University of Idaho's Clean Snowmobile Design Using a Direct-Injection Two-Stroke with Exhaust Aftertreatment

Russell Schiermeier, Tyler Harris, Nathan Bradbury
SAE Student Members, University of Idaho

Dr. Karen R. DenBraven
Mechanical Engineering, University of Idaho

ABSTRACT

The University of Idaho's entry into the 2005 SAE Clean Snowmobile Challenge was a second-generation gasoline direct-injection (GDI) two-stroke powered snowmobile. A battery-less direct-injection system was used to decrease exhaust emissions and improve fuel economy without reducing the power output of the engine. Under-hood noise was reduced with sound absorbing materials and a sealed hood, while a spiral exhaust silencer decreased exhaust noise. Chassis noise was addressed using a spray-on rubberized material that absorbed vibrations transferred through the chassis. Power transfer and space issues were lessened by adding a direct-drive system that eliminated the jackshaft. The final design was a lightweight, fun-to-ride, powerful, fuel efficient, clean, and quiet snowmobile.

INTRODUCTION

Snowmobiles are often ridden in environmentally sensitive areas such as Yellowstone National Park. Traditionally snowmobiles have been loud, have had high levels of toxic exhaust emissions, and were fuel inefficient. Concerns over the impact of snowmobiles in national parks prompted the National Park Service (NPS) to issue a Proposed Rule in December of 2000 concerning snowmobiles and their use in National Parks [1]. The proposed rule capped the snowmobile use in the winters of 2001-02 and 2002-03 with complete elimination of snowmobiles by the 2003-04 season. On January 22, 2001, the NPS published the "Snowcoach Rule," allowing snowmobile use to continue in 2001-02, while mandating significant reductions in snowmobile use in 2002-03 and the elimination of snowmobiles in National Parks in favor of snowcoaches in 2003-04 [1].

The NPS later published a revised alternative to the "Snowcoach Rule" in 2003, allowing for a set number of snowmobiles to enter National Parks. The snowmobiles allowed to enter the Parks would be required to conform to the Best Available Technology (BAT) standards, an "adaptive management" program, and 80% of the snowmobiles would have to be guided through the Parks [1].

On December 16, 2003, U.S. District Court Judge Emmet Sullivan ordered the final 2003 rule of the NPS be vacated [1]. This ruling left the January 22, 2001, Final Rule in effect, as modified by the November 18, 2002 Final Rule. This ruling limited the number of snowmobiles allowed into the park for the 2003-04 season and phased out snowmobiles in favor of snowcoaches in the future. However, the court remanded the case to the NPS for further investigation. This ruling did not permanently close the door on snowmobiles entering Yellowstone. Rather, it required the NPS to scientifically determine the full environmental impact of allowing snowmobiles in the park. This decision has placed more pressure on the NPS to continue its research on environmentally safe ways to include snowmobiles in Yellowstone and other National Parks.

On February 10, 2004 U.S. District Court Judge Clarence A. Brimmer stated that the January 2001 Rule is not valid, and required the NPS to provide temporary rules for the 2004 snowmobile season that are "fair and equitable" to all parties [2]. In response to this ruling, the NPS produced a compendium amendment describing the temporary rules [3]. The temporary rules allowed for 780 snowmobiles, rather than the previous 493, to enter Yellowstone each day. According to the 2004 proposed rules, the additional snowmobiles allowed into the park had to meet BAT standards and all snowmobiles had to be commercially guided. The 2003-2004 BAT standards stated that all snowmobiles must achieve a 90% reduction in hydrocarbons and a 70% reduction in carbon monoxide, relative to EPA's baseline emissions testing for conventional two-stroke snowmobiles. Beginning with 2005 model year, snowmobiles must be certified under the 40 CFR 1051, to a Family Emission Limit (FEL) no greater than 15 g/kW-hr for UHC and 120 g/kW-hr for CO. In addition to the exhaust emissions standard for BAT, the snowmobiles must also produce less than 73 dBA sound pressure measured at full throttle according to the SAE J192 (1985, NPS modified) test procedure [3].

The NPS released a final rule concerning snowmobile usage in Yellowstone National Park on November 10, 2004, which became effective on December 10, 2004. The only change to the 2004 proposed rules discussed above limits the total number of snowmobiles allowed in the park each day to 720. All emissions and noise requirements remained the same [4].

The Society of Automotive Engineers, along with many others concerned with the impact of snowmobiles on environmentally sensitive areas, began the SAE Clean Snowmobile Challenge (CSC) Student Design Competition in 2000. This competition aims to encourage the development of touring snowmobiles for use in environmentally sensitive areas [5]. The snowmobiles designed for the competition are expected to produce less unburned hydrocarbons (UHC) and carbon monoxide (CO) without significantly increasing the levels of oxides of nitrogen (NO_x) when compared to a current production touring snowmobile. The snowmobiles are also expected to be quieter than the current available technology. If two-stroke snowmobiles are to be allowed back into Yellowstone and other National Parks, they must have a reduced impact on the environment.

DESIGN GOALS - The first goal for the competition was to reduce the exhaust emissions when compared to a standard consumer model touring snowmobile. This reduction included CO and UHC, without significantly increasing NO_x, caused by lean air/fuel mixtures. Points awarded for emissions reduction we based on a weighted five-mode EPA testing procedure compared to the control snowmobile and the other competitors [5].

Reducing the noise emitted from the snowmobile was also a large priority for the competition. To receive points for sound reduction, the snowmobiles must produce a sound intensity 0.5 dBA less than the control snowmobile when measured at a steady speed [5]. The control snowmobile used in the 2005 competition was a “2005 Bombardier Ski-Doo 2-TEC GSX Sport 600 H.O. SDI” [5].

Another goal was to improve fuel efficiency beyond that of conventional touring snowmobiles. The target range for the competition endurance event is 100 mi (161 km). Each snowmobile must complete the endurance event while following a trail judge pacing them at a speed of no more than 45 mph (72 km/h) [5]. This allowed all the competition snowmobiles fuel consumption to be based on the same duty cycle.

To quantify performance and handling characteristics, the snowmobiles also compete in an acceleration event as well as two handling events. The acceleration event was based on the time it took to travel 500 ft (152 m) starting from a stop. To pass the event, the snowmobiles needed to complete the course in less than 12 seconds. To assess handling, each of the snow machines was ridden through a slalom course by a member of the team and a professional snowmobile rider. In the student portion, the snowmobiles completed two laps, and the shortest time of the laps was recorded for scoring. Professional snowmobile riders scored the snowmobiles based on specific handling and drivability criteria. The snowmobiles are also subjected to a morning cold start, and have to start within 20 seconds without starting fluids [5].

Students submit a technical design paper describing the approach taken and the challenges met during the design and building of the snowmobiles. The teams also present an oral design presentation and a static display. These presentations focus on how the teams’ snowmobiles accomplish the goals of the competition and “sell” the product to potential buyers. With these design goals in mind, the 2005 University of Idaho Clean Snowmobile Challenge Team (UICSC) began designing a clean and quiet snowmobile.

UICSC SNOWMOBILE DESIGN

CHASSIS SELECTION - The University of Idaho design started with a 2003 Polaris Pro-X chassis. This chassis was used for several reasons. It is lightweight, durable, comfortable to ride, and has a short-track. All of these characteristics make it ideal for use as a trail snowmobile chassis. This racing style chassis benefits from lightweight aluminum radius rods and chrome molybdenum trailing arms, both of which feature improved strength over a standard trail snowmobile. The Walker Evans Racing Shocks are lightweight, tunable, and very durable. The independent front suspension (IFS) features lightweight, dual-rate single coil springs and its weight was further reduced by 2.7 lbs (1.22 kg). by using aluminum spindles [6].

The driver ergonomics of the race chassis are better than a standard touring snowmobile. The forward position of the steering post allows for better driver control. The race seat provides for an easy transition from sit down to standing positions due to a 3 inch (7.62 cm) higher lift and a more forward position. The combination of the chassis improvements and the ergonomic improvements reduces driver fatigue [6].

ENGINE SELECTION - It has been proven in the past that four-stroke engines can be used in snowmobile designs to produce a fuel efficient, clean, and quiet snowmobile. However, avid snowmobile riders still prefer a lighter and more powerful two-stroke engine. The major downfalls to carbureted two-stroke engines are their high exhaust emissions and poor fuel economy.

Results from experiments at Southwest Research Institute (SwRI) shown in Table 1 clearly demonstrate the difference in exhaust emissions between two- and four-stroke snowmobile engines. This standardized testing shows that, on average, four-strokes have a 97% reduction in UHC, 85% reduction in CO, and increased fuel economy.

Engine	UHC g/hp-hr	CO g/hp-hr	NO_x g/hp-hr	BSFC lb/hp-hr
Four-Stroke Mean	3.50	59.3	6.57	0.65
Two-Stroke Mean	140.7	385.1	0.54	1.08

Table 1: Four-stroke and two-stroke five-mode engine brake-specific emissions and fuel consumption running on 10% ethanol fuel [7].

Table 2 illustrates the fuel economy results from the 2002 and 2003 SAE Clean Snowmobile Challenges. The four-stroke engines used by the Championship UICSC teams in 2002 and 2003 had significantly better fuel economy than the two-stroke control snowmobiles under the same trail conditions [8,9]. Tables 1 and 2 clearly demonstrate the major disadvantages of current stock two-stroke snowmobile engines.

Snowmobile	Fuel Economy (miles/gal)
2002 UICSC Competition 749cc 4-stroke	18.3
2002 Control snowmobile 600cc 2-stroke	11.7
2003 UICSC Competition 833cc 4-stroke	20.1
2003 Control snowmobile 600cc 2-stroke	8.7

Table 2: 2002 and 2003 SAE CSC four-stroke and two-stroke fuel economy results [8,9].

While standard two-stroke engines are very fuel inefficient, they have a simple mechanical design compared to their four-stroke counterparts. After considering all the options available and the large potential for improvement over current carbureted two-stroke engines, it was decided to build a clean and quiet high-power output two-stroke powered snowmobile.

The UICSC chose to use a Polaris 600cc engine. The engine displacement falls within the guidelines of the competition and fits into the Pro-X chassis. [5]. This engine is very typical in terms of performance and size for trail snowmobiles that use two-stroke engines.

Two-stroke operation - The characteristics that make two-stroke engines mechanically simple also cause them to have poor fuel economy, poor low load operation, and high exhaust emissions. These are caused by the way the air/fuel mixture is introduced into the combustion chamber. Scavenging is the process of emptying the cylinder of burned gases and replacing them with a fresh mixture (or air) [10]. 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 back flow of fresh charge of exhaust gas residuals into the combustion chamber due to the ramming effect of tuned exhaust pipes [11].

Stone [12] identifies two very undesirable side effects of the two-stroke cycle: the short-circuiting of the fresh charge and the mixing of the fresh fuel/air mixture with the exhaust gas residuals. Tests performed at the University of Idaho show that as much as 50% of the fresh charge can be short-circuited, Figure 1. The range of throttle position and engine speed that matches the 50% short-circuited fuel is an operating zone that never actually occurs in snowmobile operation [13]. The clutches used to transfer power from the crankshaft to the track do not engage until well above 4000 rpm. Normal snowmobile two-stroke engine operating ranges see short-circuited fuel ranging between 20% and 35%.

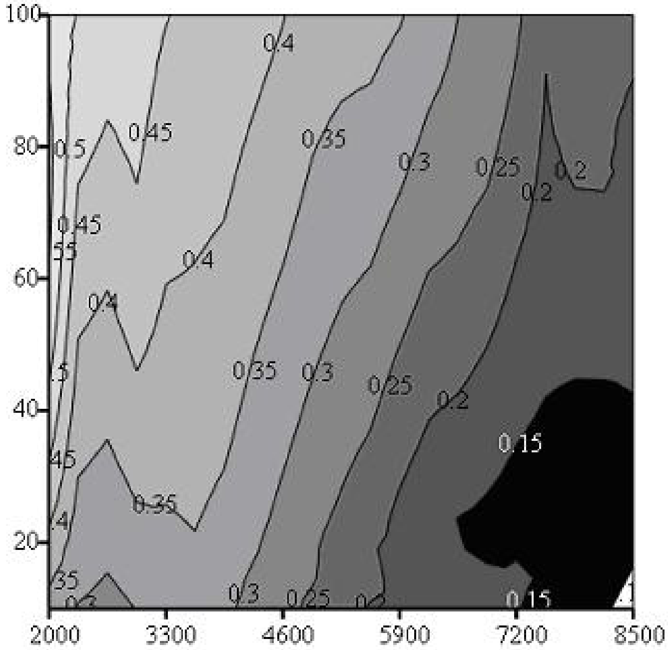

Figure 1: Fraction short-circuited fuel from an Arctic Cat 600 EFI two-stroke: percent throttle vs. engine rpm [13].

The literature states that the largest percentage of UHC emissions, based on a mass/power basis, can be expected at low engine rpm with small throttle openings [14]. This is due to incomplete combustion, low scavenging efficiency, misfire and fuel short-circuiting [15]. The poor combustion and misfire are attributed to air-intake throttling. The restriction on the intake side of the scavenging reduces the scavenging efficiency and leaves excessive residual exhaust gases in the cylinder. The large amounts of exhaust gases present in the chamber lead to incomplete combustion and high emissions. Incomplete combustion is also responsible for poor idle quality and light load operation [16]. As engine speed increases, the scavenging process becomes more efficient, less residual exhaust gases are present, and combustion is more complete. Short-circuited fuel is the greatest contributor to UHC emissions. Improving the idle quality, light load operation, and reducing short-circuited fuel would have a large positive effect on fuel economy and emissions.

Direct-injection – Direct-injection can lessen the effects of charge and exhaust gas mixing, and significantly reduce, if not eliminate, short-circuiting. It is also known to improve cold start reliability [16]. In a GDI 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. Two modes of combustion are used for GDI engines: homogeneous and stratified.

Homogenous combustion occurs when the fuel is completely mixed with the air before combustion takes place, as in a standard two-stroke engine. For the GDI engine, homogeneous operation is accomplished when fuel is injected early in the cycle when there is plenty of time for it to completely mix with the freshly scavenged air. The homogenous mixture is then ignited and the power stroke begins. As stated earlier, at low engine speeds residual exhaust gases cause incomplete combustion in a homogeneously charged two-stroke engine. It is suggested to use homogenous operation only during part load to high load operation [17].

Stratified combustion occurs when the injection event is late in the cycle and ignition is timed to occur when there is a fuel rich mixture surrounding the spark plug. With the rich condition occurring at the onset of combustion, a reaction rate high enough to sustain stable combustion will occur [16]. The flame front moves out from the spark plug gap, burning the ever-leaner mixture until combustion can no longer be sustained. Stratified combustion can eliminate poor idle quality and poor low load operation [16]. Strauss [17] suggests that stratified charge combustion should be used during idle and light load operation. One potential disadvantage to this type of combustion is a potential for an increased production of NO_x from the lean combustion occurring at the outer edges of the flame front [16]. This can be combated with the use of a catalyst designed for a GDI two-stroke and the natural exhaust gas recirculation (EGR) effect of two-stroke engines with tuned exhaust pipes. For stratified combustion to occur, the injector/spark plug relationship and the geometry of the combustion chamber play a significant role in combustion stability.

Although direct-injection is considered the best technology available to reduce emissions from two-stroke engines, many obstacles need to be overcome for a GDI system to be successful in a snowmobile application. The injectors need to be able to atomize the fuel quickly and completely to ensure UHC emissions are kept to a minimum. The shape of the combustion chamber needs to be changed significantly in order to have a combustible mixture near the spark plug during ignition. Additionally, it is recommended that the engine have a multiple spark discharge system to ensure a spark event occurs when a rich mixture is near the spark plug during stratified operation [17].

Another factor limiting the development of high power-output GDI two-stroke engines are the high engine speeds. As engine speed increases, the amount of time available to inject the fuel decreases. Problems incurred in designing injectors that can supply fuel quickly enough have limited the production of high power output GDI two-strokes.

UICSC GDI DESIGN - For the 2004 CSC competition, the UI team started its first attempts to produce a GDI snowmobile engine. For that engine, Evinrude's FICHT electromechanical injectors were adapted to an Arctic Cat 600cc engine. Due to problems associated with operating the injectors and the injectors' inability to operate reliably above 6000 RPM, the engine never performed as expected.

Evinrude's latest two-stroke outboard marine engines have a new DI system. The new E-Tec injectors operate in a similar manner to the FICHT injectors. However, instead of being driven in only on direction, like the FICHT, the E-Tec injectors are driven in both directions, similar to a voice coil. These new injectors can be operated at much higher engine speeds. The UICSC team decided to adapt the new E-Tec system to the Polaris 600cc engine.

Several modifications had to be made to the carbureted two-stroke for GDI operation. The E-Tec system requires both 12V and 55V to operate, therefore an electrical system capable of producing both voltages needed to be adapted. One solution was to use the stock 12V permanent magnet alternator with a DC to DC converter to produce the 55V circuit, similar to the 2003 UICSC snowmobile. The second option was to adapt the E-Tec permanent magnet alternator that produces 55V and the charging circuit that produces 12V. The second option was selected. After several modifications the E-Tec 55V alternator and flywheel were mounted to the Polaris engine in the same location as the stock 12V alternator was located. Placing the power source there maintained a clean, stock appearance. The E-Tec alternator produces enough power with one pull of the starter-rope to start the engine. This makes starting the engine easy. In addition, there is no need for a battery. All of the other components required to make the E-Tec system work were also adapted the engine. This included:

- Engine temperature sensor
- Intake air temperature sensor
- Crankshaft position sensor

- Throttle position sensor
- E-Tec injectors and coil assemblies

Figure 2 shows a schematic of the GDI system.

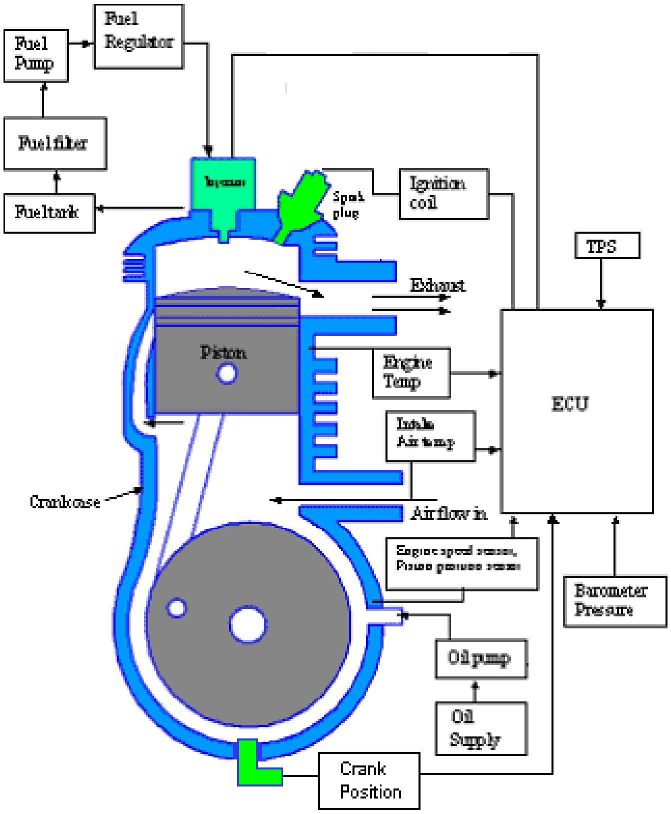

Figure 2: GDI two-stroke engine component schematic.

Combustion chamber design - While simpler than its four-stroke counterpart, the GDI head is more complex than standard two-stroke heads. The most important factors to consider when designing the combustion chamber are the direction of flows. In a DI engine, there are three things to consider: incoming airflow, fuel injected into the cylinder, and the exhaust gas residuals. Strauss [17] shows that wall impingement of the fuel spray is a major source of UHC. He also shows that near-nozzle geometry and especially the distance of the fuel cone from the cylinder wall are “critical” for optimal fuel spray development and mixture preparation. During homogeneous combustion, the geometry of the combustion chamber, piston, and ports need work together to aid in complete mixing of the fuel and air while keeping short-circuited fuel to a minimum. During stratified operation, a fuel rich condition needs to exist near the spark plug for combustion to occur.

Several design factors were investigated to improve the combustion chamber for direct-injection operation. The major design factors included:

- Location and angle of the injector
- Location of sparkplug
- Combustion chamber offset
- Squish area
- Compression ratio

To begin the design of the head, a solid model was created of the stock 600cc engine. The tall combustion chamber was used because of the narrow cone angle and the high exiting sheet velocity of the fuel [17]. This helps reduce the amount of fuel that can impinge on the piston surface, especially during stratified combustion. The injectors were angled 11° towards the intake ports to aid in mixture preparation and to reduce the amount of short-circuited fuel. The chamber was offset slightly towards the exhaust side to center the fuel cone in the cylinder to reduce wall impingement.

During both stratified and homogeneous operation, a fuel rich condition needs to occur near the spark plug. To accomplish this during stratified combustion, the spark plug needs to be located near the injected fuel. Also, it has been shown using CFD modeling of GDI two-strokes with combustion chambers similar to the UICSC design that, at the time of ignition during homogeneous injection, the richest air/fuel mixture tends to exist on the exhaust side of the chamber [21, 22]. Based on these requirements the spark plug was located on the exhaust side just below the injector. To aid in mixture preparation by increasing the swirl inside the cylinder, the squish area was increased by 22% over the stock squish area. Figure 3 shows the design of the UICSC GDI engine.

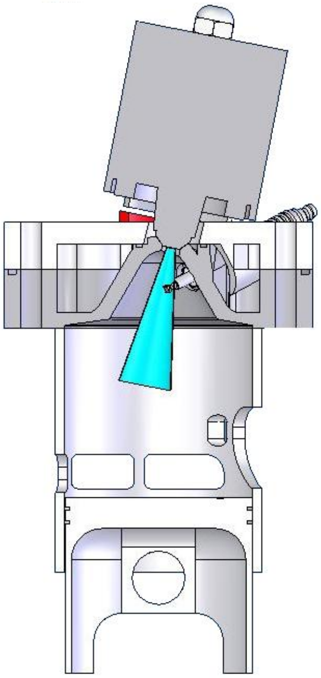

Figure 3: Solid model of one cylinder and head assembly.

The classifications for the combustion chamber are [16]:

- Narrow Spacing: Spark plug gap is located close to the injector tip.

- Spray-Guided: A narrow spacing concept where the stratification results from fuel spray penetration and mixing.
- Squish/Swirl Based: Both the squish area and swirling motion of the intake ports are used to assist in charge stratification.
- Centrally-Mounted: The injector is located near the center of the combustion chamber.

Another benefit with the E-Tec injection system is the relatively low fuel-supply pressure of 35-40psi (2.41-2.76 bar). Many GDI systems have fuel-supply pressures greater than 1700psi (120 bar) [22]. A low-pressure fuel pump can be used with an in-line regulator to route excess fuel, used to cool the injectors, back to the fuel tank.

The UI GDI engine uses the total-loss oil injection system found on the stock Polaris 600 engine. Oil for the engine is stored in an oil reservoir and pumped into the engine by the stock Polaris mechanical oil pump. Oil is also added to the fuel at a 100:1 ratio to reduce carbon build up on the injector nozzles and lubricate the top of the cylinder. In the future, the team would like to adapt an E-Tec style oil-injection system that has been shown to greatly reduce oil consumption [19].

The GDI head manufacturing was done in the University of Idaho Mechanical Engineering machine shop. Many of the pieces of the head were complex, requiring the expertise of an experienced machinist. A HAAS 4-axis CNC mill was used to make a majority of the parts. The machined head with the injector and coil assemblies is shown in figure 4. All of the design work was done in SolidWorks, and the models were converted to MasterCAM format to prepare the CNC code for machining.

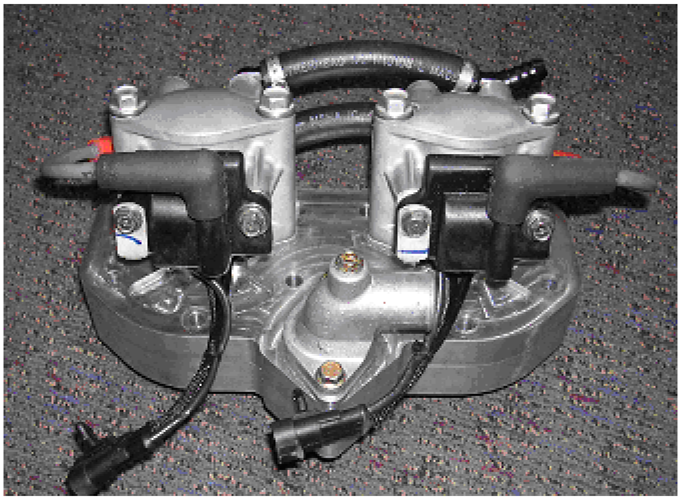

Figure 4: Completed UICSC GDI head with the injector/coil assemblies.

Exhaust after-treatment – Because the GDI engine was in development for most of the design year it was necessary to use proven exhaust aftertreatment methods to reach the low emissions goals. The limited operation time of the completed GDI engine made the addition of more complex systems such as secondary combustion or water cooling methods impractical. The selection of an oxidation catalyst provided an opportunity to design around the limitation of not having the necessary engine emissions data. Catalysts are a proven emissions reduction method that can be easily adapted to any engine. Using an oxidation catalyst allows the UHC and CO emissions to be targeted while a reduction catalyst can be used to target NO_x emissions.

The effectiveness of the oxidation catalyst is dependent upon the wash-coat selected, the substrate structure, and the catalyst location. The wash-coat selected was a sulfur resistant alumina catalyst. This is a composition particular to two-stroke applications. A metallic substrate was chosen over a ceramic substrate to provide more durability [18].

The catalyst is constructed with two sections of an oversized substrate measuring 3.875-inch diameter by 3.5-inch length (9.84 cm x 8.9 cm)). The larger size ensures a long lifetime and high activation levels. The catalyst substrate was solidly loaded into a custom structure fitted to the stock exhaust system.

The UICSC team decided to integrate the catalyst and exhaust pipe to conserve under-hood space. The 2004 design consisted of adding the catalyst body onto the end of the stock pipe, effectively increasing the length of the stinger and the tuning characteristics of the pipe. The 2005 design replaced the end of the pipe and stinger with the catalyst body at a point where the diameter of the pipe and catalyst are closely matched. With this new design, the length and diameter of the catalyst and stinger combination resembled the stock stinger, ensuring the stock tuning characteristics would remain intact. In addition, the location of the catalyst promotes maximum exhaust temperatures to ensure continuous emission conversion.

The selection of engine lubricant played a vital role in catalyst operation and life expectancy. McCullough has shown that lubrication oils with minimal levels of sulfur, calcium, and phosphorus should be strictly used in two-stroke catalyst applications [19]. The total loss oil system used by the GDI engine provided a threat to the operation of the catalyst. Unburned oil base-stock and additives can cause catalyst poisoning through losses in micro-porosity or sulfur layering [19]. Additionally, under conditions of light loading and low temperatures, a major concern was that heavy oil oxidation might cause localized thermal deactivation. To prevent these effects, the UICSC team used Bombardier XD100 two-stroke oil, which has been designed to provide maximum burning in the combustion chamber, limiting the amount of oil that can reach the catalyst [20].

NOISE REDUCTION - The noise event at the competition measured sound pressure weighted against the A-scale. The A-scale mimics the threshold of human hearing, which is approximately 2 KHz to 20 KHz [11]. For the UICSC snowmobile to be competitive in the noise event, the team needed to address the entire range of noise. There are three sources of noise in a snowmobile: air intake noise, engine exhaust noise, and mechanical noise emitted from the engine, drive system and track. To effectively reduce the overall noise of a snowmobile all three of these sources must be addressed.

In order to focus noise elimination efforts the UICSC team performed pass-by sound measurement tests on the snowmobile. In past Clean Snowmobile Competitions, noise testing standard SAE J192 was used to test the noise level of competing snowmobiles. Tests performed at the University of Idaho followed this standard with some modifications due to equipment limitations and experimental goals.

Test runs were performed in both directions along the track. Maximum sound levels were recorded for both the clutch and exhaust sides of the snowmobile at full throttle acceleration, constant 30 mph (48 kmh) , and constant 40 mph (65 kmh) runs. A second set of passes were performed with the addition of sound damping materials to the engine compartment. Due to a lack of snow in the Moscow, Idaho area the tests were performed in a field, and are not quantitatively representative of results to be expected in snow. Results of these tests are shown in Figure 5.

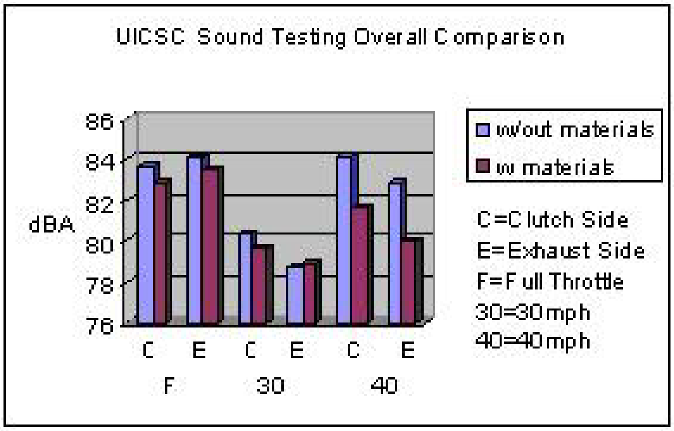

Figure 5: Comparisons of average sound output of stock and sound damped engine compartments.

It was concluded from the noise tests that the sound damping materials being used were effective in reducing noise output. In addition, the clutch side of the UICSC snowmobile was shown to be louder than the exhaust side under constant speed.

Based on the test results, the decision was made to focus damping efforts on three areas: mechanical noise emitted from the engine compartment, intake, and exhaust. By focusing on trapping noise inside the engine compartment, all causes of noise but the track and the exhaust are targeted.

Intake and exhaust noise - High pressure pulses are created in the intake and exhaust ducting of a crankcase scavenged two-stroke engine when the piston opens the ports in the engine. These pressure pulses travel through the exhaust and intake ducting at the local speed of sound until a change in area is encountered, where the waves are reflected. A reduction in area reflects a positive pressure pulse back towards the source while an increase in area reflects a negative pressure pulse back towards the source. By developing a system that can take advantage of this phenomenon, the sound pressure energy can be used to cancel itself out over a wide frequency range [11].

In the case of the intake system, it is common for stock snowmobiles to be equipped with baffled air-boxes designed specifically for the sound frequencies emanating from the intake system. In order to address the noise from the intake system, the interior of the air-box was lined with a dense sound absorbing material. This increases the level of acoustical energy required to make the box resonate, limiting the noise that can pass through [11].

To decrease the noise coming from the exhaust a new muffler was incorporated consisting of a spiral passage of constant cross sectional area. The spiral passage is partially lined with sound absorbing stainless steel wool and bleed holes that allow gases to pass between the passages. “Sound waves travel in straight-line paths at a speed much higher than the speed of exhaust gases passing through the silencer and therefore are continually bounced off the smooth wool covered wall where they are diffused [21].” Sound waves may also pass through the bleed holes and sound is attenuated by wave cancellation as the gasses move through the spiral.

Mechanical noise - Noise can escape from the engine compartment in two ways. One is through vibrations in the belly pan, chassis, and hood. The other is direct emission from the exhaust pipe or vents in the engine compartment.

Absorption and redirection were the two methods used to reduce emission of noise through body vibration. In the case of absorption, two materials were chosen to be installed in the engine compartment. In the belly-pan, a cotton composite material was installed over the top of a vibration-absorbing layer. On the underside of the hood, a sound damping insulation commonly found in the engine compartments of boats was installed. Also, a seal was added in-between the hood and belly pan in order to eliminate passage of sound through the hood seam.

All but the vents necessary for sufficient heat transfer and air delivery to the engine were closed off in an attempt to limit direct noise emission from the engine compartment. Silencers were designed for the outflow vents that remained open. The goal of these silencers is to absorb sound passing out of the vent and redirect the excess sound back into the engine compartment. The silencers are made out of sheet aluminum and layered with the vibration absorbing material. The semi-circle is packed with the cotton composite material.

An additional material used to reduce mechanical noise was a dense spray on pickup bed liner. It was applied to all large metal surfaces to prevent them from resonating, Figure 6. The bed liner material is 1/4 inch (.65 cm) thick and added approximately 8 lbs. (3.63 kg) to the snowmobile.

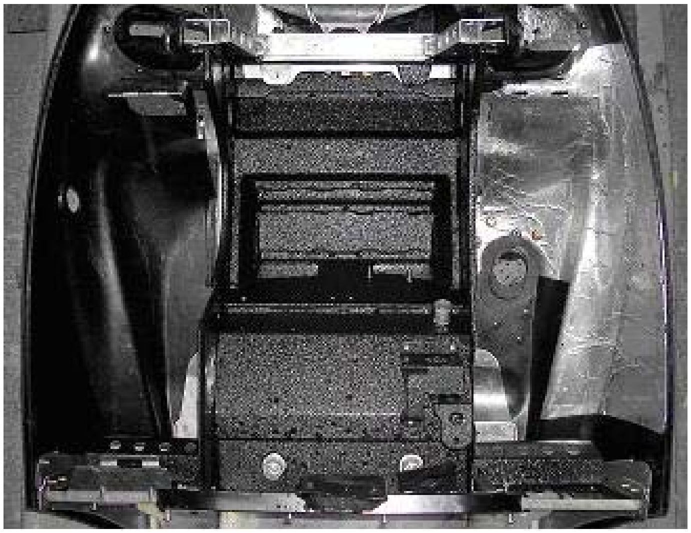

Figure 6: Spray-on liner applied to the bulkhead and underside of the tunnel used to absorb mechanical sound energy transferred through the chassis.

To gain the most benefit from the sound insulation in the engine compartment a Lexan™ hood was used. The hood is completely sealed, allowing more sound insulating material to be applied as well as eliminating openings in the hood that allow sound to escape. The Lexan™ hood is also significantly lighter than its plastic counterpart. An added feature of this hood was that it was slightly taller than the stock hood, giving more room for the exhaust system. The Lexan™ hood is shown in Figure 7.

CHASSIS MODIFICATIONS - Several changes were made to the chassis to improve the efficiency of the snowmobile. A Radical Machines Industries (RMI) gear drive system was installed to address under-hood space issues and improve power transmission from the engine to the track. A 2.26 gear ratio was chosen to replicate the stock gear ratio found in the existing chain drive. Ground gears were used to reduce the amount of sound emission. The addition of the RMI reduced the overall weight of the drive system and eliminated components found in restrictive areas such as the silencer and air-box. The stock Hyfax was replaced with Teflon impregnated Hyperfax to decrease the friction between the track and the slides of the suspension. Aluminum spindles were used to decrease the weight of the snowmobile. Larger bogey wheels were used at the rear of the track to reduce the track bend and alleviate friction.

Figure 7: The Lexan™ hood used on the UICSC snowmobile.

COMFORT AND SAFETY - Since this snowmobile was designed for touring use, comfort, ease of operation, safety and reliability are primary design goals. These goals were accomplished with an ergonomically superior chassis and several design strategies. The forward rider position reduces rider fatigue and improves the drivability of the snowmobile. As with most snowmobiles, this design includes hand-warmers and a thumb warmer on the throttle.

There are several other features included to improve the safety and reliability of the snowmobile. For safety, two methods can be used to stop the engine. The rider can use the switch mounted on the handlebars. Additionally, if the rider falls from the machine, a tether switch connected to the rider will automatically stop the engine. Another added safety feature is the addition of a clutch cover that extends to the centerline of the clutches. The clutch cover has woven belting riveted to the underside of the guard to protect the rider in the unlikely event of clutch failure.

COST - The cost of producing this snowmobile would be very similar to that of the current two-stroke touring snowmobiles. The only components that increased the cost of manufacture are the high-pressure injectors, exhaust catalyst, and the sound insulating materials. After comparing the Technology Implementation Cost Assessments (TICA) for both the Bombardier Ski-Doo 2-Tec GSX Sport 600 H.O. SDI and the UICSC GDI snowmobile it was found that the added manufacturer's cost for implementing the technologies found in the UICSC snowmobile is only $563 over the control snowmobile. The catalyst is 70% of the increase in cost. The snowmobile's final design is shown in Figure 8.

TESTING AND RESULTS - Testing is required to determine the improvement a new design over an existing design. For the UICSC GDI snowmobile to be considered a success it needed to have better fuel economy, improved emissions, and reduced noise levels.

Noise - The pass-by sound testing performed, described earlier, showed that the sound insulating materials and the sealed hood reduced the sound level of the snowmobile. Based on previous use of the spiral silencer on the championship UICSC snowmobiles the team is confident that the silencer will also reduce engine noise.

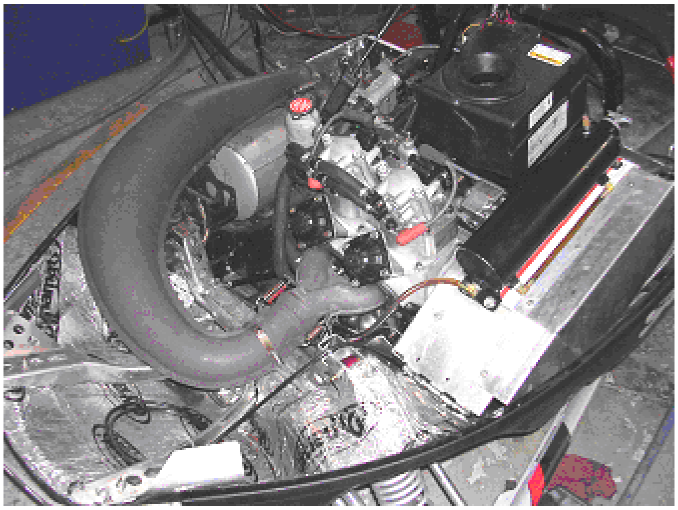

Figure 8: Final design of the UICSC GDI snowmobile.

Engine power and emissions - Before the competition, the team conducted five-mode emissions tests for the stock carbureted engine, and the UICSC GDI engine with no catalyst. The five-mode test was based on the same procedure used at the CSC competition [5]. The map created for the GDI engine was not refined completely before these experiments were performed. The tests were aimed to provide information for selecting catalyst materials and to provide a direction for future engine tuning. The results show a significant reduction (50-90%) in UHC +NO$_x$ at all five mode points. The CO emissions were reduced 30-80% at all mode points except mode four. Figures 9 and 10 present the HC + NO$_x$, and CO results for each engine.

Figure 11 presents the percent fuel reduction of the UICSC GDI engine compared with the stock carbureted two-stroke engine. The UI engine required 50-75% less fuel except at mode four. Based on these results, it was expected that the UI direct-injected two-stroke engine will improve fuel economy by 30-50% over the stock engine.

Figure 12 shows the power output for each engine.

These results show that the engine was short-circuiting less fuel but operating with a rich air/fuel mixture, especially in modes three and four. This initial testing showed the team where to focus engine tuning.

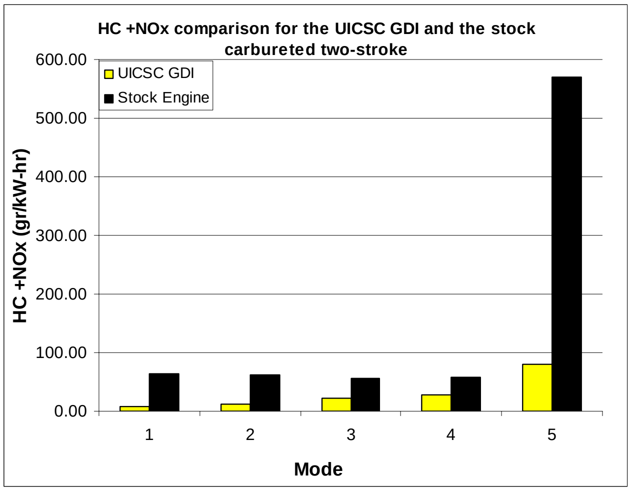

Figure 9: Five-mode HC + NO$_x$ emissions for the UICSC GDI and stock engine.

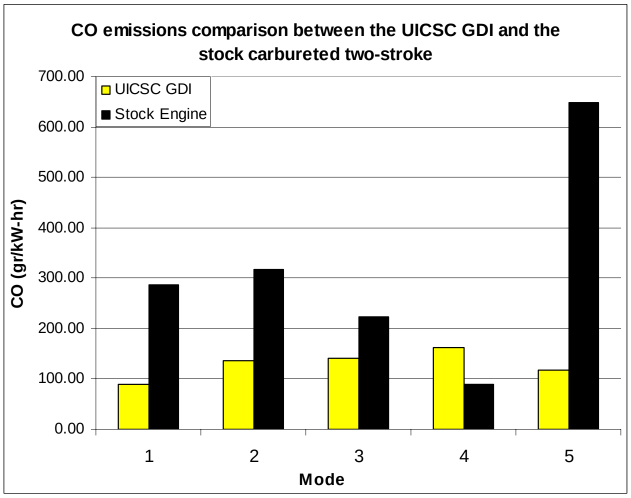

Figure 10: Five-mode CO emissions for the UICSC GDI and stock engine

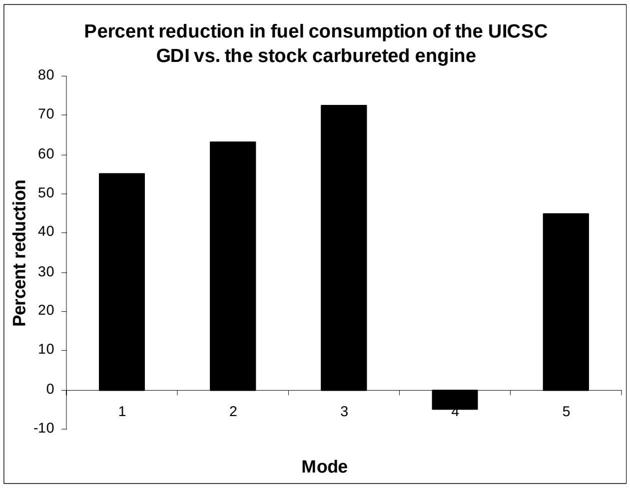

Figure 11: Five-mode percent reduction in fuel consumption of the UICSC GDI compared to the stock engine.

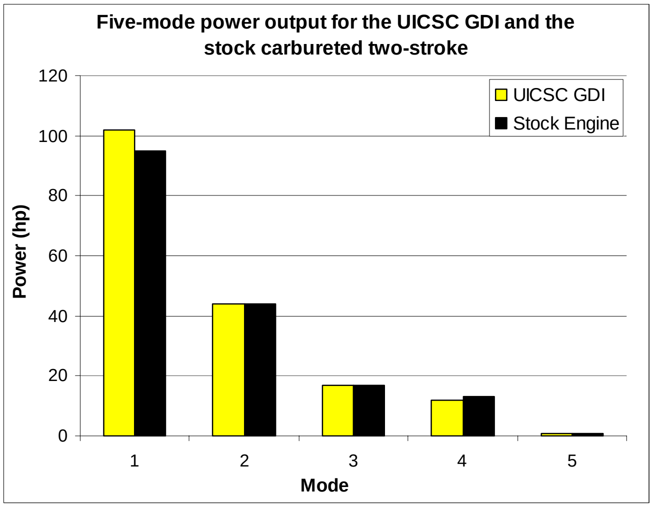

Figure 12: Five-mode power out put of the UICSC GDI engine and the stock engine.

As engine testing continued, the team found that the engine was experiencing excessive detonation and was unstable at the rpm locations where the power-valves were opening. After several attempts of re-calibrating fuel delivery, the team decided that the problems were associated with too much turbulence. This engine already has very aggressive port timing that creates turbulence in the combustion chamber. It was thought that increasing the squish area and the compression ratio over the stock head lead to this problem. A second head was made, using the same injector/spark plug arrangement that had a reduced compression ratio and reduced squish area. Testing of that engine will provide the needed information to evaluate the new head design.

CONCLUSION

The University of Idaho has developed a cost-effective direct-injection two-stroke snowmobile engine that does not require an external high-pressure fuel pump or air pump. The incorporation of the E-Tec injectors and power system has provided the means to create a working GDI two-stroke engine without the need of a battery. This design provides empirical evidence that a GDI system can produce stock power while significantly reducing pollution and sound emissions and decreasing fuel consumption. Further engine tuning and the addition of the catalytic converter should further decrease the emissions output. In addition, the University of Idaho GDI two-stroke maintains the power, handling, mechanical simplicity and low weight riders enjoy.

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