the fresh air/fuel/oil mixture travels through the crankcase, an oil film is deposited on the surfaces. Any oil that does not attach to a wall is scavenged into the combustion chamber. This system does not require oil filters, oil changes, or a sealed crankcase.

The 2009 UICSC engine uses a mechanical total-loss oil injection system from a stock Rotax 600cc two-stroke. This system eliminates premixing of oil and fuel and only delivers oil to specific locations.

Fuel Delivery System – Due to the SAE CSC 2009 rule change requiring all spark ignition engines to be fueled with gasoline/ethanol flex fuel, the UICSC team had to modify their fuel system for ethanol fuel. Ethanol fuel is very corrosive and can destroy many of the materials in a stock fuel system. In order to handle blended ethanol fuels, the stock parts of the snowmobile fuel system were either replaced or tested to ensure they would withstand ethanol for a duration suitable for competition use. This included the fuel pump, filter, lines and fittings.

The stock fuel pump assembly, including pump and filter, were removed in favor of an in-tank flex fuel pump and a standard automotive inline fuel filter. Flex fuel lines (Gates Hose SAE 30R9) replaced the existing fuel lines throughout the rest of the fuel system, and the remaining fittings were all soak tested to ensure compatibility with the new fuel.

Another major fuel system concern with the use of ethanol blends is the extra-required fuel. In many cases, the use of an auxiliary fuel tank is required to carry ample fuel. To determine if added fuel capacity was required for the 2009 UI snowmobile, a series of on-snow fuel economy runs were made. It was found that the 2009 UICSC snowmobiles stock fuel tank at 10 gallons would suffice for the 100+ required miles of the CSC endurance test. Details of fuel economy testing will be shown in the testing section.

Cold start strategy – Blended ethanol fuel has a higher heat of vaporization than gasoline and therefore requires more energy to initiate combustion [1]. Under ambient conditions, this is not normally an issue. However, when blended ethanol fuels are used in reduced temperatures, such as in a snowmobile application, cold start can be an issue. At the 2008 CSC, all of the two-stroke snowmobiles passed cold start while running on E75, but only two of the four-stroke snowmobiles passed. This is because two-stroke engines have been proven to reliably start in temperatures down to -40°C [22]. Due to the two-stroke engines cold start ability, there was no need to improve the cold start while running ethanol fuel.

WEIGHT REDUCTION – In keeping with the two-stroke performance tradition, the 2009 UICSC team further reduced the weight of the base snowmobile, improving its already high power-to-weight ratio. The weight reduction in 2009 served two purposes. First, performance, handling, and fuel economy were all improved, and second, the weight reduction allowed for the use of more sound deadening materials without negatively influencing the snowmobile's performance.

The weight reduction was accomplished through the replacement of several components. Suspension weight was reduced with the use of 4130 chromoly upper and lower A-arms, Fox Float air shocks, C & A skis, aluminum runners and sway bar elimination. Along with the reduction in weight, there was a significant improvement in suspension performance and handling, allowing for a more responsive control of the snowmobile.

Other weight reduction strategies include fastener length reduction and carbon fiber body panels. Track weight was reduced with the use of a Camoplast Ice-Ripper track with built in studs, eliminating the use of conventional studs. The pre-competition weight of the snowmobile was 524 lbs. (238 kg) wet with 10 gallons of fuel.

NOISE REDUCTION – As stated earlier, the SAE CSC noise event measured sound pressure weighted on the A-scale. The A-scale mimics the threshold of human hearing, which is approximately 20 Hz to 20 kHz [15]. Figure 3 shows the standard A contour filter. As the figure shows, the A-scale effectively filters out inaudible low frequency sounds that have a low response.

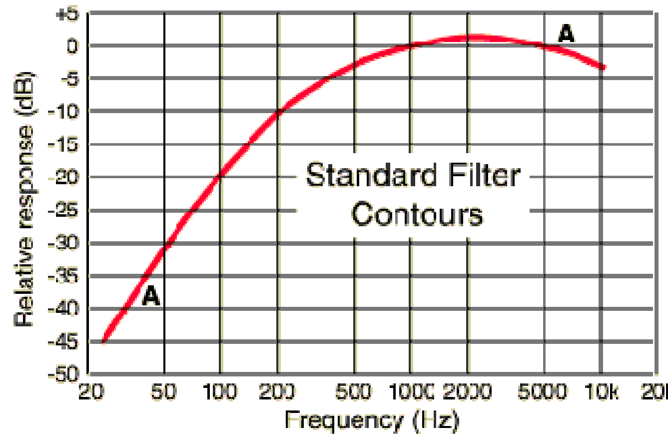

Figure 3: The A contour is sensitive to sounds occurring between 1 and 5 kHz [15].

Sound Testing – In 2008, the UICSC team worked intensively to reduce noise emissions, achieved a score of 73dBA in a standard SAE J-192 test, and was voted best sounding snowmobile at competition [23]. In continued efforts to reduce noise emissions, new strategies and testing procedures were created for 2009. In past years, it was observed that testing conditions have a large impact on the J-192 test. In 2009, a noise control snowmobile was used to track how changes in testing environments affected the overall noise level of the competition snowmobile. Comparative data had to be taken on the same day due to varying test conditions. Due to lack of facilities at the test site, only small changes to the snowmobile could be made during a testing session. The control snowmobile made it possible to compare data taken on different days and at different test sites.

Along with the on-snow J-192 testing, a materials testing procedure was also created to test different materials and configurations in a more controlled environment. The layout of this test can be seen in Figure 4. This test consisted of a speaker mounted in an open-ended box. Then different samples of material were placed on the open end of the box. A power source, with variable power and frequency capabilities, along with a sound meter, like that used in a J-192 test, were used to create and measure sound through the test panels. The sound meter was placed two feet from the sample panel and the power setting was fixed so that the meter read 80dB at 1 kHz when no sample panel was present. To test a sample, a frequency sweep from 1 kHz to 5 kHz was performed and recorded at the previously mentioned power setting for each material and configuration. The results of this test are shown in Figure 5.

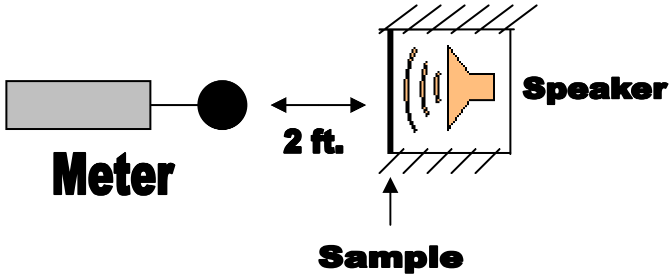

Figure 4: Schematic of the material-sample test configuration.

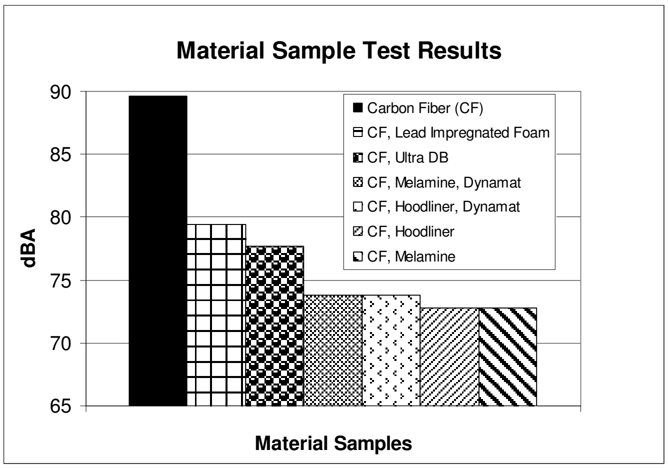

Figure 5: Results of sample material testing.

For the UICSC snowmobile to be competitive in the noise event, the entire range of human hearing had to be addressed. There are four main sources of noise in a snowmobile: 1) mechanical noise emitted from the engine, and drive system, 2) track noise, 3) air intake noise and 4) engine exhaust noise.

Sound Data Analysis – Various analysis techniques were used to determine the sources of sound in the snowmobile. One of these techniques was Fast Fourier Transform (FFT) analysis. FFT analysis shows peak sound magnitudes across a frequency range. This can be used to determine the adequacy of sound deadening materials and to determine frequencies that need to be reduced from the snowmobile. Another technique was Fast Fourier Transform vs. time analysis. FFT vs. time was used to analyze sound sources that change frequency with time. This analysis can be used to determine what frequency the engine, drive train, and track produce.

Mechanical Noise – There are several sources of mechanical noise. These include the clutches, chain drive, and the engine. Mechanical noise can escape from the engine compartment through vibrations in the belly pan, panels, and hood as well as from vents in the hood and body panels.

Absorption and redirection were the two methods used to reduce emission of noise through body vibration. Through the previously mentioned material sample testing combined with on-snow J-192 testing, it was found that a material consisting of various density foams and rubber with a reflective heat barrier, was the most effective.

In an attempt to contain and redirect noise, all hood and side panel vents that were not necessary for engine compartment cooling were sealed. Those needed were fitted with scoops to reduce direct noise emission and maintain airflow through the engine compartment. Figure 6 shows a Fast Fourier Transform analysis of both stock and carbon fiber body panels from a J-192 test. It can be seen that the stock panels with sound deadening materials reduce the peak magnitudes.

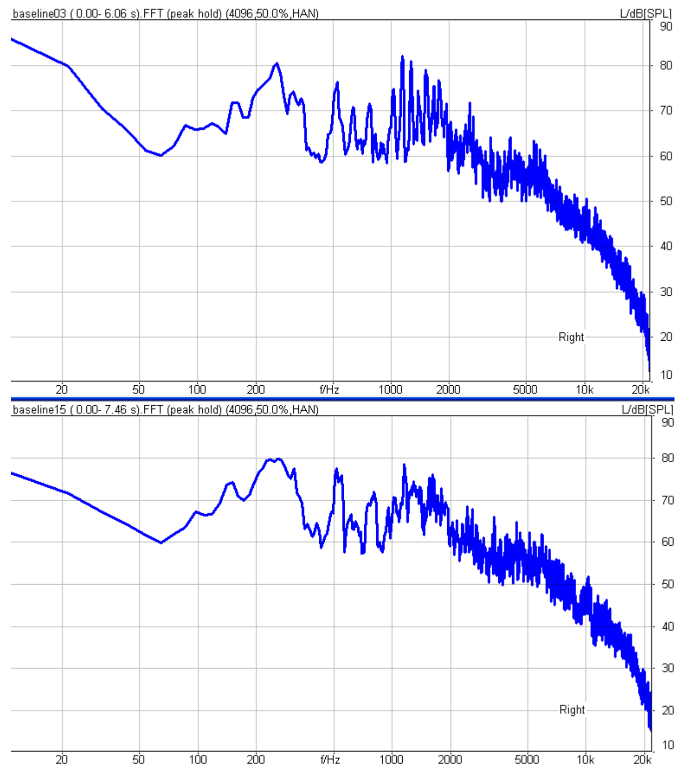

Figure 6: Comparison of stock panels with deadening materials (bottom) and carbon panels without deadening materials (top) using FFT analysis.

Tunnel Noise – Through FFT vs. time analysis of J-192 tests, it was determined that the tunnel of the snowmobile chassis produced a significant amount of vibration that added to the overall sound production of the snowmobile. Figure 7 is a comparison between UICSC's 2008 and 2009 snowmobiles using Fast Fourier Transform vs. time. It can be seen in figure 7 that the 2009 UICSC snowmobile is significantly louder across the frequency spectrum than the 2008 snowmobile. To reduce tunnel vibration, tunnel stiffeners were added to the previously flimsy areas of the tunnel. These rigid supports were added to the inside of the tunnel so as not to cause rider discomfort.

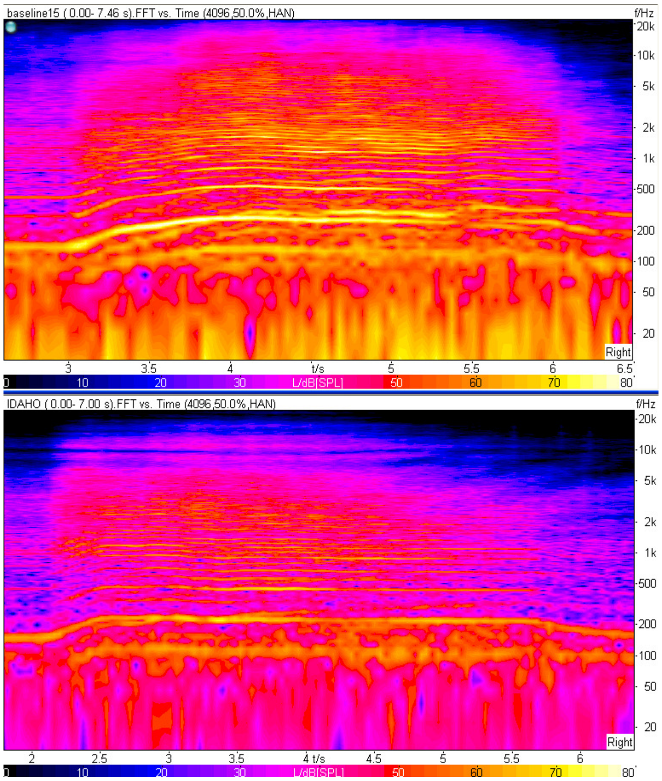

Figure 7: Comparison of UICSC's 2008 (bottom) and 2009 (top) snowmobiles using FFT vs. time analysis.

Intake Noise – Previous UICSC intake designs focused on noise reduction through modifying the geometry of the stock intake system. These intake designs failed to produce an overall noise level reduction and significantly restricted airflow to the engine. In 2008, UICSC lined the air intake box with high-density foam to absorb sound while minimizing flow restriction. This was combined with a uni-directional air intake that was designed to direct sound through an opening in the hood. This intake proved to reduce noise emissions over the stock configuration. For 2009, a Helmholtz resonator designed to eliminate a known engine frequency of 512Hz was built and added to the stock air intake. The resonator was built to be adjustable so that fine-tuning could be done in between J-192 tests and so the most effective configuration could be achieved.

Exhaust Noise – Several exhaust system setups were tested for 2009 including the 2007 competition exhaust with a 3in catalytic converter, a student designed Laminar flow muffler and a stock muffler with a Helmholtz resonator incorporated into it. Figure 8 shows a comparison of the intake and exhaust noise of UICSC's 2009 snowmobile during a J-192 test.

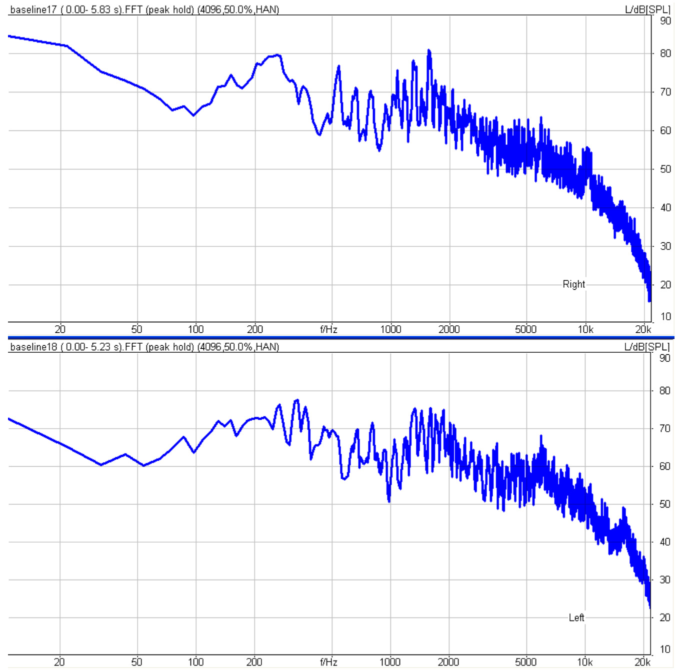

Figure 8: Comparison of intake (top) and exhaust (bottom) sides of the 2009 snowmobile during a J-192 test.

Final Approach – Several methods proved to significantly reduce noise produced by the snowmobile. Sound deadening material, hood scoops, Helmholtz resonators and tunnel stiffeners were all implemented to reduce noise levels. Implementation of all of these methods yielded an average score of 80 dBA using the SAE procedure J-192. At the time this paper was written, efforts continued in an attempt to reduce the sound levels below 78 dBA.

COMFORT AND SAFETY – The 2009 UICSC snowmobile was designed for touring use; comfort, ease of operation, safety and reliability were primary design goals. These goals were accomplished with an ergonomically superior chassis along with several other design strategies. For comfort and convenience, a few typical stock accessories were kept, this included hand and thumb warmers. An easy to read gauge cluster was also constructed.

There are several other features included to improve the safety and reliability of the snowmobile. The rider can use the switch mounted on the handlebars to kill the engine. Additionally, if the rider falls from the machine, a tether switch connected to the rider will stop the engine. Another added safety feature is the addition of a clutch cover with woven nylon belting and aluminum extending to the centerline of the clutches. This will protect the rider in the unlikely event of clutch failure

COST – With the price of snowmobiles rising every year, cost is fast becoming a primary concern for riders. The base price for a comparable 2009 model snowmobile, a Ski-Doo MX-Z 600 E-Tec, is \$8799. With all modifications included, the Manufacturers Suggested

Retail Price (MSRP) of the 2009 UICSC SDI, totaled $10,882. Chassis components that add to the MSRP were justified by weight reduction, increased performance, and sponsor product awareness. The engine modifications total $689, which includes the elements necessary for an active flex fuel system. The final design is shown in Figure 9.

Figure 9: Final design of the 2009 UICSC SDI snowmobile.

TESTING AND RESULTS – Testing is required to determine the improvement of a new design over an existing design. To verify that the 2009 UICSC snowmobile is better than previous designs, dynamometer testing totaled over 80 hours and on-snow testing totaled over 300 miles. This was completed to verify improvements in fuel economy, emissions, reliability, and noise levels. On-snow endurance and fuel economy is shown in figure 10.

Figure 10: Endurance and fuel economy testing

Calibration Strategy – Engine calibration for blended ethanol fuel was completed using a Borghi and Saveri eddy current dynamometer with Superflow supporting software and systems. The engine dynamometer system is shown in figure 11. Calibration was based on finding ideal torque, air-fuel ratio, exhaust gas temperature, and fuel flow for each ethanol blend and engine operating point. Air-fuel ratio was measured with a lambda sensor. Because of excess air in the exhaust stream due to the nature of a two-stroke engine, the lambda sensor was not completely accurate. Once the lean/rich limits were found, the Lambda sensor provided a guide to creating smooth engine maps. Emission tuning was completed using a hand held five-gas analyzer. The strategy for testing was focused on BSFC and run quality throughout the map, followed by emission reduction at each of the mode points, without sacrificing run quality.

Figure 11: Eddy-current dynamometer system.

Engine emissions – The three major factors influencing the emission production of the 2009 UICSC snowmobile was semi-direct fuel injection, catalytic converter, and fuel blend. In 2008, E85 was used to fuel the UICSC snowmobile, for 2009, flex fuel is required. As stated earlier, high ethanol fuel blends have lower EPA measured emissions than E10. Another factor affecting emissions for 2009 was the use of a catalytic converter. The catalytic converter is a 3.5 in by 4.5 in (88.9 by 114.3 mm) cylinder with a high flow honeycomb substrate donated by Aristo Inc.

At the time this paper was written, emissions testing of the 2009 UICSC snowmobile was not yet complete. Although complete emissions data were not available, the UI snowmobile was expected to be competitive at the 2009 emissions event due to the fuel system, catalytic converter, and ethanol fuel blend.

Engine power and fuel economy – During testing on groomed trails at elevations ranging from 3000 to 5500 feet, the 2009 UICSC SDI achieved 13.3 mpg (5.65 km/L) using E85 and 16.5 mpg (7.0 km/L) using E10. All fuel economy runs were at an average speed of 35 mph

(56 km/hr). The fuel economy using E10 was lower than expected due to some off-trail riding.

The advantage of the UICSC SDI two-stroke engine has in brake specific fuel consumption (BSFC) is illustrated in Figure 12 [13]. The BSFC of the 2009 UICSC SDI is comparable to the four stroke competitors at mode 2 and considerably better at modes 3 and 4. The improved BSFC at modes 3 and 4 will be seen in overall fuel economy because these modes represent the cruise points of a snowmobile. The BSFC is reduced as much as 45 percent compared with the four-stroke engines. Overall fuel economy is further improved with a lightweight engine and chassis. The poor BSFC at mode 1 is attributed to the rich calibration of two-stroke engines for survivability. The reduction in BSFC from the 2008 DI engine was expected because of the reduced engine efficiency of the SDI system.

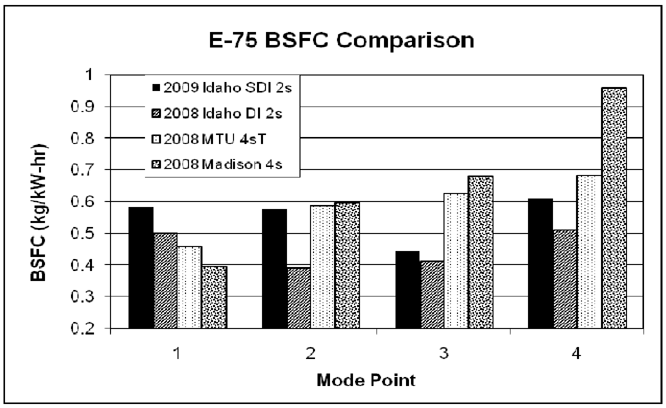

Figure 12: Four-mode BSFC comparison for the 2009 UICSC SDI vs. 2008 UICSC DI, Madison four-stroke, and MTU Turbo four-stroke [13].

The engine efficiency and BSFC of a flex fuel system varies with the ethanol blend of the fuel. The effect of ethanol's low energy content can be seen in figure 13, which compares the BSFC of 2009 UICSC flex fuel engine running on E10 and E75. It is very clear that engine efficiency is reduced with the higher ethanol content of the fuel.

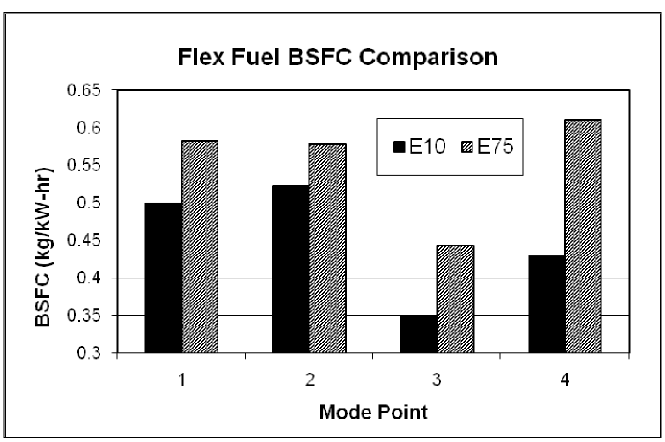

Figure 13: Four-mode BSFC comparison for the 2009 UICSC SDI Flex Fuel engine.

Peak power output for the 2009 UICSC SDI, 2008 Idaho DI two-stroke, Michigan Tech. turbo four-stroke, Madison four-stroke, and Maine four-stroke powered snowmobiles are shown in figure 14 [13]. All engines compared in figure 14 were running on the same blend of ethanol fuel (E75) [24]. The 2009 UICSC flex fuel SDI has superior peak power output compared to both naturally aspirated and turbocharged four stroke engines. The 2009 UICSC SDI engine power was improved from the 2008 DI engine because the DI fuel injector limits were reached when burning E75 fuel.

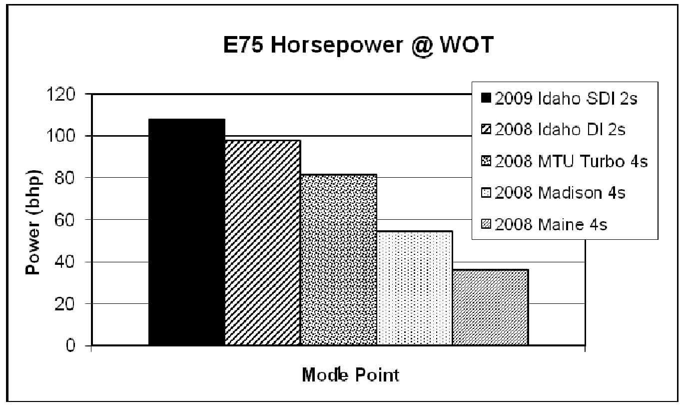

Figure 14: Peak power output of the 2009 UICSC SDI vs. 2008 UICSC DI, MTU Turbo 4-Stroke, Madison 4-Stroke, and Maine 4-Stroke engines [13].

CONCLUSION

The University of Idaho has developed a cost-effective semi-direct-injected two-stroke snowmobile engine capable of running on ethanol/gasoline flex fuel. The SDI two-stroke snowmobile maintains the mechanical simplicity and low weight avid riders enjoy, without sacrificing the clean and quiet characteristics necessary to meet current and upcoming standards. The UICSC design produces 108 hp (80.5 kW), is lightweight at 524 lbs wet (238 kg), and achieves a fuel economy of 13.3 mpg (5.65 km/L) on E85 fuel. Overall sound production measured using the SAE standard J-192 was reduced from 85 dBA to 80 dBA, not yet to the competition standard. With future regulations coming for manufacturers, consumers will expect clean and quiet snowmobiles. The end consumer will see more benefit to having increased fuel economy, better power-to-weight ratios, and reduced noise, all of which improve the riding experience.

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REFERENCES

1. Niven, R.K., "Ethanol in gasoline: environmental impacts and sustainability review article," Renewable and Sustainable Energy Reviews 9, Elsevier, pp. 536-555, 2005.
2. Society of Automotive Engineers, Inc., The SAE Clean Snowmobile Challenge 2009 Rules, 2008.
3. Lela C.C., White J.J., "Laboratory Testing of Snowmobile Emissions". Report Number SwRI 08.05486, Southwest Research Institute, San Antonio, July 2002.
4. United States Environmental Protection Agency; 40 CFR Parts 1051.103 and 1065, February 28, 2006.
5. United States Department of the Interior National Park Service, Special Regulations; Areas of the National Park System, Final Rule. 36 CFR Part 7, November 10, 2004.
6. Maximum Exterior Sound Level for Snowmobiles. SAE Surface Vehicle Recommended Practice. J-192.
7. Society of Automotive Engineers, Inc., The SAE Clean Snowmobile Challenge Results 2002.
8. Society of Automotive Engineers, Inc., The SAE Clean Snowmobile Challenge Results 2003.
9. Society of Automotive Engineers, Inc., The SAE Clean Snowmobile Challenge Results 2004.
10. Society of Automotive Engineers, Inc., The SAE Clean Snowmobile Challenge Results 2005.
11. Society of Automotive Engineers, Inc., The SAE Clean Snowmobile Challenge Results 2006.
12. Society of Automotive Engineers, Inc., The SAE Clean Snowmobile Challenge Results 2007.
13. Society of Automotive Engineers, Inc., The SAE Clean Snowmobile Challenge Results 2008.
14. Morikawa K., Takimoto H., Ogi T., "A Study of Direct Fuel Injection Two-Stroke Engine for High Specific Power Output and High Engine Speed", SAE Paper 1999-01-3288 / JSAE 9938043, 1999.
15. Blair G.P. "Design and Simulation of Two-Stroke Engines". Society of Automotive Engineers, Inc. Warrendale, Pa, 1996.
16. Stone R. "Introduction to Internal Combustion Engines". Antony Rowe Ltd. Chippenham, Wiltshire, 1997.
17. Heywood J.B., "Internal Combustion Engine Fundamentals". McGraw Hill, Inc. 1988.
18. Nuti M., "Emissions from Two-Stroke Engines". Society of Automotive Engineers, Inc. Warrendale, Pa, 1998.
19. Bradbury N., French F., DenBraven K., "Improving the University of Idaho Snowmobile", SAE Paper 03-SETC-87, 2003.
20. Zhao F., Harrington H.L., Lai M., "Automotive Gasoline Direct-Injection Engines". Society of Automotive Engineers, Inc. Warrendale, PA. 2002.
21. Yucesu, H.S., Topgul, T., Cinar, C., and Okur, M., "Effect of ethanol – gasoline blends on engine performance and exhaust emissions in different compression ratios," Applied Thermal Engineering 26, Elsevier, pp. 2272-2278, 2006.
22. Wright C.W., White J.J., "Development and Validation of a Snowmobile Engine Emission Test Procedure", SAE Paper 982017, 1998.
23. Harker N., Johnson J., Findlay A., DenBraven K., "University of Idaho's Clean Snowmobile Design Using a Direct-Injection Two-Stroke Engine", SAE Paper 08SETC-0006, Sept. 2008.
24. Gage Certificate of Analysis 3/04/08
25. Strauss S., Zeng Y., Montgomery D.T., "Optimization of the E-TEC® Combustion System for Direct-Injected Two-Stroke Engines Toward 3-Star Emissions", SAE Paper 2003-32-0007/20034307, 2003.
26. Heywood, J., Sher, E., "The Two-Stroke Cycle Engine, Its Development, Operation, and Design", Taylor and Francis Inc., Braun-Braumfield, Ann Arbor, MI. 1999.
27. Bradbury N., Findlay A., Johnson J., Van Patten E., DenBraven K., "University of Idaho's Clean Snowmobile Design Using a Direct Injection Two-Stroke", SAE Paper 2006-32-0050, 2006.
28. Strauss S., Zeng Y., "The Effect of Fuel Spray Momentum on Performance and Emissions of Direct-Injected Two-Stroke Engines", SAE Paper 2004-32-0013 / JSAE 20044300, 2004.
29. Wasil J., Montgomery D., Strauss S., Bagley S.T., "Life Assessment of PM, Gaseous Emissions, and Oil Usage in Modern Marine Outboard Engines". SAE Paper 2004-32-0092/20044379, 2004.
30. Johnson W. P., Zanforlin S., Gerber K., "Electronic Direct Fuel Injection (EDFI) for Small Two-Stroke Engines", SAE Paper 1999-01-3312, 1999.