DEVELOPMENT OF A DIRECT-INJECTED TWO-STROKE SNOWMOBILE USING E85 FUEL

Final Report

KLK751

Development of an Ethanol Fueled, Two-Stroke, Direct-Injection Snowmobile for Use in the Clean Snowmobile Challenge and National Parks

N09-02

National Institute for Advanced Transportation Technology

University of Idaho

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April 2009

DISCLAIMER

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Development of a Direct-Injected Two Stroke Snowmobile Using E85 Fuel	5. Report Date April 2009
	6. Performing Organization Code KLK751
7. Author(s) Dixon, Dylan; Hanks, Benjamin; Harker, Nicholas; Stock, Charles; Den Braven, Dr. Karen	8. Performing Organization Report No. N09-02
9. Performing Organization Name and Address National Institute for Advanced Transportation Technology University of Idaho PO Box 440901; 115 Engineering Physics Building Moscow, ID 838440901	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. DTRT07-G-0056
12. Sponsoring Agency Name and Address US Department of Transportation Research and Special Programs Administration 400 7th Street SW Washington, DC 20509-0001	13. Type of Report and Period Covered Final Report: August 2007– January 2009
	14. Sponsoring Agency Code *USDOT/RSPA/DIR-1*

Supplementary Notes:

16. Abstract

The University of Idaho's entry into the 2008 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. The emissions output was further reduced using an oxidation catalyst located after the exhaust silencer. Noise from the engine compartment was reduced by custom-carbon fiber hood and side panels, which allowed placement of extra sound absorbing materials. Pre-competition testing had the snowmobile entering the 2008 SAE CSC competition weighing 580 lbs (263 kg) wet, achieving 13.25 mpg (5.63 km/L) running on blended ethanol fuel, and a J-192 sound magnitude score of 80 dBA.

17. Key Words Snowmobiles; recreational vehicles; environmental impacts; ethanol; parks; two-stroke engines; competition; education; direct injection	18. Distribution Statement Unrestricted; Document is available to the public through the National Technical Information Service; Springfield, VT.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 37	22. Price …

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

TABLE OF CONTENTS

FIGURES

TABLES

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 2008 Clean Snowmobile Challenge continued to encourage snowmobile development by mandating the use of blended ethanol/gasoline fuel. The required winter blend E85 fuel consisted of approximately 74 percent ethanol and 26 percent gasoline. 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 [percentage of rated]	Torque [percentage of rated]	Weighting [percent]
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.

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

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

Another goal was to improve fuel efficiency beyond that of conventional touring snowmobiles. The target range for the competition endurance event 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 100 points. The other teams received points based on their relative performance to the fastest and slowest snowmobiles. The first handling test was subjective. Professional riders scored the snowmobiles based on specific handling and drivability criteria [2]. The winner of the subjective handling event received 50 points with the other teams receiving points based on their relative scores. The second handling event was used to evaluate the agility and maneuverability of each snowmobile. A member of the team rode the snowmobile twice through 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. Snowmobiles were also weighed with a full fuel tank. The lightest snowmobile received 100 points, with other teams receiving points based on a comparison with the lightest and heaviest competitors.

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 2008 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 also easily accepted the selected engine.

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-stoke engines also have torque curves well suited for the belt-type continuously variable transmissions (CVT) that are used in snowmobiles [3].

After considering the above information and the large potential for improvement of emissions over current two-stroke engines, it was decided to build a clean and quiet two-stroke powered snowmobile without sacrificing the high-power output. A major design constraint was that any method used to increase fuel economy and reduce emissions 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. [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].

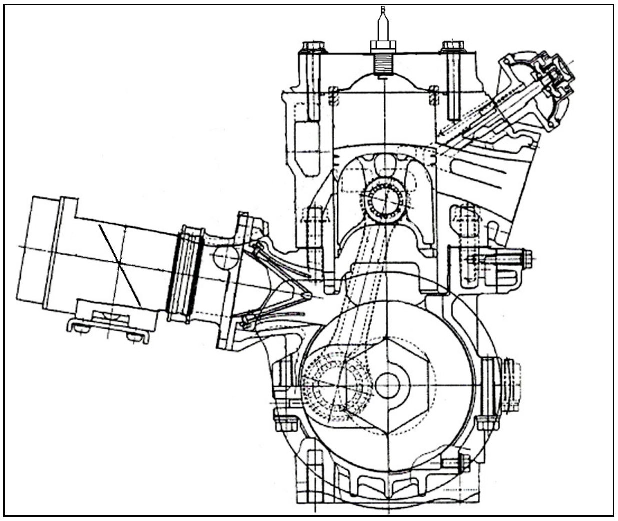


Figure 1: Cross section of a two-stroke engine similar to the one used for the UICSC engine [13].

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 showed that typical two-stroke engines also produce more CO emissions than four-stroke engines. The formation process for CO in two-stroke engines is the same as that for other engines [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 [20]. 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 [20]. 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 [20]. 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 [20]. Strauss [21] suggests using stratified charge combustion during idle and light load operation.

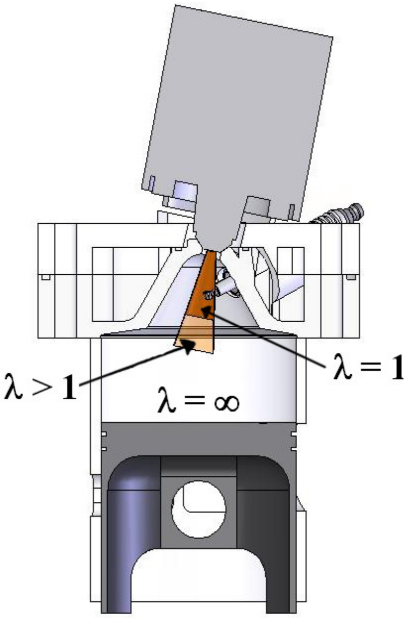
A DI system can also create a homogeneously charged combustion chamber. For the DI engine, homogeneous operation is accomplished when fuel is injected early in the cycle so there is time for the fuel to completely atomize and mix with the freshly scavenged air. Homogeneous combustion is used for medium 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 [22]. 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 [20]. 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. This challenge is only increased with the added fuel requirements of E85. This means that an injector nozzle designed to deliver high quantities of fuel quickly usually has poor light-load and idle fuel-spray qualities [20]. A two-stroke DI running on E85, at full power can use in excess of 55 kg/hr of fuel while at idle only needs 0.5 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 [21].

Stratified Charge: Late Injection: 70-30° BTDC



Homogeneous Charge: Early Injection: 230-120°

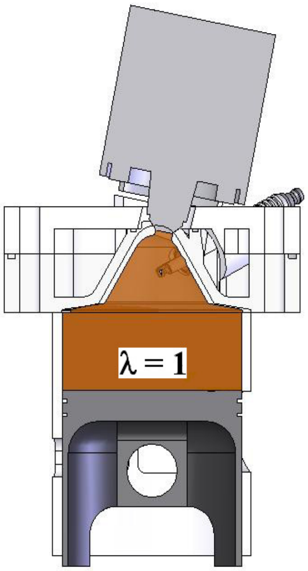


Figure 2: The equivalence ratios and charge stratification for stratified and homogeneous combustion.

UICSC DI DESIGN

For 2008, the UICSC team again chose 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 [23, 24].

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 [20, 25].

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.

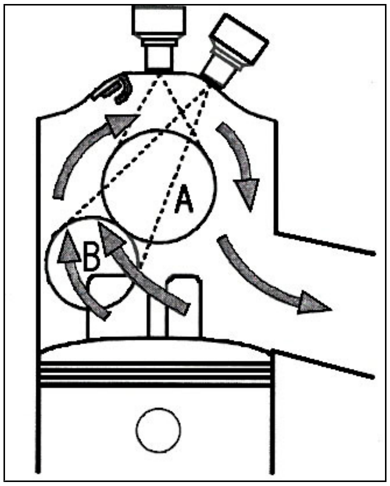


Figure 3: Two different fuel-spray targeting strategies for a loop-scavenged HPDI engine [11].

Another study, based on the E-TEC injectors, offered more insight into injector targeting, droplet size, and UHC emissions [25]. 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 [21] 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.

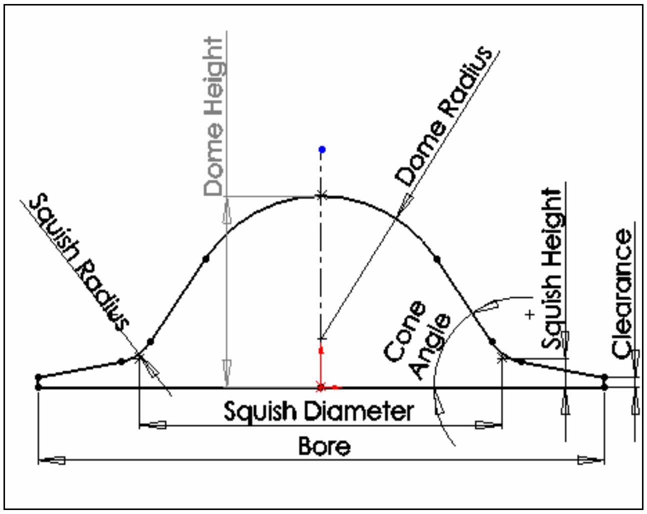


Figure 4: Combustion chamber cross-section for the 2007-08 UICSC DI engine.

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 [26, 27]. 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.

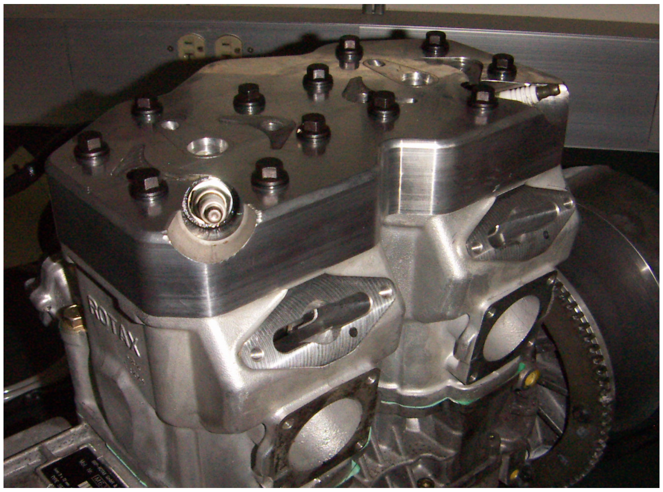


Figure 5: Completed UICSC DI head installed on the Rotax 600 H.O. engine.

Inductive Ignition System

For 2008, 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 2008 UI DI engine uses an electronic total-loss oil injection system from a stock Evinrude E-TEC outboard, 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 2008 rule change requiring all spark ignition engines to be fueled with blended ethanol fuel, a major design goal for the 2008 SAE CSC competition was to tune and modify the UICSC DI snowmobile to run on a blended ethanol fuel (E85). 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.

In order to handle blended ethanol fuels, the stock parts of the snowmobile fuel system were either replaced or tested to ensure they would withstand ethanol for a duration suitable for competition use. This included the fuel pump, filter, lines and fittings.

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

Another major fuel system concern with the use of ethanol blends is the extra-required fuel. In many cases, the use of an auxiliary fuel tank is required to carry ample fuel. To determine if added fuel capacity was required for the 2008 UI snowmobile, a series of on-snow fuel economy runs were made totaling more than 150 miles. It was found that the 2008 UICSC snowmobiles stock fuel tank at 10 gallons would suffice for the 100+ required miles of the CSC endurance test.

Fuel Delivery Strategy

As stated earlier, the DI engine can operate with either a stratified or 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 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. [23].

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 percentage 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 [24]. 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 2008, the same homogeneous cruise strategy was implemented. Even though the analysis was completed with 10 percent blended ethanol fuel, similar trends are expected to exist with E85.

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

In keeping with the two-stroke performance tradition, the 2008 UICSC team further reduced the weight of the base snowmobile, improving its already high power-to-weight ratio. The weight reduction in 2008 served two purposes. First, performance, handling, and fuel economy were all improved, and second, the weight reduction allowed for the use of more sound deadening materials without negatively impacting the snowmobile's performance.

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, C & A skis, aluminum runners and sway bar elimination. These component replacements reduced suspension weight by approximately fifteen 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.

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.

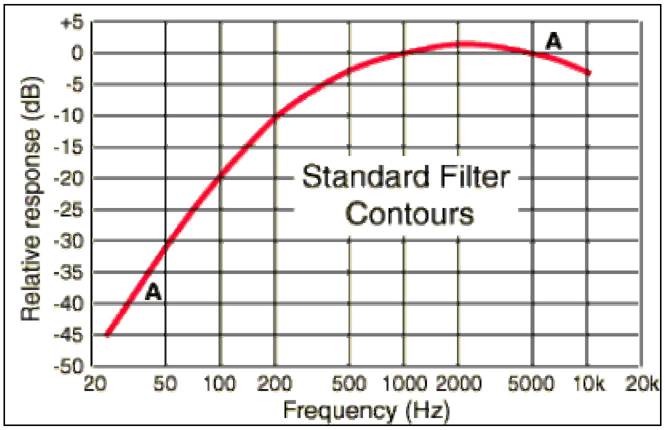


Figure 6: The A contour is more sensitive to sounds occurring between 1 and 5 kHz [28].

SOUND TESTING

In 2007 the UICSC team worked intensively to reduce the noise emissions of the 2007 CSC snowmobile entry and achieved a score of 73dBA in a standard SAE J-192 test [24]. In continued efforts to further reduce noise emissions, new strategies and testing procedures were created for 2008.

In past years, it was observed that testing conditions have a large impact on the J-192 test. Although extensive and standardized J-192 testing was performed in 2007, it was deemed inaccurate to compare data from day to day because of differing ambient atmospheric and snow conditions. Comparative data had to be taken in the same day. Due to lack of facilities at the test site, only small changes to the snowmobile could be made during a testing session. So in 2008, to be able to compare data from day to day, a noise control snowmobile was used.

Along with the on-snow J-192 testing, a materials testing procedure was also created to test different materials and configurations in a more controlled environment. The layout of this test can be seen in Figure 7. This test consisted of a speaker mounted in an open-ended box. Then different samples of material were placed on the open end of the box. A power source, with variable power and frequency capabilities, along with a sound meter, like that used in a J-192 test, were used to create and measure sound through the test panels. The sound meter was placed two feet from the sample panel and the power setting was fixed so that the meter read 80dB at 1 kHz when no sample panel was present. To test a sample, a frequency sweep from 1kHz to 5kHz was performed and recorded at the previously mentioned power setting for each material and configuration. The results of the material samples test are shown in Figure 8.

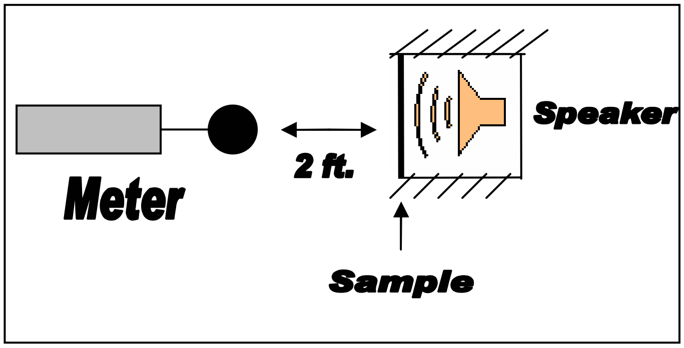


Figure 7: Schematic of the material-sample test configuration.

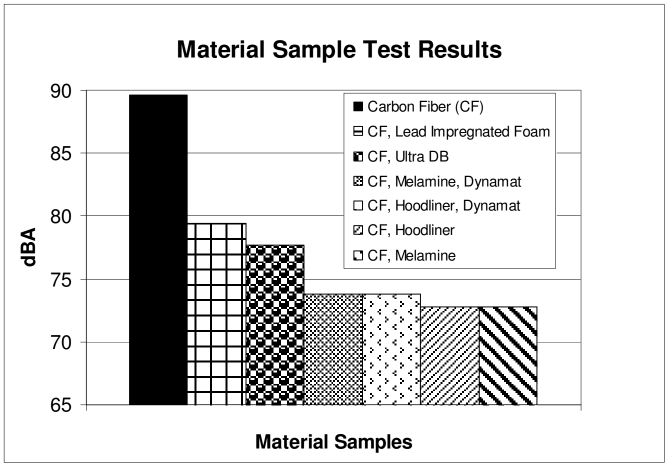


Figure 8: Results of sample material testing.

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

Mechanical Noise

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

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

In an attempt to contain and redirect noise, all hood and side panel vents that were not necessary for engine compartment cooling were sealed. Those needed were fitted with scoops to reduce direct noise emission and maintain airflow through the engine compartment. To allow for ample airflow with substantial sound insulation installed new, larger, side panels were created out of carbon fiber. 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 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. In 2007 UICSC lined the air intake box with a high density foam to absorb sound while minimizing flow restriction. For 2008, a new type of foam lining for the air box was chosen based on materials testing data. This was combined with a uni-directional air intake which was designed to direct sound through an opening in the hood. This intake proved to reduce noise emissions over the stock configuration. The uni-directional intake consisted of a ten-inch section of the intake pipe, cross-drilled and wrapped in high-density foam around the holes. The foam was then encased with a larger pipe. Upon testing all three air intake configurations, the cross drilled uni-directional intake proved to reduce sound significantly. Figure 9 shows a comparison of engine air intake configurations tested.

Exhaust Noise

Several exhaust system setups were tested for 2008 including the 2007 competition exhaust with a 3in catalytic converter, a student designed Laminar flow muffler, and the final design which consisted of a stock tuned exhaust pipe, muffler and a 3.5 in catalytic converter. The catalyst is contained in an extension added to the stock muffler that moves the exhaust outlet twelve inches to the rear of the stock outlet. This relocation was needed to accommodate the larger catalyst and to allow for greater heat retention. Figure 10 shows a comparison of exhaust systems tested during the J-192 tests.

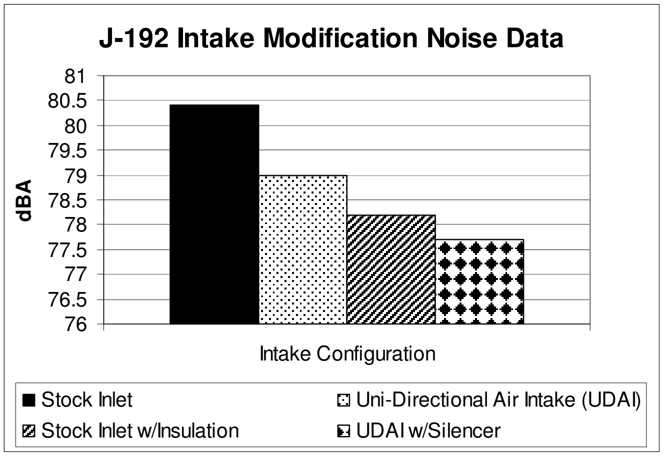


Figure 9: Comparison of engine air intake systems.

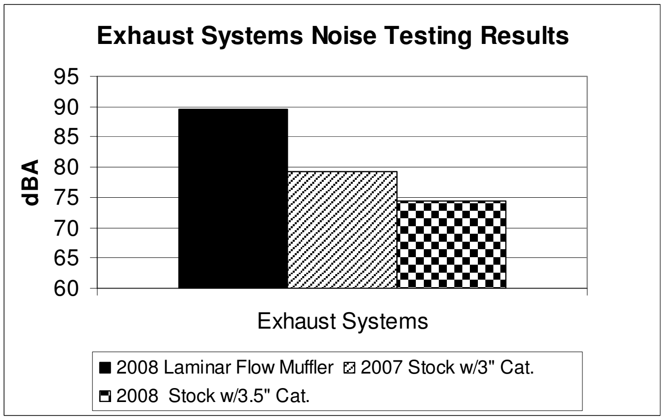


Figure 10: Comparison of sound levels with different exhaust systems.

Final Approach

No one method adequately reduced noise, so a combination of several methods was implemented in the final sound reduction approach for 2008. Sound deadening material, hood scoops, intake lining, bump track, and uni-directional engine air intake 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 continued in an attempt to reduce the sound levels below 78 dBA.

COMFORT AND SAFETY

The 2008 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 2008 Ski-Doo MX-Z 600 SDI is $8799. With all modifications included, the Manufacturer's Suggested Retail Price (MSRP) of the 2008 UICSC DI, totaled $9989. This includes the price of donated chassis components totaling $950. Chassis components that add to the MSRP, were justified by weight reduction, increased performance, and sponsor product awareness. The engine modifications total $240, which includes the injectors, fuel pump, cylinder head, and catalytic converter. The final design is shown in Figure 11.

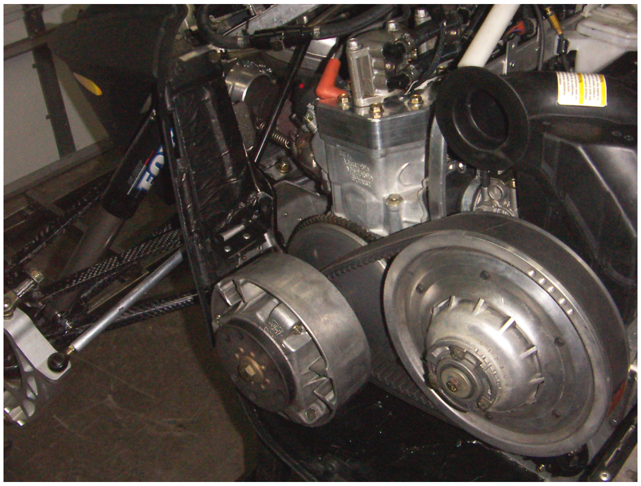


Figure 11: Final design of the 2008 UICSC DI snowmobile.

TESTING AND RESULTS

Testing is required to determine the improvement of a new design over an existing design. To verify that the 2008 UICSC snowmobile is better than previous designs, dynamometer testing totaled over 60 hours and on-snow testing totaled over 300 miles. During on-snow and dynamometer testing over 150 gallons of E85 were consumed. 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 Land and Sea water brake dynamometer, Lambda sensor, exhaust gas temperature sensors, and in-cylinder pressure traces. 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 E85 engine map. The in-cylinder pressure trace was used to detect detonation while tuning. Emission tuning was completed using a hand held five-gas analyzer. The strategy for testing was focused on BSFC and run quality throughout the map, followed by emission reduction at each of the mode points, without sacrificing run quality.

Engine Emissions

Two major factors influencing emissions were changed for the 2008 UICSC snowmobile: fuel and catalytic converter. In 2007, E10 was used to fuel the UICSC snowmobile, for 2008, E85 is required. As stated earlier, E85 has lower EPA measured emissions than E10. Another factor affecting emissions for 2008 was the use of a larger catalytic converter. The new catalytic converter is a 3.5 in by 4.5 in (88.9 by 114.3 mm) cylinder with a high flow honeycomb substrate donated by Aristo Inc. This catalyst modification was brought about as an attempt to further reduce backpressure seen in the exhaust system while simultaneously increasing the surface area of the catalyst.

At the time this paper was written, emissions testing of the 2008 UICSC snowmobile was not yet complete. Although complete emissions data were not available, the UI snowmobile was expected to be competitive at the 2008 emissions event due to the fuel change (E10 to E85) combined with the reductions expected from a catalytic converter (as seen from 2007 competition).

Engine Power and Fuel Economy

During testing on groomed trails at an elevation of 4000 feet, the UICSC DI achieved 13.25 mpg (5.63 km/L) using E85 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.

The advantage the UICSC DI two-stroke engine has in brake specific fuel consumption (BSFC) is illustrated in Figure 12 [12]. The 2008 UICSC snowmobile is comparable or better than E85 snowmobiles from the 2007 CSC competition. The 2007 Idaho E10 entry was corrected by 1.27 for energy in tank to compare to E85. The BSFC is reduced as much as 25 percent compared with the other engines. Vehicle fuel economy on-trail is further improved with a lightweight engine and chassis.

Figure 13 compares peak power output for the 2008 UICSC DI with the 2007 Idaho DI two-stroke, Duluth turbo four-stroke, Michigan Tech. turbo four-stroke and Madison four-stroke powered snowmobiles [12]. This graph shows the 2008 Idaho DI running on E85 is capable of retaining the power output of Idaho's 2007 DI running on E10, and has more power than the naturally aspirated and turbo-charged 750cc engines found in the Polaris FS and FST, respectively.

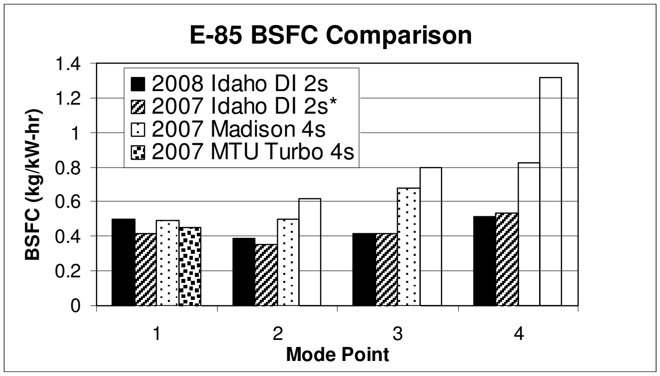


Figure 12: Four-mode BSFC comparison for the 2008 UICSC DI vs. 2007 UICSC (*corrected by 1.27 for E85), Madison with a four-stroke, and MTU Turbo four-stroke.

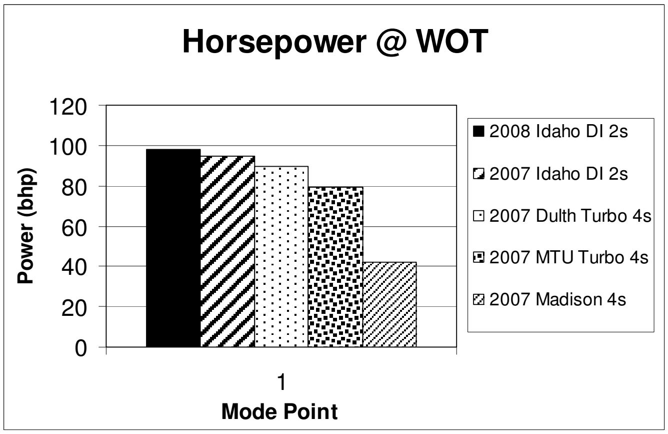


Figure 13: Peak power output of the 2008 UICSC DI vs. 2007 UICSC DI, Duluth Turbo 4-Stroke, MTU Turbo 4-Stroke and Madison 4-Stroke engines.

COMPETITION RESULTS

The University of Idaho Clean Snowmobile Team showed that a snowmobile can be successfully run using E85. The team received the Yellowstone National Park Award for Second Place in the 2008 CSC competition, and five other awards, including Quietest Snowmobile, Best Acceleration, Cold Start Award, Best Presentation and Best IC Engine Design Paper. The UI competition snowmobile maintained stock power, and achieved National Park Service sound reduction requirements for park admission with a J192 sound magnitude of 73 dBA. It was the second lightest combustion powered snowmobile in the competition.

EDUCATIONAL BENEFITS

The SAE Clean Snowmobile Challenge has proven to be of enormous benefit to the education of students at the UI. The project itself is unique. It is not only a technical challenge of balancing the apparently opposite characteristics of performance and environmental responsibility, but also forces students to become aware of the societal and political realities behind technology decision-making. Students learn firsthand the discomfort that can come from being involved in a politically charged issue. They also are required to present their designs in a written paper and in an oral presentation.

Figure 14: University of Idaho Clean Snowmobile wins the Acceleration Competition at the 2008 Clean Snowmobile Challenge.

The University of Idaho Clean Snowmobile Team is fully integrated into the academic fabric of the mechanical engineering (ME) department at the University of Idaho. The team consists of students ranging from freshmen, through graduate students who act as mentors to the team. The clean snowmobile is one of the projects utilized in the ME department's Senior Capstone Design sequence. In addition to leading the team, upperclass and graduate students are responsible for teaching and mentoring the new students. The UI ME department has created an environment where the compartmentalization between undergraduate and graduate education and research has been removed. All team members take a class for academic credit for participation on the team.

For the CSC team, fifteen students typically receive class credit, an additional three to six are involved in senior design, three in a senior laboratory class related to the snowmobile, and 2-3 graduate students are doing related research. The students realize that retained knowledge is a key to success.

The Clean Snowmobile Project has also been instrumental in recruiting students into mechanical engineering and other transportation related fields.

CONCLUSION

The University of Idaho has developed a cost-effective direct-injected two-stroke snowmobile engine capable of running on blended ethanol fuel (E85). 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 98 hp (73 kW), is lightweight at 580 lbs wet (263 kg), and achieves a fuel economy of 13.25 mpg (5.6 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 2008 UICSC E85 DI two-stroke snowmobile is an economical response to that demand.

ACKNOWLEDGEMENTS

The University of Idaho CSC Team would like to thank our many supporters: National Institute for Advanced Transportation Technology, Bombardier Recreational Products, NGK Sparkplugs, Nextech, Fastenal, AMDS, Stud Boy, Spokane Winter Knights, Slednecks, HMK, Klim, McNamar Racing, Janicki, Aristo, Jimmy G's Motorsports, Elk Butte Recreation, Dr. Karen DenBraven, Dan Cordon, Russ Porter, Joe Plummer, Steve Beyerlein, Dana Dixon, Nathan Bradbury, Justin Johnson, Andrew Findlay, C-Bass, Dr. Bubba, Ralphi, Danno, E-lab, and the many others that made this project possible.

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