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# University of Idaho's Clean Snowmobile Design Using a Direct-Injection Two-Stroke Engine

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## ABSTRACT

The University of Idaho's entry into the 2007 SAE Clean Snowmobile Challenge (CSC) was a third-generation gasoline direct-injection (GDI) two-stroke powered snowmobile. The modulated and battery-less direct-injection system used to decrease exhaust emissions and improve fuel economy did not reduce the power output of the engine. The emissions output was further reduced by using a reduction catalyst located in the exhaust silencer. Noise from the engine compartment was reduced by using sound absorbing materials and a sealed hood. Pre-competition testing had the snowmobile entering the 2007 SAE CSC competition weighing 550 lbs (250 kg) wet, achieving 20 mpg (8.5 km/L) on lightly groomed trails with a pre-catalyst EPA five-mode emissions score of 158, 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), and the Department of Energy (DOE) supported the effort to begin the CSC in 2000.

DESIGN GOALS - The first goal for the competition was <u>to reduce exhaust emissions. The primary emphasis is</u> on reducing carbon monoxide (CO) and unburned hydrocarbons (UHC) without increasing the already low emission of oxides of nitrogen ($NO_x$) of traditional two-stroke snowmobile engines. Scoring was based on the 2012 EPA snowmobile standards using the weighted five-mode testing procedure as published by SwRI [1]. The SwRI five-mode test weights emissions of CO and UHC+$NO_x$ at engine speed and load points indicative of snowmobile operation [2]. 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 sled emission number E [3]. 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.

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

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While the EPA will require a standard of 100, the NPS requires 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 [4].

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 is based on the SAE J192 pass-by sound pressure testing procedure [5]. 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 J192 test, the team received 150 points and was then eligible to receive more points in the subjective noise test. The subjective test used the recordings of the J192 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 is 100 mi (161 km). Each snowmobile had to complete the endurance event while following a trail judge [1]. 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 as well as 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 [1]. 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 a slalom course. The fastest team through the slalom 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.

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 2007 University of Idaho Clean Snowmobile Challenge (UICSC) Team began designing a clean and quiet snowmobile.

## UICSC SNOWMOBILE DESIGN

CHASSIS SELECTION – The UICSC team chose to use a 2006 Ski-Doo MXz Chassis. It is a lightweight chassis with good handling characteristics and comfortable rider positioning. The chassis easily accepted our engine selection.

ENGINE SELECTION – It has been proven in past CSC competitions that four-stroke engines can be used in snowmobile designs to produce fuel-efficient, clean, and quiet snowmobiles [6, 7, 8, 9, 10]. The University of Idaho's 2002 and 2003 entries placed first at CSC with a BMW EFI four-stroke engine. Four-stroke powered snowmobiles have continued to place at the top of the competition every year. However, avid snowmobile riders still prefer the lighter and more powerful two-stroke engine. Two-stroke engines have traditionally been less fuel-efficient and have had poor exhaust emissions. This is due to the method used to introduce fuel to the engine, carburetors or throttle-body fuel injection.

With recent 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 [9]. However, the SDI two-stroke engines still have poor emissions compared to four-stroke engines. Results from the control snowmobile used at several CSC competitions, shown in Table 2, clearly show 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 [7, 8, 9].

| 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. 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. It is the lightweight design and improved fuel delivery system that allows SDI two-stroke engines to have good fuel economy and better performance characteristics. Table 3 compares weight, engine size, and power output of several different snowmobiles.

**Table 3:** Comparison between competition two-stroke and four-stroke snowmobile engine displacement, power, and weight. Data from competition results.

| University and Engine Type | Engine size [cc] | Engine power [hp,kW] | Weight [lb,kg] | Power-to-weight [hp/lb,kW/kg] |
|---|---|---|---|---|
| 2007 Idaho<br>2-Stroke DI | 593 | 108/80 | 550/250 | 0.20/0.31 |
| 2006 U. Wisconsin Platteville<br>2-Stroke SDI | 593 | 101/75 | 674/306 | 0.15/0.24 |
| 2006 U. Minnesota Duluth<br>4-Stroke EFI Turbo | 750 | 88/66 | 707/321 | 0.12/0.20 |
| 2006 U. Wisconsin Madison<br>4-Stroke EFI | 750 | 51/38 | 654/256 | 0.08/0.15 |

It is evident 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 [2].

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 constraint is that any method used to increase fuel economy and reduce emissions cannot 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 for modification by the UICSC team was a carbureted, 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. 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 [1].

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 [12].

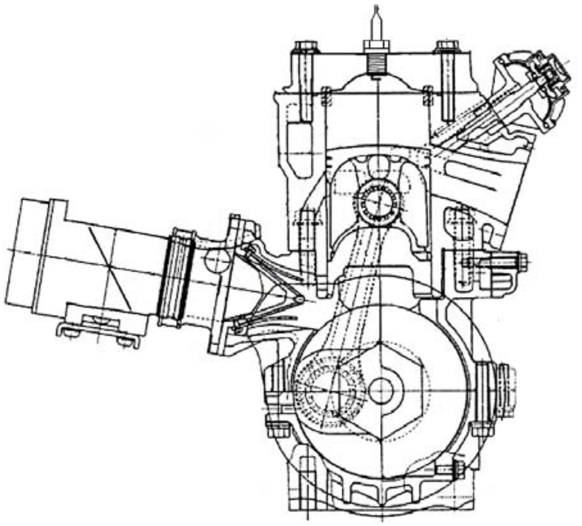


**Figure 1:** Cross section of a two-stroke engine similar to the one used for the UICSC engine [11].

Stone [13] 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% [13, 14, 15].

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 [14]. 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 operated fuel rich to produce maximum power and to cool the piston to prevent seizure [14]. 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 SDI 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 [12]. 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 [14]. Nitrogen oxide formation depends on two basic factors: (1) peak temperatures reached during combustion, and (2) oxygen content in the trapped mixture [14]. 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 [16]. One goal for new two-stroke technologies is to maintain the low $NO_x$ emissions.

DIRECT INJECTION SELECTION – 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. It lessens the effects of charge and exhaust-gas mixing, significantly reduces short-circuiting, and offers precise air/fuel ratio control. It is also known to improve cold start reliability [17]. Additionally, two different modes of combustion can be used for GDI engines: stratified and homogeneous.

Stratified combustion in a two-stroke GDI is achieved when fuel injection occurs late in the cycle and ignition is delayed from the start of injection until there is a fuel rich mixture surrounding the spark plug. The rich condition occurring at the onset of combustion provides a reaction rate high enough to initiate combustion [17]. The flame front occurs at the interface between the fuel and oxidant, moving out from the spark plug gap burning the ever-leaner mixture until combustion can no longer be sustained [18]. Stratified combustion eliminates poor idle quality and poor low load operation [17]. Strauss [19] suggests using stratified charge combustion during idle and light load operation.

A GDI system can also create a homogeneously charged combustion chamber. For the GDI engine, homogeneous operation is accomplished when fuel is injected early in the cycle so there is time for the fuel to completely atomize and mix with the freshly scavenged air. Homogeneous combustion is used for medium to high loads and is accomplished two ways. The first is during medium loads. The fuel is injected early and an overall trapped lean air/fuel ratio with some EGR is desired to limit heat release [13]. The second is used during high loads, where the goal is to maximize air utilization and to operate the engine with a stoichiometric or slightly rich condition to maximize power [13]. The timing of the fuel injection, while much earlier than stratified injection, must be late enough to avoid any fuel from becoming involved with the scavenging flows to avoid short-circuiting fuel [20]. Figure 2 shows the difference between in-cylinder equivalence ratios (λ), ratio of actual air/fuel to the stoichiometric air/fuel ratio, for a stratified and homogeneously charged engine.

Two-stroke GDI engines exist in the marine outboard industry where they have been shown to have UHC+$NO_x$ emissions similar to four-stroke engines while having less CO emissions [17]. Although GDI has been successful in the marine industry, many obstacles need to be overcome for a GDI system to be successful in a snowmobile application. The main reason why GDI systems have not appeared on snowmobile engines is their high-performance nature. Snowmobile two-stroke engines operate at significantly higher engine speeds with greater fuel demands. They operate at speeds in excess of 8000 rpm with specific power outputs of nearly 150 kW/liter, compared to marine engines with rated engine speeds around 6000 rpm and specific power outputs of just 70 kW/liter. At peak loads, a short period of time (< 4 ms) exists where a large amount of fuel must be injected and fully atomized without being short-circuited.

Large peak-load fuel requirements pose a challenge for low load and idle fuel requirements. An injector nozzle designed to deliver high quantities of fuel quickly usually has poor light-load and idle fuel-spray qualities [17]. A two-stroke GDI at full power can use in excess of 40 kg/hr of fuel while at idle only needs 0.6 kg/hr, leading to the difficult task of designing a precision nozzle capable delivering high flow rates and precise fuel metering.

The shape of the combustion chamber also needs to be changed significantly. It needs to be designed to provide efficient combustion while ensuring a combustible mixture occurs near the spark plug during ignition. Additionally, it is recommended that the engine have a multiple spark discharge or long duration spark system to ensure a spark event occurs when a rich mixture is near the spark plug during stratified operation [19].

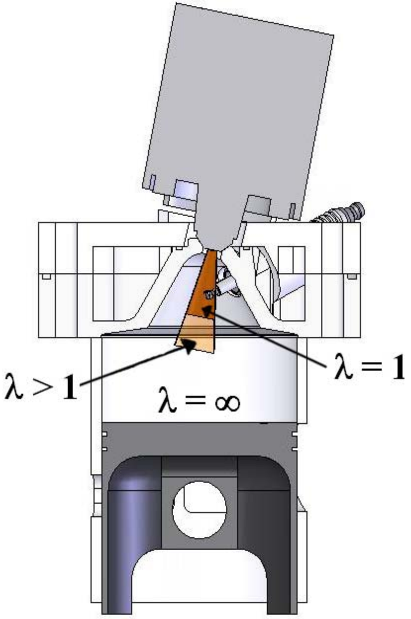
UICSC GDI design – For 2007, the UICSC team continued to use the E-TEC DI system but changed engine platforms from a Polaris Liberty 600 to a Rotax 593. System adaptation to the Rotax engine was the same as the adaptation to the Polaris engine. The requirements for adaptation and benefits of the E-TEC system can be found in the 2006 Idaho CSC Design Paper [21].

Combustion chamber design - While simpler than its four-stroke counterpart, a GDI head is more complex than a standard two-stroke head. It needs to be designed around the fuel-spray characteristics and the in-cylinder fluid motion. The E-TEC injectors have a fuel spray with a narrow cone angle, high exiting sheet velocities, relatively large droplet size, and deep penetration [17, 22].

A study of a GDI engine similar the UICSC engine considered two-different fuel cones, their locations, and their targeting [11]. This research found that an injector with a narrow-cone, deeper penetration, and larger fuel droplets aimed at the intake ports had reduced CO formation when compared to a centrally mounted, wide-angle, and small-droplet injector. Figure 3 shows the two fuel-injector targeting scenarios investigated with injector targeting location "B" considered better. It is suspected that the larger droplets of injector "B", which have greater momentum, were better able to resist the scavenging flows.

**Stratified Charge**

Late Injection: 70-30° BTDC



**Homogeneous Charge**

Early Injection: 230-120°

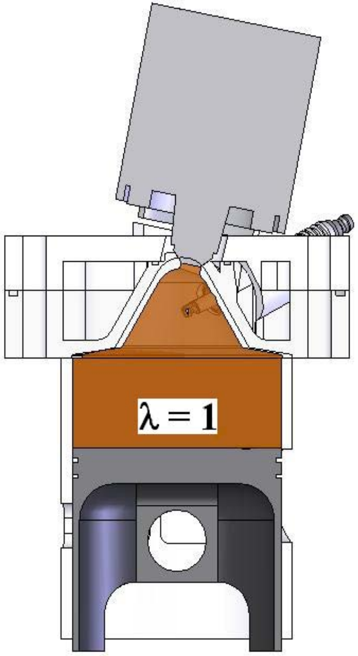


**Figure 2:** The equivalence ratios and charge stratification for stratified and homogeneous combustion.

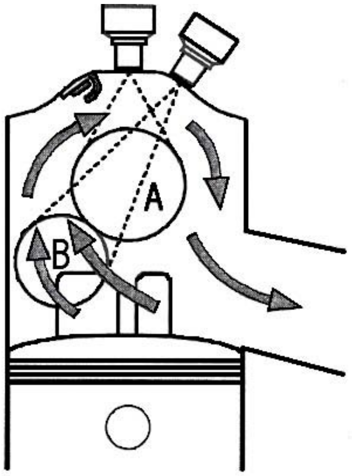


**Figure 3:** Two different fuel-spray targeting strategies for a loop-scavenged HPDI engine [11].

Another study, based on the E-TEC injectors, offered more insight into injector targeting, droplet size, and UHC emissions [22]. This study showed that in-cylinder mixture distribution is largely driven by the momentum exchange between the fuel spray and the scavenging flows. The study showed that larger droplets are less affected by airflows than smaller droplets. A snowmobile two-stroke engine has very aggressive port geometry that causes intense scavenging flows during high loads. For this reason, an injector with larger droplets targeted deep into the cylinder can provide good mixture preparation without excessive UHC emissions for homogeneous combustion.

Strauss [19] shows that wall impingement of the fuel spray is a major source of UHC emissions. 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 to 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.

With these factors in mind, the GDI head was modeled using the bolt pattern and coolant passage patterns from the baseline head. The 2007 combustion chamber geometry was designed to promote stratified operation and even fuel mixing. Near injector nozzle geometry was improved by using a larger dome radius and chamfer at the injector nozzle location. In-cylinder flow characteristics were improved by the increase in dome and squish radii. The injector angle was reduced to centralize the fuel spray in the chamber for improved high load operation. Angling the injector toward the intake aids in mixture preparation and reduces the amount of short-circuited fuel during homogeneous operation. The chamber was centered in the cylinder to reduce wall impingement and improve stratified operation. The UICSC GDI head also allows for the use of Kistler 6052C pressure transducers to obtain in-cylinder pressure data. These data were used to tune for run quality and monitor detonation. They can also be used for optimization of spark timing during stratified operation. Figure 4 is a cross-section of the UI GDI combustion chamber.

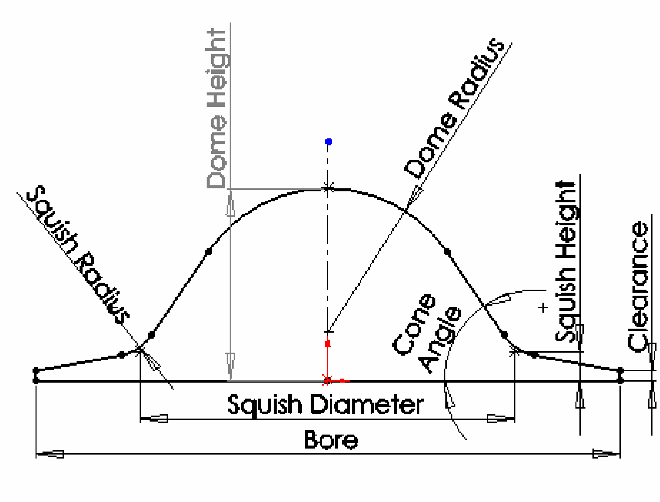


**Figure 4:** Combustion chamber cross-section for the 2007 UICSC GDI engine.

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 protrude into the fuel spray. In addition, CFD modeling has shown that at the time of ignition during homogeneous injection, the richest air/fuel mixture tends to exist on the exhaust side of the chamber [23, 24]. Based on these studies the spark plug was located on the exhaust side just below the injector. The squish area, squish height, and clearance were designed for proper mid to high load operation, which requires a squish velocity of 15 to 20 m/s [12].

The classifications for the combustion chamber are [17]:

- 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 Based: The squish area and motion induced by the intake ports are used to assist in charge stratification.
- Centrally-Mounted: The injector is located near the center of the combustion chamber.

The GDI head design, CNC coding, and manufacturing were done in the University of Idaho Mechanical Engineering Department machine shop. Students and graduate mentors performed all of the machining procedures aided by the mechanical engineering department's machinist. The machined head installed on the Rotax engine is shown in Figure 5.

**Figure 5:** Completed UICSC GDI head installed on the Rotax 600 H.O. engine.

Inductive Ignition System – An inductive ignition replaced the previous capacitive discharge ignition (CDI) to increase combustion robustness. An inductive ignition discharges energy continuously into the fuel-air mixture as opposed to the multiple strike strategy of a capacitive discharge system. As the fuel-air mixture passes through the spark gap, the continual supply of ignition energy aids in the initiation and development of a flame kernel into a fully developed flame capable of sustaining itself and growing. With the inductive ignition, the engine was able to run under a wider range of fuel quantities, thus allowing leaner calibrations, which further improved fuel economy, and reduced emissions without sacrificing run quality. This design is superior to a multiple spark plug system and decreases cost and complexity.

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 UI GDI engine uses a total-loss oil injection system from a stock Rotax two-stroke engine. This system eliminates premixing of oil and fuel and only delivers oil to bearing locations. Less oil is required in a GDI engine because the oil is not diluted by fuel in the crankcase. Oil consumption was reduced approximately 50% over traditional carbureted two-stroke engines.

Fuel delivery strategy – As stated earlier, the GDI engine can operate with a stratified or a homogeneous mixture. A homogeneous mixture is used when medium to maximum power is required while stratified combustion is used when reduced power is required. During the 2005 CSC competition the team only used stratified combustion during idle. For the 2006 design year, the team investigated the power requirements to propel a snowmobile on groomed trails at varying incline angles and speeds; this data is shown in Table 4. Through dynamometer testing, it was determined that stratified combustion could produce the required power for cruising conditions, as shown in Table 5, measured at an elevation of 2600 ft. [21]

**Table 4:** Predicted power requirements for the UICSC snowmobile to travel 45 mi/hr on various inclines.

| Incline [deg] | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| Power [hp] | 18 | 19 | 21 | 22 | 23 | 25 |

**Table 5:** Measured stratified power and percent change in BSFC at various engine speeds.

| Engine Speed [rpm] | 4000 | 4500 | 5000 | 5500 |
|---|---|---|---|---|
| Power [hp] | 13 | 15 | 18 | 23 |
| BSFC % Change | 4 | 10 | 6 | -1.7 |

For 2007, a more detailed approach to stratified engine calibration was used in order to verify which mode of combustion was better for the cruise points of the engine map. An engine being developed in parallel to the Rotax engine was first calibrated for homogeneous combustion throughout the cruise range and then re-calibrated for stratified operation. During both calibration procedures, brake specific fuel consumption (BSFC) was recorded so a direct comparison between the two could be made. These tests confirmed that stratified combustion could meet the power requirements for cruising, however, homogeneous combustion resulted in lower BSFC values. Table 5 also shows the percent difference in BSFC values between homogeneous and stratified combustion for the engine speeds and power outputs. A positive number represents an increase in BSFC while a negative value is a decrease. Although there was a slight improvement at 5500 rpm, it was decided to pursue a homogeneous calibration strategy for the cruise points.

WEIGHT REDUCTION – In keeping with the two-stroke performance tradition, the 2007 UICSC team further reduced the weight of the base snowmobile, improving its already high power-to-weight ratio. Suspension performance, handling, and fuel economy were also improved by this weight reduction. The weight reduction was accomplished through the replacement of several components.

Suspension weight was reduced with the use of donated carbon fiber reinforced polymer (CFRP) upper and lower A-arms, Fox Float air shocks, Slydog skis, aluminum runners and sway bar elimination. These component replacements reduced suspension weight by approximately seventeen pounds. 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 reductions include fastener length reduction, unused bracket elimination and headlight replacement. All of these weight reductions allowed for addition of sound deadening material with no weight increase over the base snowmobile.

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 [12]. Figure 6 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.

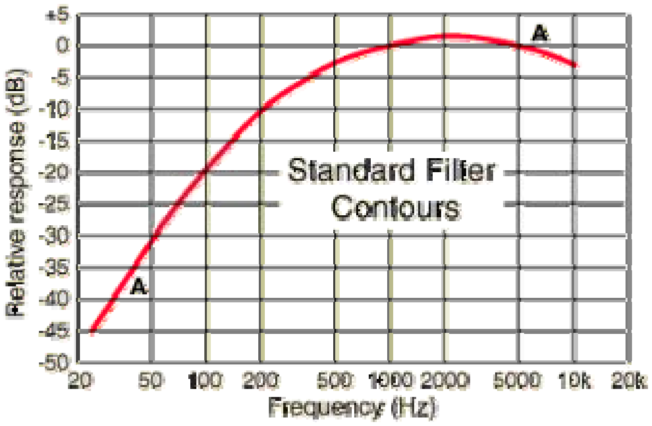


**Figure 6:** The A contour is more sensitive to sounds occurring between 1 and 5 kHz [25].

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 Testing – In the past several years, the UICSC team has failed to meet the sound test criteria for competition. This year sound reduction was a major focus for the UICSC team. Extensive testing was performed to determine the performance of sound reduction methods and all tests were performed in accordance with SAE procedure J192.

Several baseline measurements were taken with the chassis in stock configuration. This testing resulted in an average baseline value of 85 dBA. Figure 7 shows the sound magnitude over a frequency range for the baseline setup. The performance of each sound reduction method was quantified by comparison of the SAE J192 scores. Figure 8 shows this comparison for several sound reduction methods.

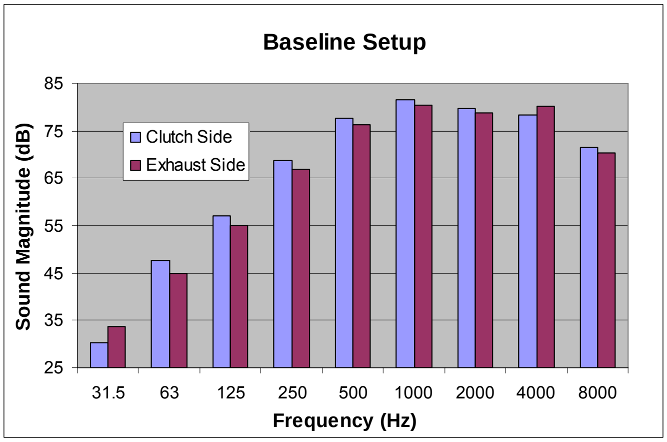


**Figure 7:** Sound magnitude at different frequencies for the baseline setup.

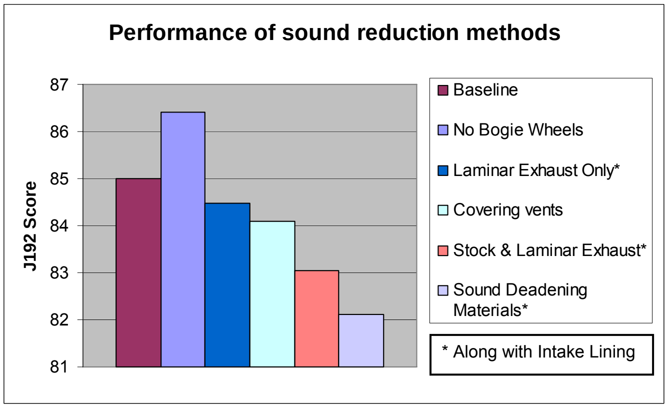


**Figure 8:** Performance of several sound reduction methods.

Mechanical Noise – In the engine compartment, there are several sources of mechanical noise. These include the clutches, chain drive, and the engine. 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 panels.

Absorption and redirection were the two methods used to reduce emission of noise through body vibration. Many noise-eliminating materials are found in the car audio industry. In past years, the UICSC team found that the best materials were cotton composite and lead impregnated foam. This year the use of lead impregnated foam was limited in order to reduce the snowmobile's weight.

Cotton composite, lead impregnated foam, and an automotive reflective material, were used everywhere in the chassis where clearances would allow. In the belly-pan and on any open metal surface, a vibration-absorbing layer was installed.

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.

Track Noise – Unlike noise in the engine compartment, the track noise cannot be absorbed or redirected only reduced. There are many different methods to reduce noise from the track. The UICSC snowmobile uses two industry proven methods to reduce track noise. One method is staggering the bogie wheels on the skid, which reduces track noise by preventing two bogie wheels from hitting the track's internal fiberglass rods at the same time. The other sound reduction is with a commercially available "bump track" which reduces the severity of the track's internal fiberglass rod bumps by providing a smooth transition.

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. This year the focus was on reducing noise with minimum air restriction. To do this, the intake system was lined with high-density foam suited to the tight corners of the intake system interior. The high-density foam served as a sound absorber instead of sound reflector. Testing showed reduced sound levels over a wide frequency range compared to the previous design that focused on a very narrow frequency band.

Exhaust Noise - The exhaust system on the UICSC snowmobile consists of a stock tuned exhaust pipe and muffler along with a catalytic converter designed for the emissions of the GDI two-stroke. The catalyst is a 3 by 3 inch (76.2 by 76.2 mm) cylinder with a high flow honeycomb substrate donated by Aristo. The catalyst is located in the stock exit location of the muffler for packaging and heat dissipation purposes.

A laminar flow muffler [12] was designed and built to attenuate the peak driving frequency of the engine. The laminar flow muffler functioned well individually, but when placed in series with the stock muffler, a high pitched whistle was produced that adversely affected overall sound results. In addition to the muffler design, outlet location was also evaluated. The exhaust was routed to the rear of the vehicle. Then the outlet was directed vertically up, down and into the tunnel area. No appreciable difference was measured in sound level as seen in Figure 9. Due to equipment malfunctions, no data was recorded for the exhaust outlet in tunnel on the clutch side of the snowmobile. It was determined that the stock muffler with an integrated catalyst was the best option for noise attenuation.

Final Approach – No one method adequately reduced noise so a combination of several methods was implemented in the final sound reduction approach. Sound deadening material, hood scoops, intake lining, bump track, and staggered bogie wheels were all implemented to reduce noise levels. Implementation of all of these methods yielded an average score of 80 dBA using the SAE procedure J192. Further testing continues in an attempt to reduce the sound level below 78 dBA.

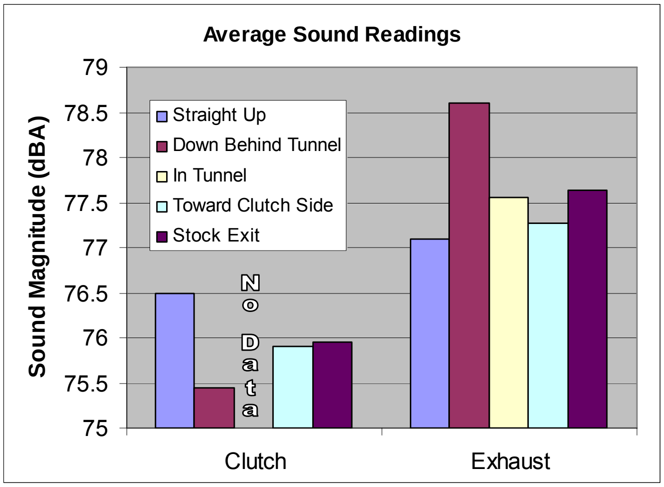


**Figure 9:** Comparison of sound levels with various exit locations and reduced engine speed.

COMFORT AND SAFETY - This snowmobile was designed for touring use; comfort, ease of operation, safety and reliability were the primary design goals. These goals were accomplished with an ergonomically superior chassis and several design strategies. 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. 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 belting extending to the centerline of the clutches. This will protect the rider in the unlikely event of clutch failure.

COST - The cost of producing this snowmobile would be very similar to that of current two-stroke touring snowmobiles. The base price for a stock carbureted Ski-Doo MX-Z 600 is $7,999. With all modifications included, the Manufacturers Suggested Retail Price (MSRP) totaled $8958. This includes the price of donated chassis components totaling $635. Chassis components add to the MSRP, which is justified by weight reduction, increased performance, and sponsor product awareness. The engine modifications total $323, which includes the injectors, fuel pump, throttle bodies, cylinder head, and catalyst. The final design is shown in Figure 10.

TESTING AND RESULTS - Testing is required to determine the improvement of a new design over an existing design. To verify that the 2007 UICSC snowmobile is better than previous designs, on-snow testing totaled over 300 miles. This was completed to verify improvements in fuel economy, emissions, reliability, and noise levels. In the previous sections, results of noise testing were presented, showing the effectiveness of noise emissions reduction.

**Figure 10:** Final design of the UICSC GDI snowmobile.

Calibration Strategy - In past years, the use of a Lambda sensor during engine calibration was ignored. This was due to the thought that a GDI two stroke would operate with excess air in the exhaust system, which results in false lean readings. This year it was decided to tune with a Lambda sensor and although not completely accurate, it served as a rich/lean indicator and greatly reduced the time needed to create a full engine map. Once the engine map was complete, calibration time could be spent on mode points and transitions from stratified to homogeneous combustion. 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.

Engine emissions – The emissions data provided are with no catalyst in the exhaust system and with 87 octane non-ethanol fuel. For these data, peak power output was 108 hp (80 kW) at 8000 rpm. On the five-mode EPA emission test, the UICSC GDI two-stroke engine scored a 158 with an UHC+$NO_x$ of 30.3 g/kW-hr and CO of 127 g/kW-hr, which passes the 2012 EPA score. Figures 11 and 12 compare the mode point UHC and CO emissions (respectively) of the UICSC GDI engine to the 2005 CSC Ski-Doo 600cc SDI Control Vehicle. The numbers reported are the weighted mode point values and highlight the advantages of the direct injection system.

Final catalyst results were not available at the time this paper was written. The catalyst should further reduce UHC and CO emissions by 40-80 percent [25]. With this amount of reduction, the emission level approaches the NPS requirements.

The advantage the UICSC GDI two-stoke engine has in brake specific fuel consumption (BSFC) is illustrated in Figure 13. The BSFC is reduced as much as 30 percent compared with the other engines. The mode 5 point (idle) is the actual measured fuel quantity in kg/hr. The advantage of the UICSC engine at idle is 50-65 percent less fuel flow. Vehicle fuel consumption is further improved with a lightweight engine and chassis. Mode 4 is a difficult area (high BSFC) for the engine due to the throttled intake and mistuning of the pipe. These conditions cause large cycle-to-cycle variations, high EGR content, and fluctuations in power output. This can be improved with better control of the exhaust auxiliary ports. Mode 5 fuel consumption is greatly reduced compared to the other engines because of the ability to run stratified, only injecting the fuel necessary to turn the engine over at very late injection angles.

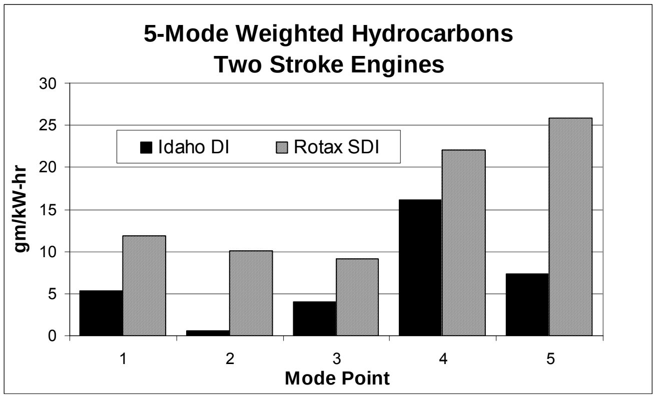


**Figure 11:** Five-mode HC + $NO_x$ emissions for the UICSC GDI vs. Rotax 2-Stroke SDI [9].

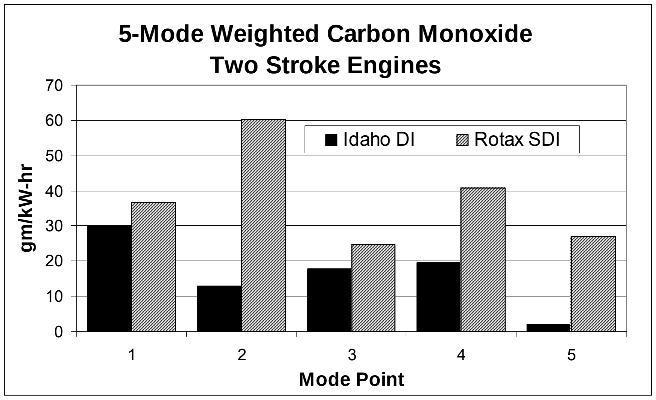


**Figure 12:** Five-mode CO emissions for the UICSC GDI vs. Rotax 2-Stroke SDI [9].

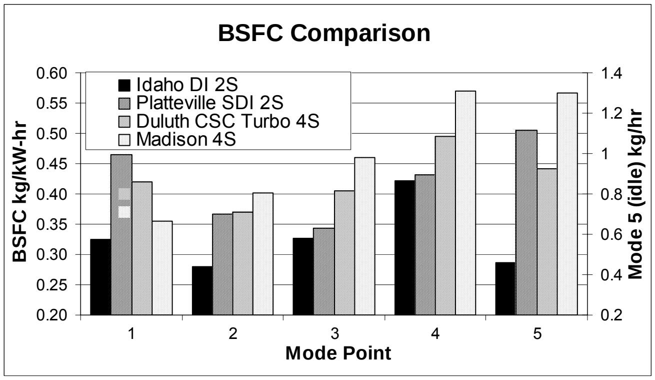


**Figure 13:** Five-mode BSFC comparison for the 2007 UICSC GDI vs. 2006 entries for Platteville with a 2-

stroke SDI, Duluth with a turbo four-stroke, and Madison with a four-stroke.

Engine power and fuel economy – During testing on groomed trails at an elevation of 4000 feet, the UICSC GDI achieved 20 mpg (8.5 km/L) at an average speed of 40 mph (64 km/hr). For comparison, a Yamaha carbureted two-stroke chase sled was recorded to have 9.5 mpg (4 km/L).

Figure 14 compares power output at full power for the 2007 UICSC GDI with 2006 entries for Platteville with a two-stroke SDI, Duluth with a turbo four-stroke, and Madison with a four-stroke powered snowmobile [10]. This graph shows the Idaho GDI is capable of retaining the power output of a SDI engine, and has more power than the naturally aspirated and turbo-charged 750cc engines found in the Polaris FS and FST, respectively.

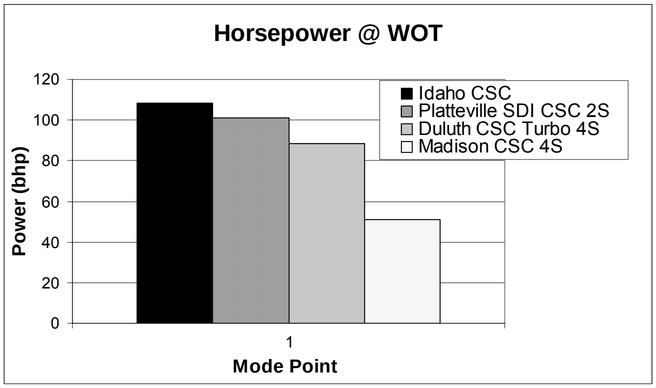


**Figure 14:** Five-mode power output of the UICSC GDI vs. Platteville 2-Stroke SDI, Duluth Turbo 4-Stroke, and Madison 4-Stroke engines.

## CONCLUSION

The University of Idaho has developed a cost-effective direct-injected two-stroke snowmobile engine. The GDI two-stroke snowmobile maintains the mechanical simplicity and low weight avid riders enjoy. The UICSC design produces stock power of 108 hp (80 kW), is lightweight at 550 lbs wet (250 kg), scores 158 on the EPA five mode emission test, and achieves a fuel economy of 20 mpg (8.5 km/L). Overall sound production measured using the SAE standard J192 was reduced from 85 dBA to 80 dBA, not quite to the competition standard. With future regulations coming for manufacturers, consumers will expect production snowmobiles that meet emissions requirements. 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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