University of Idaho's Direct-Injected Two-Stroke Snowmobile Using E2X Fuel

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ABSTRACT

The University of Idaho's entry into the 2010 SAE Clean Snowmobile Challenge (CSC) was a direct-injection (DI) two-stroke powered snowmobile modified to use blended ethanol fuel. The modulated and battery-less direct-injection system used to decrease exhaust emissions and improve fuel economy maintained near stock power output of the engine. Noise from the engine compartment was reduced by custom placement of sound absorbing materials. Pre-competition testing had the snowmobile entering the 2010 SAE CSC competition weighing 507 lbs (230 kg) wet, before adding sound deadening material.

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.

The 2010 Clean Snowmobile Challenge continued to encourage snowmobile development by mandating use of blended ethanol/gasoline fuel. The required blend ranged from 20 to 30 percent ethanol per volume. Ethanol is a renewable fuel that has 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.

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 the 2012 EPA snowmobile standards using the weighted five-mode testing procedure as published by SwRI [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].

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 was 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.

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 thermally activated retractable scoops to reduce direct noise emission and maintain airflow through the engine compartment. To allow for ample airflow with substantial sound insulation installed, larger side panels were used. In addition to the added sound insulation room, these panels allowed for the creation of exhaust systems that would not have fit within the original side panels.

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 [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 50 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 a slalom course. The fastest team through the slalom course received 50 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 for comparison purposes.

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 2010 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 2009 Ski-Doo XP Chassis. It is a lightweight chassis with good handling characteristics and comfortable rider positioning. The 600cc Rotax engine chosen by the team easily installs into this chassis.

ENGINE SELECTION – In 2007, the CSC competition was won by a DI two-stroke snowmobile. This 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, 11, 12]. 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 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 [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, 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 [12].

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]
2008 Idaho 2-Stroke DI (E85)	593	94.4/70	585/266	0.161/0.26
2007 Idaho 2-Stroke DI (E10)	593	94.4/70	577/261	0.163/0.268
2007 MTU 4-Stroke EFI Turbo (E85)	750	79/58.9	740/336	0.11/0.18
2007 U. Wisconsin Madison EFI 4-Stroke (E85)	750	42/31	689/313	0.06/0.10

It is clear that two-stroke snowmobiles have better power-to-weight ratios. Two-stroke engines also have torque curves well suited for the belt-type continuously variable transmissions (CVT) 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 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 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. [13] 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 [14].

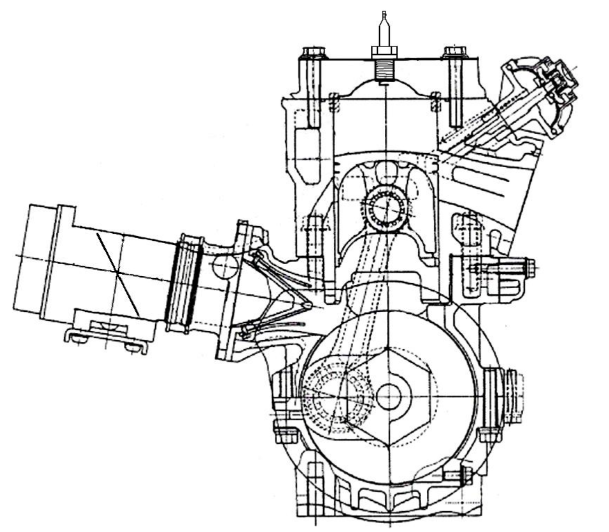


Figure 1: Cross section of a two-stroke engine similar to the one used for the UICSC engine [13].

Stone [15] 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% [16, 17, 18].

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 [17]. 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 [17]. 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 shows 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 [14]. 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 [17]. Nitrogen oxide formation depends on two basic factors: (1) peak temperatures reached during combustion, and (2) oxygen content in the trapped mixture [17]. 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 [19]. One goal for new two-stroke technologies is to maintain the low NO_x emissions.

DIRECT INJECTION SELECTION – 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. It is also known to improve cold start reliability [19]. Additionally, two different modes of combustion can be used for DI engines: stratified and homogeneous.

Stratified combustion in a two-stroke DI 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 [19]. 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 [15]. Stratified combustion eliminates poor idle quality and poor low load operation [19]. Strauss [20] suggests using stratified charge combustion during idle and light load operation.

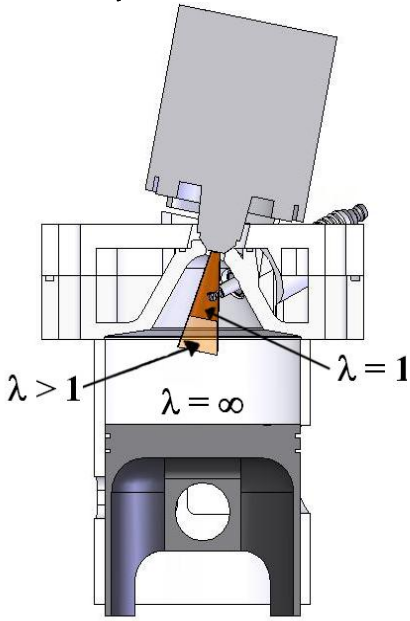
A DI system can also create a homogeneously charged combustion chamber. For the DI engine, homogeneous operation is accomplished when fuel is injected early in the cycle so there is time for the fuel to completely atomize and mix with the freshly scavenged air. Homogeneous combustion is used for medium 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 [16]. 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 [16]. 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 [21]. 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 DI 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 [19]. Although DI has been successful in the marine industry, many obstacles needed to be overcome for a DI system to be successful in a snowmobile application. The main reason why DI systems had not appeared on snowmobile engines until recently was 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 [19]. A two-stroke DI running on blended ethanol fuel, 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 [20].

Stratified Charge
Late Injection: 70-30° BTDC



Homogeneous Charge
Early Injection: 230-120°

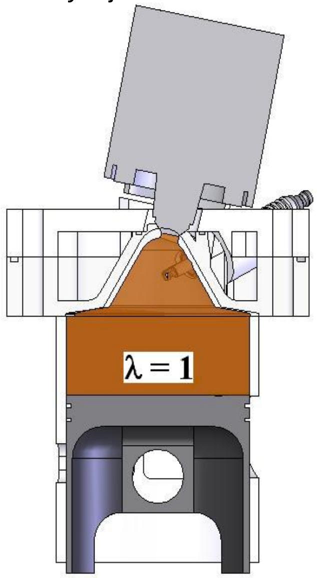


Figure 2: The equivalence ratios and charge stratification for stratified and homogeneous combustion.

UICSC DI design – For 2010, the UICSC team has chosen to use the E-TEC DI system adapted to a Rotax 593cc engine. The requirements for adaptation and benefits of the E-TEC system can be found in the 2006 and 2007 Idaho CSC Design Papers [22, 23].

Combustion chamber design - While simpler than its four-stroke counterpart, a DI 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 [19, 24].

A study of a DI 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.

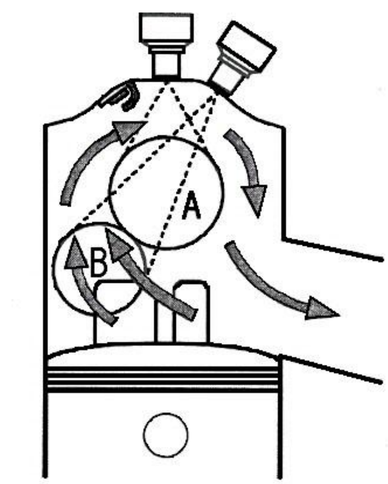


Figure 3: Two different fuel-spray targeting strategies for a loop-scavenged HPDI engine [11].

Another study, based on the E-TEC injectors, offered more insight into injector targeting, droplet size, and UHC emissions [24]. 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 [20] 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 DI head was modeled using the bolt pattern and coolant passage patterns from the baseline head. The 2007-08 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 DI 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 DI combustion chamber.

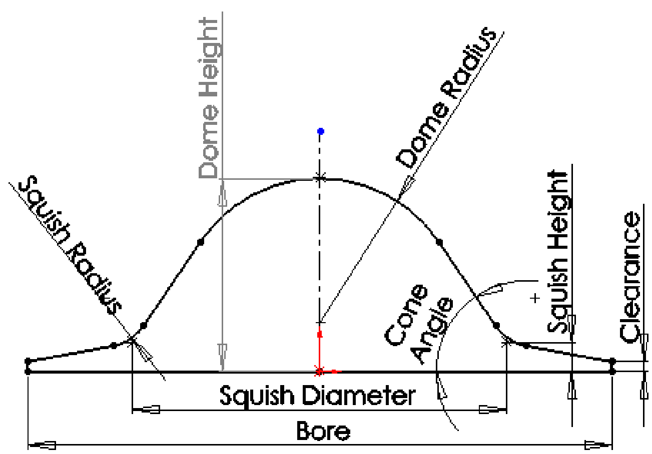


Figure 4: Combustion chamber cross-section for the 2009-01 UICSC DI engine.

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 [25, 26]. 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 [14].

The classifications for the combustion chamber are [20]:

- 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 DI head design, CNC coding, and manufacturing were all done in 2006, 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 DI head installed on the Rotax 600 H.O. engine.

Inductive Ignition System – For 2010, 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 2010 UI DI engine uses an electronic total-loss oil injection system from a stock Skidoo 600 E-TEC snowmobile, replacing the stock Rotax mechanical pump. This system eliminates premixing of oil and fuel and only delivers oil to specific locations. Less oil is required in a DI engine because the oil is not diluted by fuel in the crankcase. With the precision control added by the electronic pump, oil consumption was significantly reduced by approximately 50% over traditional carbureted two-stroke engines.

Fuel Delivery System – Due to a SAE CSC 2010 rule change requiring all spark ignition engines to be fueled with blended ethanol fuel, a major design goal for the 2010 SAE CSC competition was to tune and modify the UICSC DI snowmobile to run on a blended ethanol fuel. Taking advantage of the benefits of the fuel, i.e. the lower measured exhaust emissions and greater knock resistance while dealing with the downfalls such as the corrosive nature, extra-required fuel amounts and difficult cold-start characteristics turned out to be a difficult task.

Ethanol blended fuels are more corrosive and can pose a threat to engine and fuel system components. Based on prior material compatibility testing done by the team it was determined that the 10 to 19 percent increase of ethanol over standard E10 gasoline would not harm the stock components so they were left in place.

Fuel delivery strategy – As stated earlier, the DI engine can operate with either a stratified or homogeneous mixture. A homogeneous mixture was used when medium to maximum power was required while stratified combustion was used when reduced power was required. During the 2005 CSC competition the team only used stratified combustion during idle. For 2006, the team investigated the power required 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. [22]

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

In 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. Details of this analysis can be found in the 2007 Idaho CSC Design Paper [23]. It was found that 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.

For 2010, the same homogeneous cruise strategy was implemented. Even though the analysis was completed with 10% blended ethanol fuel, similar trends are expected to exist with E2x.

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 becomes an issue. It appears that because of the way fuel is introduced to the combustion chamber, stratified calibration strategy helps to improve the poor cold start characteristics of blended ethanol fuel.

WEIGHT REDUCTION – Due to a change in the competition rules, the overall weight of the snowmobile is no longer considered for points. However, the UICSC team has always strived to keep their machine light for several reasons. First a light snowmobile will achieve better fuel economy and handle more easily, lessening rider fatigue. Lightweight is also important for market-ability. As snowmobile manufactures continue to reduce the weight of their machines in response to consumer needs the UICSC team must as well. Pre-competition testing had the snowmobile entering the 2010 SAE CSC competition weighing 507 lbs (243 kg) wet. An added weight of 30 lbs is expected when sound deadening material is installed.

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 [14]. 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.

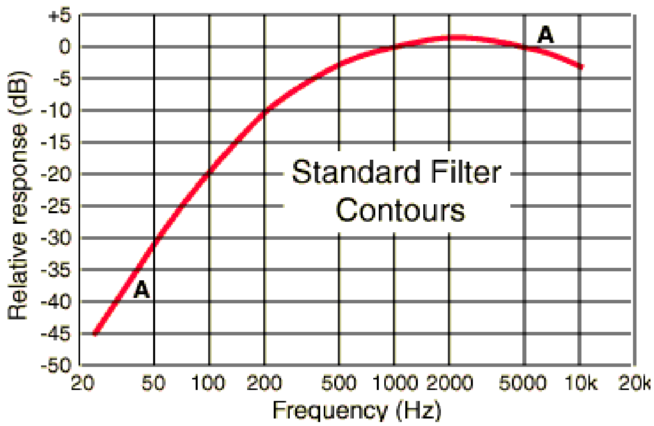


Figure 6: The A contour is more sensitive to sounds occurring between 1 and 5 kHz [27].

Sound Testing – The method for reducing sound emission in the past has been to add sound material wherever possible. In 2008 a test apparatus was constructed to evaluate sound deadening material effectiveness. This was a step in the right direction [28]. It allowed sound deadening material to be selected based on general frequencies to be attenuated. To improve on this, and determine the most effective use of the sound material, coherence and impedance testing have been implemented.

Impedance testing of materials can be done using two main methods: standing wave tube with one microphone and an impedance tube using two microphones [29]. A standing wave tube was selected to make the measurements mainly because the apparatus was available. Figure 7 shows a diagram of the apparatus. The actual apparatus is shown in Figure 8. The cart allows the microphone to be moved back and forth in the tube to find the location of minimum and maximum sound pressure peaks within the tube. Using this data the impedance of the material verses frequency can be determined.

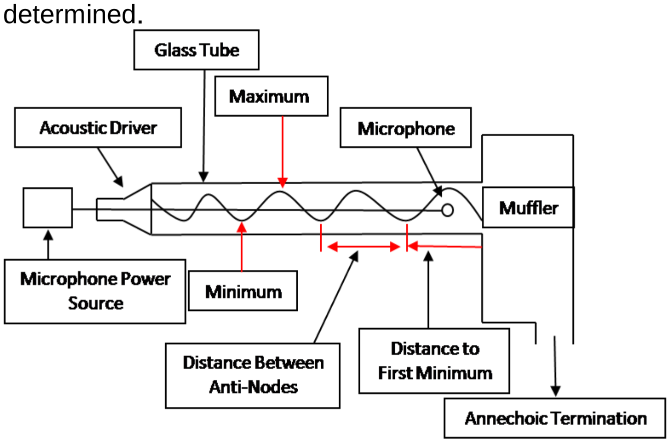


Figure 7: Schematic of standing wave tube test.

Figure 8: Standing wave tube apparatus and equipment used.

Coherence testing takes an overall sound sample of the snowmobile and compares it to a local sound sample taken from locations of interest on the chassis. The test determines the percentage of sound at a frequency that contributes to the overall sound pressure level (SPL) of the snowmobile. After testing a variety of materials, the coherence test determines where a material with certain properties should be placed making more efficient use of space and saving weight. Coherence testing not only helps with sound deadening material but it also aides in chassis modifications. Knowing where the bulk of sound energy was emitted from and the difficulty of dampening the sound determined priority areas making more effective use of time and resources. Equation 2 is the general equation for coherence.

$$\gamma^2(f) = \frac{|G_{xy}(f)|^2}{G_{xx}(f)\,G_{yy}(f)} \quad \left(0 \le \gamma_{xy}{}^2 \le 1\right) \tag{2}$$

Where $G_{xy}(f)$ is the cross-spectral density between the two sound samples and $G_{xx}(f)\ G_{yy}(f)$ are the autospectral densities [30].

A frame had to be constructed to hold the microphone shown in Fig. 9. After testing it was determined that wind noise was over powering the noise of the snowmobile and a airfoil was designed and tested in the University of Idaho wind tunnel to minimize unwanted noise from turbulent air.

Figure 9: Airfoil and frame to hold Microphone for coherence testing.

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 thermally activated retractable scoops to reduce direct noise emission and maintain airflow through the engine compartment. To allow for ample airflow with substantial sound insulation installed new, larger, stock panels were fitted. In addition to the added sound insulation room, these panels allowed for the creation of exhaust systems that would not have fit within the stock side panels.

Track Noise –Unlike noise in the engine compartment, track noise was difficult to absorb or redirect and was not specifically addressed by team.

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 2007 UICSC lined the air intake box with a high density foam to absorb sound while minimizing flow restriction. For 2010, a new type of foam lining for the air box was chosen based on materials testing data.

Exhaust Noise - In previous years, reducing the sound of the exhaust system came through testing of different combinations of tuned pipes, mufflers, and catalytic converters [28]. For 2010, the UICSC design team took a new approach to exhaust noise reduction. Using the fundamental frequency of the engine at max RPM, a Helmholtz Resonator was designed to cancel exhaust noise. The design frequency for the Helmholtz Resonator was 532 Hz, the second harmonic of the engine. The fundamental frequency was calculated knowing the number of pressure pulses through the exhaust system at 8000 RPM. With two pulses every revolution the fundamental frequency at 8000 RPM is 266 Hz.

One type of Helmholtz Resonator is a side branch resonator as shown in Figure10 that uses the pressure waves within a pipe to create the resonance within a cavity. Resonators are on type of reactive noise cancelation [31]. The purpose of the resonator is to create destructive interference between the sound traveling through the pipe and the sound from the resonator effectively reducing the noise of the entire system at the design frequency.

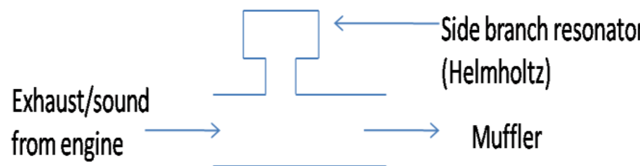


Figure 10: Schematic of side branch resonator.

When calculating the resonance frequency and reflection coefficient the specific impedance of the rest of the exhaust system needed to be known. Using a standing wave tube, the specific impedance of the tuned pipe and muffler was determined. These values were then inserted into the Helmholtz resonator math model to help design the resonator more accurately. By changing the volume diameter, volume length, neck diameter, and neck length a resonator can be designed around the fundamental frequency of the engine. the final reflection coefficient vs. frequency graph is shown in Figure11.

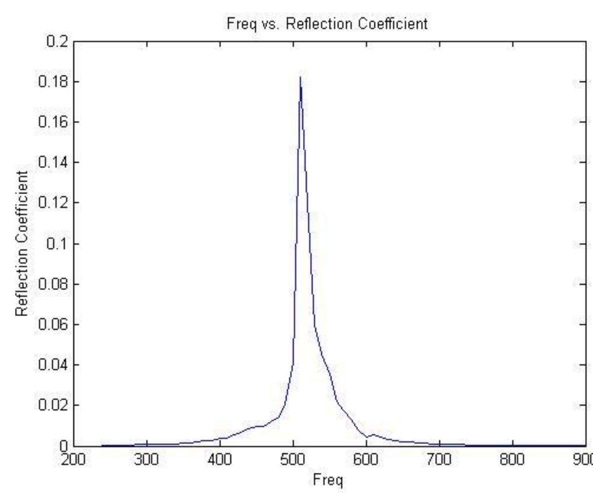


Figure 11: Resonator reflection coefficient.

The diameter of the neck had the greatest effect on system performance. Therefore, once a neck diameter was chosen from a standard tubing size, the length was adjusted to move the reflection curve over the design frequency. The neck diameter and length enclose a plug of air that acts as the mass of the system. Next by changing the volume of the resonator, the spring and dampening coefficient of the system were changed to match the mass and tune to the design frequency. When building the resonator, the volume diameter was fixed but the length was made adjustable to allow for fine-tuning of the resonator under operating conditions. The final resonator design can be seen in Figure12.

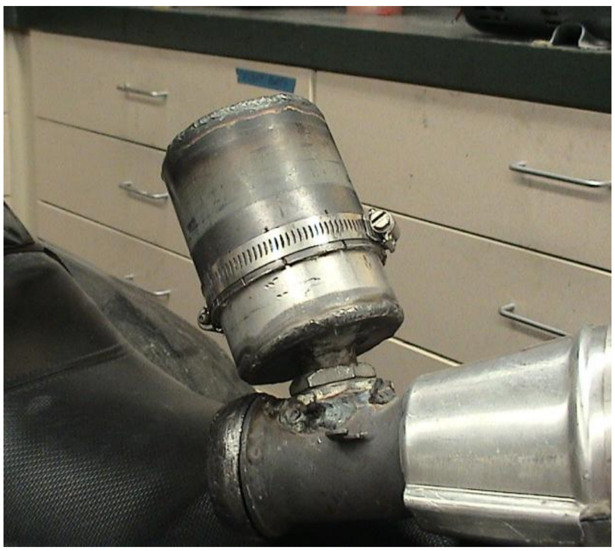


Figure 12: Helmholtz Resonator Model

Final Approach – No one method adequately reduced noise, so combinations of several methods were implemented in the final sound reduction approach for 2010. Selective sound deadening material, intake lining, and Helmholtz resonator 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, further testing and the addition of sound deadening material will be added in an attempt to reduce the sound levels.

COMFORT AND SAFETY – The 2010 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-warmers, a thumb warmer on the throttle, and an easy to read gauge cluster.

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 stock 2010 Ski-Doo MX-Z 600 E-tec is $9699. With all modifications included, the Manufacturer's Suggested Retail Price (MSRP) of the 2010 UICSC DI, totaled $11,820. This includes the price of donated chassis components totaling $568. Chassis components that add to the MSRP were justified by weight reduction, increased performance, and sponsor product awareness. The exhaust modifications total $123, which includes a Helmholtz resonator and heat shielding. The drive train modifications totaled $1309.

TESTING AND RESULTS - Testing is required to determine the improvement of a new design over an existing design. To verify that the 2010 UICSC snowmobile is better than previous designs, dynamometer testing totaled over 20 hours and on-snow testing totaled over 60 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.

Calibration Strategy - Engine calibration for blended ethanol fuel was completed using a Borghi-Saveri eddy current dynamometer, lambda sensor and exhaust gas temperature sensors. Because of excess air in the exhaust stream due to the nature of a DI two-stroke, the lambda sensor was not completely accurate. Once the lean/rich limits were found, the Lambda sensor provided a guide to creating a smooth E2x engine map. 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 – At the time this paper was written, emissions testing of the 2010 UICSC snowmobile was not yet been completed.

Engine power and fuel economy – During testing on groomed trails at an elevation of 4000 feet, the UICSC DI achieved 19 mpg (8.08 km/L) using E2x at an average speed of 35 mph (56 km/hr). For comparison, a 680 cc Polaris carbureted two-stroke triple chase snowmobile was recorded to have 9.5 mpg (4 km/L) using regular gasoline.

CONCLUSION

The University of Idaho has developed a cost-effective direct-injected two-stroke snowmobile engine capable of running on E2x blended ethanol fuel. The DI 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 kW), is lightweight at 507 lbs (230 kg) wet without sound deadening material, and achieves a fuel economy of 19 mpg (8.08 km/L). Overall, sound production measured using the SAE standard J-192 was reduced from 85 dBA to 80 dBA, not quite to the competition standard. With future regulations coming for manufacturers, consumers will expect clean and quiet snowmobiles. However, increased fuel economy, a better power-to-weight ratio, and a general enjoyable riding experience are what the majority of consumers demand. The 2010 UICSC E2x DI two-stroke snowmobile is an economical response to that demand.

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