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

Nathan Bradbury, Andrew Findlay, Justin Johnson, Erik Van Patten
SAE Student Members, University of Idaho

Dr. Karen R. DenBraven*
Mech. Eng. Dept., University of Idaho

ABSTRACT

The University of Idaho's entry into the 2006 SAE Clean Snowmobile Challenge (CSC) was a second-generation gasoline direct-injection (GDI) two-stroke powered snowmobile. A modulated and battery-less direct-injection system was used to decrease exhaust emissions and improve fuel economy without reducing the power output of the engine. The team added a reduction catalyst designed for a two-stroke to the exhaust silencer to further reduce exhaust emissions and noise. Under-hood noise was targeted by using sound absorbing materials and a sealed hood. Chassis noise was addressed by using a spray-on rubberized material that absorbs vibrations transferred through the chassis. The snowmobile entered into the 2006 SAE CSC competition was lightweight, easy-to-ride, powerful, fuel efficient, and had reduced exhaust emissions.

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 snowmobiles negative impact and proposed rules from the National Parks Service (NPS) prompted the SAE and other interested parties to begin the Clean Snowmobile Challenge (CSC) in 2000 as an effort to stimulate the production of clean and quiet snowmobiles and provide practical engineering experience for students.

DESIGN GOALS - The first goal for the competition was to reduce exhaust emissions. The primary emphasis is on reducing carbon monoxide (CO) and unburned hydrocarbons (UHC) without increasing the already low emission of oxides of nitrogen (NO_x) of traditional two-stroke snowmobile engines. Scoring was based on the 2012 EPA snowmobile café standards using the weighted five-mode testing procedure developed by SwRI [1]. The SwRI five-mode test weights emissions of CO and UHC+NO_x at engine speed and load points indicative of snowmobile operation [2]. Table 1 shows the loads, speeds, and weighting factors for the five-mode test.

* Author to whom correspondence should be addressed.

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

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

The results of the five-mode test are used in equation (1) to determine the EPA sled emission number E [3]. The EPA states that a minimum E score of 100 is required for the corporate average for the 2012 snowmobile emission standards. In addition to the minimum score, the average weighted emissions for UHC+NO_x and CO cannot exceed 90 g/kW-hr and 275 g/kW-hr respectively. Points were given to teams that achieved the minimum composite score with additional points being awarded for scores greater than 100. Snowmobiles that passed the event received 100 points, with additional points given based on how the engine performed compared to the rest of the competition.

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

While the EPA requires a café standard, the NPS requires higher standards for snowmobiles that are to be allowed into National Parks. Any snowmobile entering the Parks must be considered best available technology (BAT) with a minimum EPA score of 170, with maximum UHC+NO_x and CO emissions not to exceed 15 g/kW-hr and 120 g/kW-hr respectively [4].

Reducing noise emissions from the snowmobile was also a large priority for the competition. At the 2006 competition, there were both an objective and subjective noise test. The objective noise test is based on the SAE J192 pass-by sound pressure testing procedure [1]. It is a pass/fail test where the snowmobiles cannot produce more than 78 dBA, the standard set by the International Snowmobile Manufacturers Association. If the snowmobile passed the J192 test, the team received 150 points and was then eligible to receive more points in the subjective noise test. The subjective test used the recordings of the J192 test and played them back to a jury of CSC attendees. The team that received the most favorable subjective evaluation was awarded an additional 150 points while the team with the least favorable rating received zero additional points.

Another goal was to improve fuel efficiency beyond that of conventional touring snowmobiles. The target range for the competition endurance event is 100 mi (161 km). Each snowmobile had to complete the endurance event while following a trail judge [1]. If the snowmobile was unable to complete the event or if the trail judge determined the snowmobile could not keep pace it was disqualified. The fuel consumption was recorded and each team that finished received 100 points. Additional points were awarded based on how fuel-efficient the snowmobile was compared to the rest of the competitors.

To quantify performance and handling characteristics, the snowmobiles also competed in an acceleration event as well as two handling events. The acceleration event was based on the time it took to travel 500 ft (152 m) starting from a stop. 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 event was used to evaluate the agility and maneuverability of each snowmobile [1]. 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 second handling test was subjective. Professional riders scored the snowmobiles based on specific handling and drivability criteria. The winner of the subjective handling event received 50 points with the other teams receiving points based on their relative scores. The snowmobiles were also subjected to a morning cold start, and had to start within 20 seconds without starting fluids [1]. Each snowmobile that passed the event received 50 points.

Students submitted a technical design paper describing the approach taken and the challenges met during the design and building of the snowmobiles. The teams also gave an oral design presentation and presented a static display. These presentations focused on how the teams' snowmobiles accomplished the goals of the competition while trying to "sell" the product to potential buyers. With these design goals in mind, the 2006 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 Polaris IQ Fusion Chassis. It is a lightweight chassis with good handling characteristics. The drive train incorporates a hollow driveshaft that is lighter than previous designs while retaining the strength. This chassis also features an adjustable handlebar system to accommodate many different riding styles. The seat on the Fusion was made for comfort, and is great for trail riding [5]. The under-hood area was sized perfectly for the UICSC engine and exhaust system.

In order to reduce rolling resistance the stock Hyfax, located at the interface between the track and slides of the suspension system, was replaced with Teflon impregnated Hyperfax.

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

With recent use of semi-direct fuel injection (SDI), two-stroke powered snowmobiles are now capable of fuel economy similar to, or better than, four-stroke snowmobiles because they have remained lighter weight [8]. However, the SDI two-stroke engines still have poor emissions compared to four-stroke engines. Results from several CSC competitions, shown in Table 2, clearly show the difference in exhaust emissions and fuel economy between carbureted two-stroke, SDI two-stroke, and EFI four-stroke snowmobile engines. Both the SDI two-stroke and EFI four-stroke in Table 2 meet the 2012 EPA emissions standards with scores of 112 and 162 respectively. However, they do not meet the NPS emissions standards. Significant improvement can, and should, be made to further reduce emissions and increase fuel economy.

Table 2: Five-mode emissions and fuel economy of two and four-stroke control snowmobiles used at the CSC [7,8,9].

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

Two-stroke engines are mechanically less complex than their four-stroke counterparts. It is the lightweight design that allows SDI two-stroke engines to have good fuel economy and better performance characteristics. Table 3 compares some current model snowmobiles weight, engine size, and power output. It is evident that two-stroke snowmobiles have better power-to-weight ratios. Two-stoke engines also have torque curves well suited for the belt-type continuously variable transmissions (CVT) that are used in snowmobiles [2].

Table 3: Comparison between two and four-stroke engines displacement, power, and snowmobile weight. Data from snowmobile manufacturers.

2006 Model and Engine Type	Engine size [cc]	Engine Power [hp]	Dry Weight [lb.]	Power to Weight [lb./hp]
Polaris 700 Touring 2-Stroke SDI	755	130*	598	4.6
Ski-Doo GTX Limited 2-Stroke SDI	600	120	533	4.4
Arctic Cat T660 Touring 4-Stroke EFI Turbo	660	110	640	5.8
Polaris FST Touring 4-Stroke EFI Turbo	750	125*	643	5.1
2007 Yamaha Venture Lite 4-Stroke EFI	500	80	582	7.3

** Engine power is estimated based on [hp/cc] of similar engines.*

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

The engine chosen for modification by the UICSC team was a carbureted, reed valve, and loop scavenged Polaris Liberty 600 cc engine with a variable exhaust system (VES), and a tuned pipe, similar to the one shown in Figure 1. This engine was chosen for several reasons. The engine displacement falls within the guidelines of the competition [1]. It had the typical performance characteristics and size for trail snowmobiles that use two-stroke engines. Parts are readily available. Finally, the engine could be easily installed into the IQ chassis.

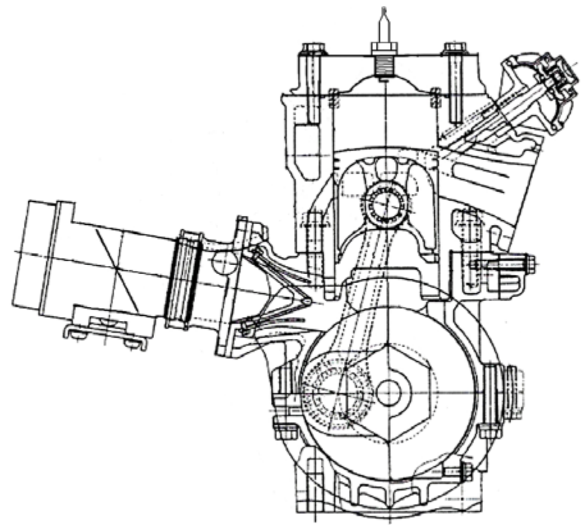

Figure 1: Cross section of a two-stroke engine similar to the one used for the UICSC engine [10].

<u>Two-stroke operation</u> - 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. Scavenging is the process of emptying the cylinder of burned gases and replacing them with a fresh mixture (or air) [11]. 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 tuned exhaust pipes [12].

Stone [13] identifies two very undesirable side effects of the two-stroke cycle: the short-circuiting of the fresh charge and the mixing of the fresh fuel/air mixture with the exhaust gas residuals. The short-circuited fuel is the single largest contributor to poor thermal efficiency, excessive UHC emissions, and particulate matter. Short-circuited fuel can account for as 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% [11, 14, 15].

The largest amount of the UHC emissions, on a mass/power basis, occur wide-open throttle (WOT) and at low engine speeds and loads. Figure 2 shows the UHC emission of the 2005 CSC SDI two-stroke control engine. The UHC emissions at low engine speeds and loads are due to incomplete combustion, low scavenging efficiency, misfire, and fuel short-circuiting [16]. The poor combustion and misfire are attributed to air-intake throttling. The restriction on the intake side of the scavenging reduces the scavenging efficiency and leaves excessive residual exhaust gases in the cylinder. 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.

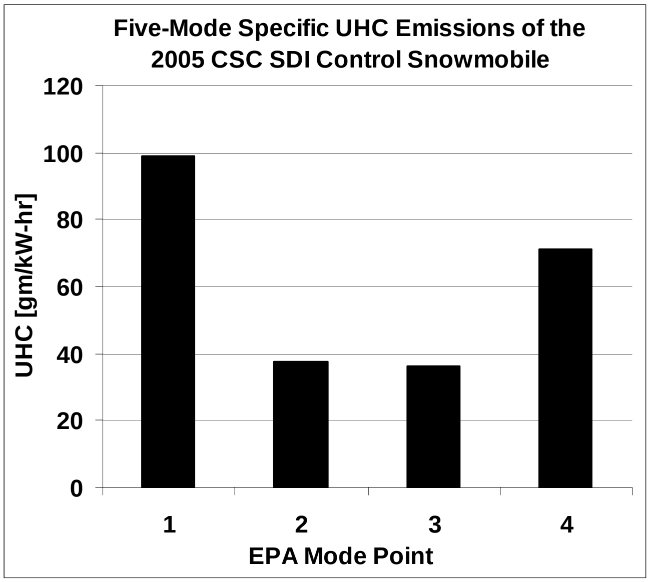

Figure 2: Hydrocarbon emissions from SDI two-stroke engine. (Mode 5 is not shown due to the negligible power produced at idle.)

The UHC emissions at WOT are due to fuel short-circuiting and rich air/fuel ratios. The engine is operated fuel rich to produce maximum power and to cool the piston to prevent seizure [14]. It is also important to look at the UHC emissions on a mass/time basis. These UHC emissions are extremely poor at Mode 1 (WOT). This is shown in Figure 3, the five-mode mass/time UHC emissions of the 2005 CSC SDI control engine.

The mass/time UHC emissions show that while the two-stroke engine produces a significant amount of power at WOT, offsetting the specific UHC emissions, there is a significant amount of fuel being wasted. 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 thermal efficiency and UHC emissions.

Table 2 showed that two-stroke SDI engines also produce more CO emissions than four-stroke engines. The formation process for CO in two-stroke engines is the same as that for other engines [12]. It is a result from 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.

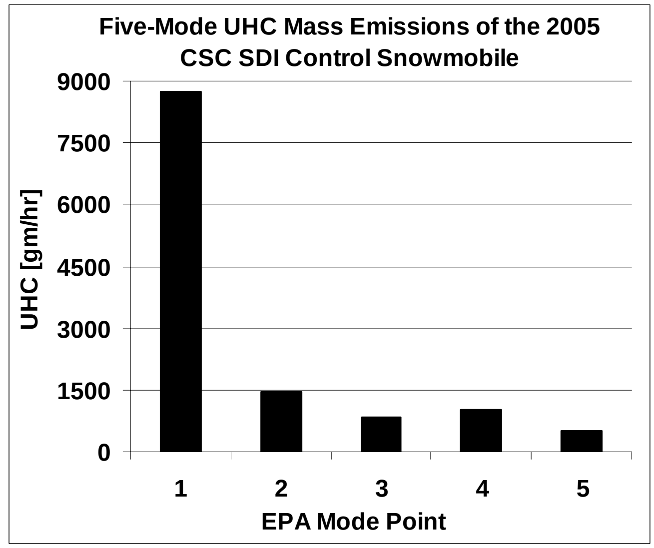

Figure 3: UHC emissions of the SDI 2005 CSC control snowmobile on a mass basis.

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. Nitric oxide represents more than 95% of the total NO_x emissions and it is a key player in the formation of smog [14]. The formation process of NO_x is called the Zeldovich mechanism. It is based on the dissociation of N_2 and O_2 molecules following the flame boundary and a lack of time available for chemical equilibrium to be reached [14]. Nitrogen oxide formation depends on two basic things; (1) peak temperatures reached during combustion, and (2) oxygen content in the trapped mixture [14]. Typical two-stroke engines have inherently low NO_x emissions because they have low effective compression ratios, they are operated fuel-rich, and have high residual exhaust gases (EGR), all of which contribute to lower peak cylinder temperatures and less trapped oxygen, leading to less NO_x formation [17]. The goal for new two-stroke technologies is to maintain the low NO_x emissions.

DIRECT INJECTION SELECTION – In a GDI two-stroke, fuel is injected directly into the cylinder at an optimal time for complete mixing and combustion. Air-assisted or high-pressure fuel injectors are used to ensure the fuel enters the combustion chamber in small droplets so the fuel can atomize quickly and mix with the freshly scavenged air. A significant amount of research exists that shows that GDI reduces the negative aspects of two-stroke engines. 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 [18]. Additionally, two different modes of combustion can be used for GDI engines: stratified and homogeneous.

Stratified combustion in a two-stroke GDI occurs when fuel injection is timed late in the cycle and ignition is delayed 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 [18]. The flame front, occurring at the interface between the fuel and oxidant, moves out from the spark plug gap, burning the ever-leaner mixture until combustion can no longer be sustained [13]. Stratified combustion eliminates poor idle quality and poor low load operation [18]. One possible disadvantage of this type of combustion is the potential for an increased production of NO_x from the lean combustion occurring at the outer edges of the flame front [18]. This can be combated with the use of a catalyst designed for a GDI two-stroke and the high EGR rates that exist at low-throttle openings. Strauss [19] suggests that stratified charge combustion should be used during idle and light load operation.

A GDI system can also create a homogeneously charged combustion chamber. For the GDI engine, homogeneous operation is accomplished when fuel is injected early in the cycle so there is time for the fuel to completely atomize and mix with the freshly scavenged air. Homogeneous combustion is used for medium to high loads and is accomplished two ways. The first is during medium loads. The fuel is injected early and an overall trapped lean air/fuel ratio with some EGR is desired to limit heat release [17]. 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 [17]. The timing of the fuel injection, while much earlier than stratified injection, must be late enough to avoid any fuel from becoming involved with the scavenging flows to avoid short-circuiting fuel [20]. Figure 4 shows the difference between in-cylinder equivalence ratios (λ), ratio of actual air/fuel to the stoichiometric air/fuel ratio, for a stratified and homogeneously charged engine.

Two-stroke GDI engines exist in the marine outboard industry where they have been shown to have UHC+NO_x emissions similar to four-stroke engines while having less CO emissions [18]. Although GDI has been successful in the marine industry, many obstacles need to be overcome for a GDI system to be successful in a snowmobile application. The main reason why GDI systems have not appeared on snowmobile engines is their high-performance nature. Snowmobile two-stroke engines operate at significantly higher engine speeds with greater fuel demands. They operate at speeds in excess of 8000 rpm with specific power outputs of nearly 150 kW/liter, compared to marine engines with rated engine speeds around 6000 rpm and specific power outputs of just 70 kW/liter. At peak loads, a short period of time (1.2-3.5 ms) exists where a large amount of fuel must be injected and fully atomized without being short-circuited.

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

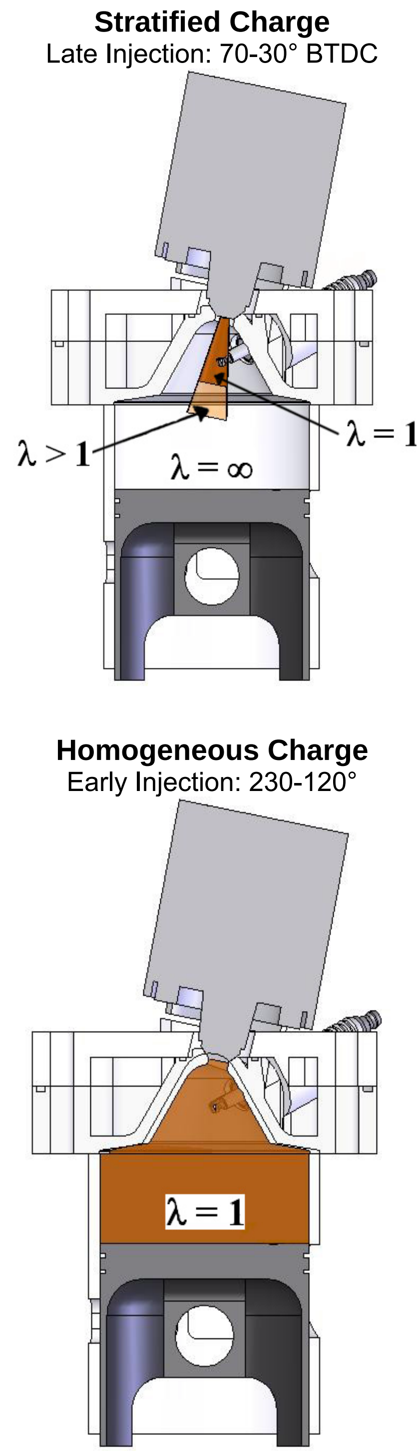

Figure 4: Schematic showing the difference between stratified and homogeneous equivalence ratios and charge stratification.

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 system to ensure a spark event occurs when a rich mixture is near the spark plug during stratified operation [19].

UICSC GDI design - The UICSC team chose to use the E-TEC single-fluid and modulated high-pressure direct-injection (HPDI) system. The E-TEC GDI system is the latest unit-injector two-stroke outboard-marine engine combustion system. The new E-TEC injectors are an improvement over the previous FICHT unit-injectors. The E-TEC injectors have a unique control strategy that allows them to operate at high speeds, up to 10,000 rpm, with reduced injection timing and greater fuel delivery [18]. Based on the success of the E-TEC combustion system, the UICSC team decided to adapt the new E-TEC injectors to the Polaris 600cc engine. Figure 5 is a cross section of an E-TEC injector showing the fuel path and injector components.

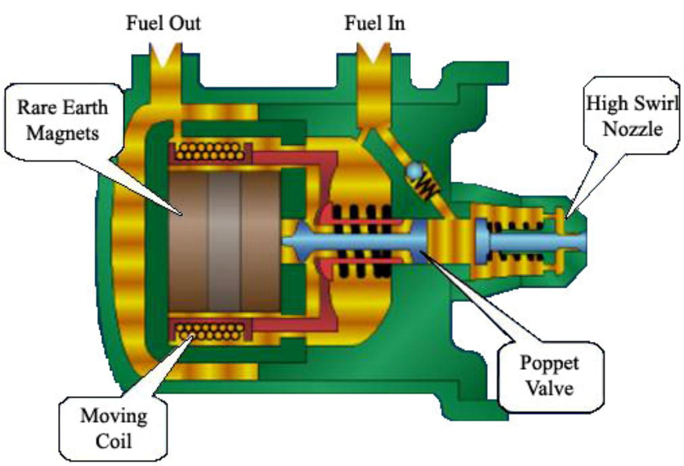

Figure 5: Evinrude E-TEC Injector schematic [Courtesy of BRP].

Electrical design - In order to use the E-TEC injectors several modifications had to be made to the carbureted two-stroke. The electrical system requires both 12V and 55V to operate, therefore an electrical system capable of producing both voltages needed to be adapted. One solution was to use the stock 12V permanent magnet alternator with a DC-to-DC converter to produce the 55V, similar to the 2003 UICSC snowmobile. The second option was to adapt the E-TEC permanent magnet alternator that produces 55V and the charging circuit that produces 12V. The second option was selected. After several modifications, the 55V alternator and flywheel were mounted to the Polaris engine in the same location as the stock 12V alternator. Placing the power source there maintained a clean, stock appearance.

Another benefit of the permanent magnet alternator is that it only produces the electrical power necessary to power the system, similar to an automotive alternator. This is different from ordinary two-stroke alternators that waste electrical power through a resistive regulator. The E-TEC alternator also produces enough power with one pull of the starter-rope to start the engine. This makes starting the engine easy. In addition, there is no need for a battery. Figure 6 shows the components that were either manufactured or modified for the UI engine.

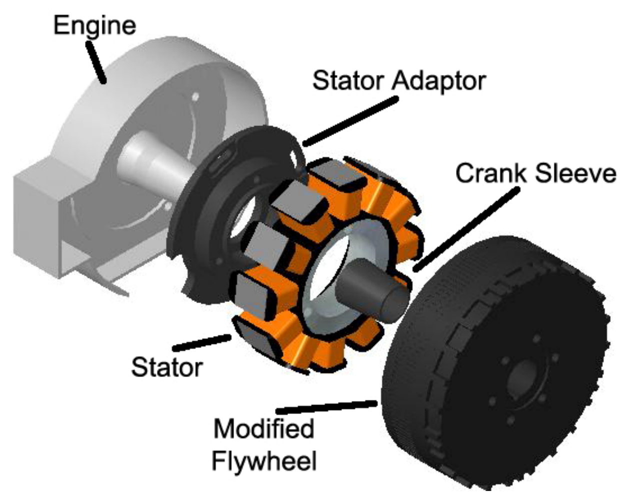

Figure 6: Designed stator adaptor, crankshaft adaptor, modified flywheel, and stator assembly.

Along with the power source, the rest of the E-TEC electrical system was also adapted the engine. This included:

- Engine temperature sensor
- Intake air temperature sensor
- Crankshaft position sensor
- Throttle position sensor
- E-TEC injectors and ignition-coil assemblies

Combustion chamber design - While simpler than its four-stroke counterpart, a GDI head is more complex than a standard two-stroke head. It needs to be designed around the fuel-spray characteristics and the in-cylinder 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 [21, 18].

A study of a GDI engine similar the UI GDI engine considered two-different fuel cones, their locations, and their targeting [10]. 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 7 shows the two fuel-injector targeting scenarios investigated where injector "B" was considered better. It is suspected that the larger droplets of injector "B", having greater momentum, were better able to resist the scavenging flows.

Another study, based on the E-TEC injectors, offered more insight into injector targeting, droplet size, and HC emissions [21]. 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. A snowmobile two-stroke 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 HC emissions for homogeneous combustion.

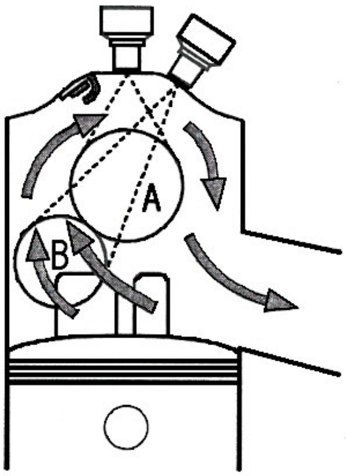

Figure 7: Two different fuel-spray targeting strategies for a loop-scavenged HPDI engine [10].

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

In order to accomplish the above mentioned criteria several design factors were investigated to improve the combustion chamber for direct-injection operation. The major design factors included:

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

To begin the design of the head, a solid model was created of the stock 600cc head and cylinder. The GDI head was modeled using the bolt pattern and coolant passages of the stock head. The tall combustion chamber was used because of the narrow fuel-spray characteristics. The chamber height reduces fuel impingement on the piston surface, especially during stratified operation when injection is late in the cycle. The injectors were angled 11° towards the intake ports to aid in mixture preparation and to reduce the amount of short-circuited fuel. The chamber was offset towards the exhaust side to center the fuel cone in the cylinder to reduce wall impingement. Figure 8 is a cross section of the UI GDI combustion chamber.

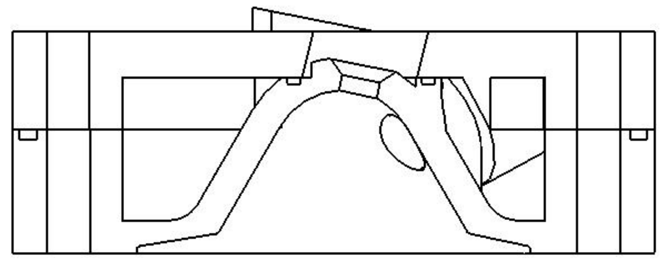

Figure 8: Combustion chamber shape for the UICSC GDI engine.

During both stratified and homogeneous operation, a fuel rich condition needs to occur near the spark plug. To accomplish this during stratified combustion, the spark plug needs to be located near the injected fuel. 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 [22, 23]. Based on these studies the spark plug was located on the exhaust side just below the injector. To aid in mixture preparation the squish area was increased over the stock squish area, which increased the Maximum Squish Velocity (MSV) [12]. The stock MSV was 20.8 m/s and the GDI head had a MSV of 26.6 m/s.

The classifications for the combustion chamber are [18]:

- 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.

Another benefit with the E-TEC injection system is the relatively low fuel-supply pressure of 35-40 psig (2.41-2.76 bar). Many other GDI systems require fuel-supply pressures greater than 1700 psig (120 bar) [23]. A standard low-pressure fuel pump was used with an in-line fuel filter and regulator to route excess fuel, used to cool the injectors, back to the fuel tank.

The GDI head manufacturing was done in the University of Idaho Mechanical Engineering machine shop.

Students aided by the mechanical engineering department's machinist performed all of the machining procedures. The machined head with the injector and coil assemblies is shown in Figure 9.

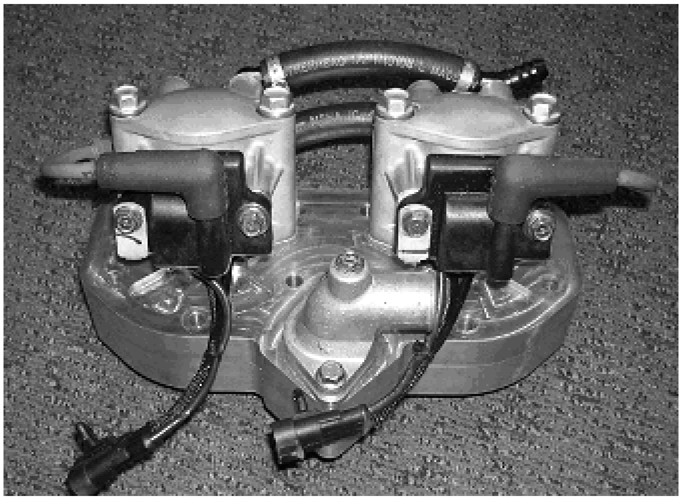

Figure 9: Completed UICSC GDI head with the injector/coil assemblies.

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

The UI GDI engine uses a total-loss oil injection system similar to the ones used by snowmobiles. It was based on the E-TEC oiling system. The new oil circuit offers more precise oiling and lowered oil consumption. Oil for the engine is stored in an oil reservoir. An electric pump sends precisely metered oil to four oiling points on the engine. These include two main bearings and each inlet air tract after the reed valves. A small amount of oil is also injected into the inlet fuel for the injectors to reduce carbon buildup on the injector nozzles.

During testing, when the engine was operating at low speeds, oil was pooling in the bottom of the crankcase. A rapid increase of engine speed would send the oil through the cylinders into the exhaust system where it would collect in the muffler and create excessive backpressure or be exhausted leaving an oil spot on the snow. To alleviate this problem, an oil recirculation system was added to the crankcase. A hole was drilled into the bottom of each half of the crankcase. Connected to the hole was a one-way check valve with tubing that led the side of the opposite cylinder where a hole was drilled into the side of each cylinder at the height of the lower piston ring when the piston was a BDC. As the piston travels down in the stroke, it pressurizes the crankcase. Oil that has pooled is forced through the check valve to the opposite cylinder where a low pressure is being created by the upward movement of that piston. This oil recirculation has reduced wasted oil and decreased piston skirt wear.

This style of precision oil-injection has been shown to greatly reduces oil consumption over traditional two-stoke engines and four-stroke engines [21]. A life assessment study of oil usage and particulate matter production showed that over the testing period a two-stroke GDI engine used 25% less oil and produced less particulate matter than both a traditional two-stroke and a four-stroke engine [21].

Fuel Delivery strategy – As stated earlier, the GDI engine can operate with a stratified or a homogeneous mixture. A homogeneous mixture is used when medium to maximum power is required while stratified combustion is be used when reduced power is required. During the 2005 CSC competition the team only used stratified combustion during idle. For the 2006 design year, the team investigated the power requirements to propel a snowmobile on groomed trails at varying incline angles and speeds.

The power produced by the engine has to be transferred from the primary clutch to the secondary clutch by a cogged belt. From the secondary clutch power is transferred to the gear reduction by the jackshaft. From the output of the gear reduction, the power is transferred to the driven shaft that is connected to the track by cogged drivers. This system can have power losses as high as 50%. A schematic of the power transfer system is shown in Figure 10.

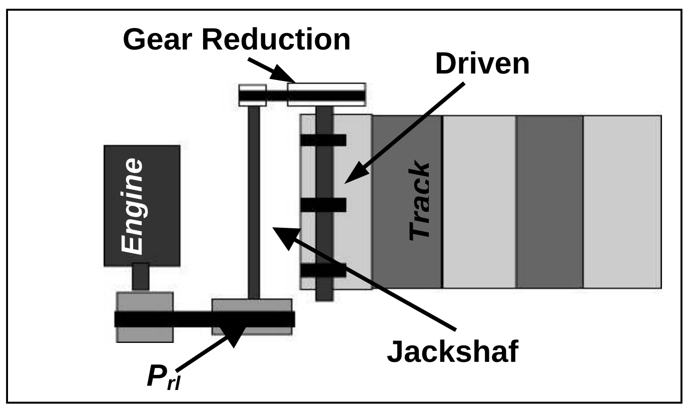

Figure 10: A schematic describing the path of power transfer for snowmobile engines.

Using research conducted at the University of Idaho, focused on developing a hybrid gasoline/electric snowmobile, the team concluded that the engine could produce enough power under stratified operation at cruising speeds [24]. Auth developed a modified road-load equation that estimated the power required (P_{rl}) to propel a snowmobile using equation (2). The coefficient C_f was based on coast down data of a snowmobile traveling at 45 m/hr (72 km/hr) on a flat and groomed trail.

Equation (2):

$$P_{rl} = \left(\frac{1}{2} \cdot C_{v3} \cdot A_p \cdot \rho \cdot V^2 + C_f \cdot M_v \cdot g \cdot \cos(\theta) + M_v \cdot g \cdot \sin(\theta) \right) \cdot V$$

Topographical data of Yellowstone National Park were used to determine the magnitude of inclines for a snowmobile trail. Using the road-load equation and the weight of the UICSC snowmobile (700 lb (N) including the rider) traveling at 45 m/hr the team was able to calculate the amount of power required at the secondary clutch. The results of the calculations are shown in Table 4.

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

Incline [deg]	θ	2	3	4	5	6	7
Power [hp]	P_{rl}	18	19	21	22	23	25

Dynamometer testing was used to determine if the engine could produce the required power during stratified operation. The engine was mapped to transfer from stratified to homogeneous operation just after a 30% throttle opening. Figure 11 shows a stratified and homogeneous control strategy similar the one used by the UICSC team. Testing was performed with the throttle set slightly below 30%, injection timing was between 60 and 80 deg BTDC, and the ignition delay was set for peak torque. Table 5 shows the results of the stratified testing. The testing shows that the engine should produce enough power to cruise under stratified operation, further increasing fuel economy.

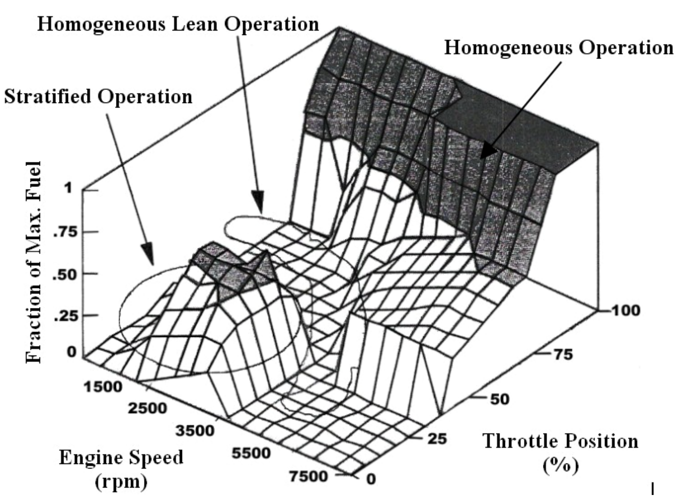

Figure 11: Stratified and homogeneous control strategy, adapted from Zhao [18].

Table 5: Measured stratified power at various engine speeds.

Engine Speed (rpm)	4000	4500	5000	5500
Power (hp)	13	15	18	23

NOISE REDUCTION – As stated earlier, the noise event measured sound pressure weighted against the A-scale. The A-scale mimics the threshold of human hearing, which is approximately 20 Hz to 20 kHz [12]. Figure 12 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.

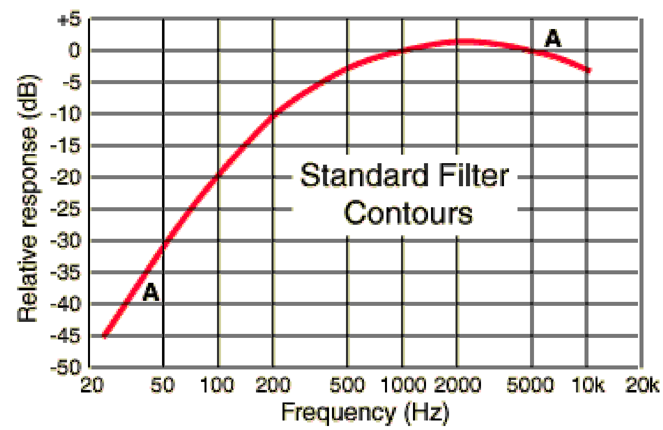

Figure 12: The A contour is more sensitive to sounds occurring between 1 and 5 kHz [25].

The A-scale mimics the human ear at 40 phons [25]. Phons are a unit of loudness that accounts for the sensitivity of the human ear at different frequencies. A loudness of x Phons is equal to an intensity of x dB at 1000 Hz [25]. Figure 13 shows equal loudness curves. Sounds at lower frequencies must have greater intensities to achieve the same loudness as sounds in the 200 Hz to 10 kHz range.

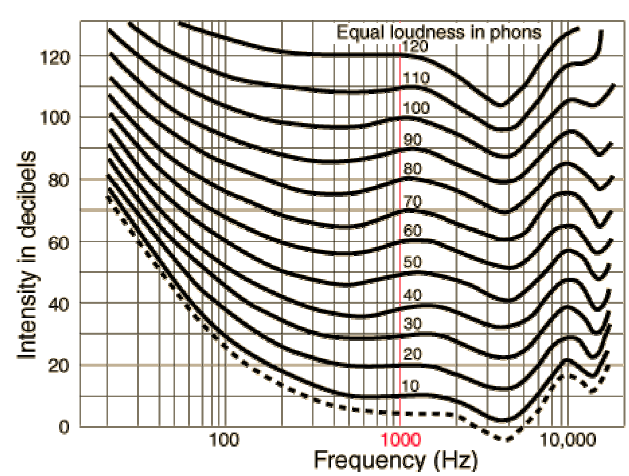

Figure 13: Phons scale showing the relationship between sound intensity and frequency [25].

For the UICSC snowmobile to be competitive in the noise event, the entire range of human hearing had to be addressed with special attention given to sounds occurring at frequencies greater than 1 kHz. There are three main sources of noise in a snowmobile: 1) air intake noise, 2) engine exhaust noise, and 3) mechanical noise emitted from the engine, drive system, and track. To reduce the noise level of the UICSC snowmobile, all three of these sources were mitigated.

Intake Noise - Intake noise in a two-stroke engine results from compression waves that travel back through the intake ducting during the scavenging cycle. As the piston travels upwards in the cylinder, a low pressure zone forms in the crankcase which opens the reed valves and allows fresh air to travel into the crankcase from the intake. When the piston travels back down the cylinder, high pressure in the crankcase forces the reed valves shut. This causes the air that was traveling into the crankcase to stack up on the reed valves creating a high-pressure region in the intake. This high-pressure region then travels back out of the air intake in the form of a compression wave. The compression wave travels through the ducting at the local speed of sound until a change in area is encountered. Stock snowmobiles are commonly equipped with baffled air boxes that are specifically designed for the sound frequencies emanating from the intake system. The air box provides a large increase in area for the compression waves traveling through the intake system, absorbing much of the exiting compression waves.

In order to provide more attenuation of intake noise, a design was incorporated into the air box to further eliminate the passage of compression waves out of the intake. The diffuser was designed to limit the amount of compression waves allowed to pass out of the air intake system while providing limited restriction of the incoming air. Figure 14 shows the diffuser design. In the figure, one of the outer shells is displaced to show the modified inner stock cone.

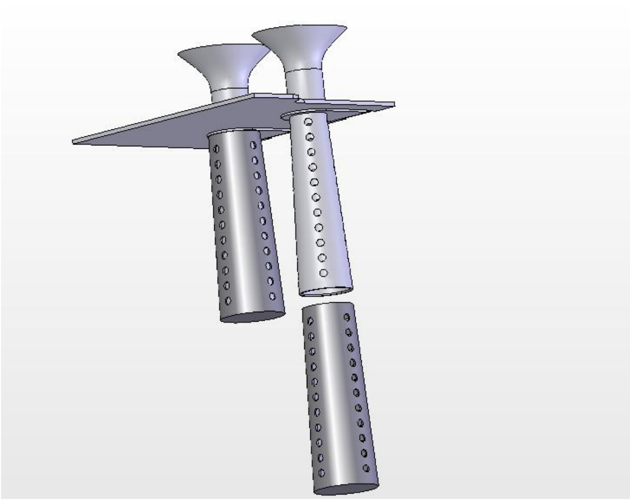

Figure 14: Solid model of the diffuser that incorporates the stock air-box cones and maintains the stock air box.

While utilizing the stock insert from the current air box, the diffuser prototype incorporates an outer shell surrounding the inner cone of the stock insert. Both the shell and cone have uniformly spaced, ¼" (0.635 cm) holes. There are 44 holes to allow the same cross-sectional flow area of a stock intake system. The holes on the outer shell and inner cone are offset 45 degrees to hinder the progression of sound while allowing air to pass through the intake.

During the prototype stage of the design, three other ideas were tested for attenuation of sounds at the same intensity. The sounds were emitted at frequencies ranging from 0 to 1 kHz and 1 kHz to 2 kHz. The results from these tests can be seen in Figure 15 below.

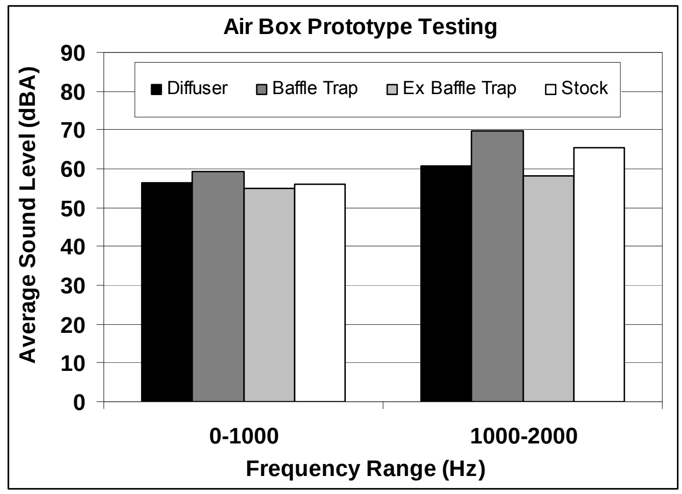

Figure 15: Experimental results for three different intake sound attenuation ideas and the stock air box.

As Figure 15 shows, the external baffle trap provided the best solution for sound attenuation. However, packaging was an issue because it needed to be mounted external to the air box. Figure 16 shows the external baffle trap mounted on top of the stock air box. Using this design would have required modifications to the hood.

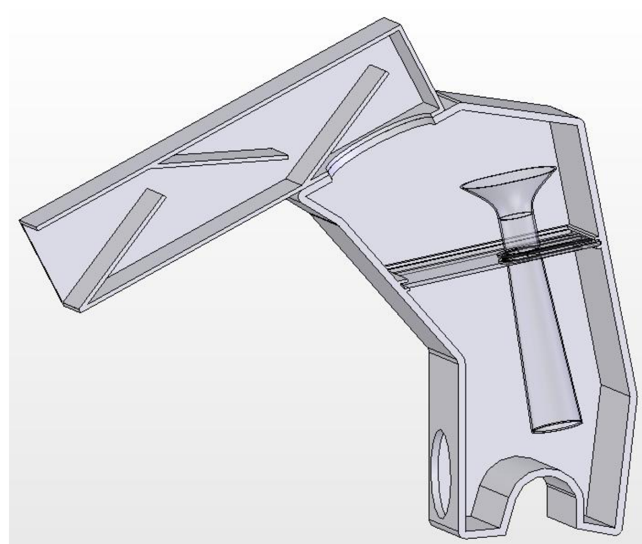

Figure 16: Solid model of the external baffle trap mounted on the stock air box with the stock inner cone.

The stock system provided the second best attenuation between 0 and 1 kHz and the third best between 1 and 2 kHz. The diffuser was third best at the lower frequencies and second best at the higher frequencies. Because the human ear is more sensitive to noises at the higher frequencies, the diffuser was used for its dampening ability in the 1 to 2 kHz range.

The next challenge that the diffuser had to overcome was to provide sufficient airflow to the engine. Testing showed that the initial diffuser prototype created a restriction of 23.3% when compared to airflow tests of a stock air box. Upon final manufacture of the diffuser, the reduction was 18.2%.

Exhaust Noise - The exhaust system on the UICSC snowmobile consists of a stock exhaust pipe and muffler along with a honeycomb style catalytic converter from a 1300 cc personal watercraft. Inside the exhaust system, the catalytic converter reflects exiting compression waves attenuating the sound emitted through the exhaust. Attached to the catalytic converter is a stainless steel extension pipe. The pipe was capped and holes were drilled in the pipe to direct sound back underneath the snowmobile. The holes also allow for the reflection of exiting compression waves and aid in attenuating noise emanating from the exhaust.

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

Absorption and redirection were the two methods used to reduce emission of noise through body vibration. Many noise-eliminating materials are found in the car audio industry. In order to determine which material combinations provided maximum noise attenuation, the UICSC team tested several of these materials in different combinations. Figure 17 below shows the results of those tests.

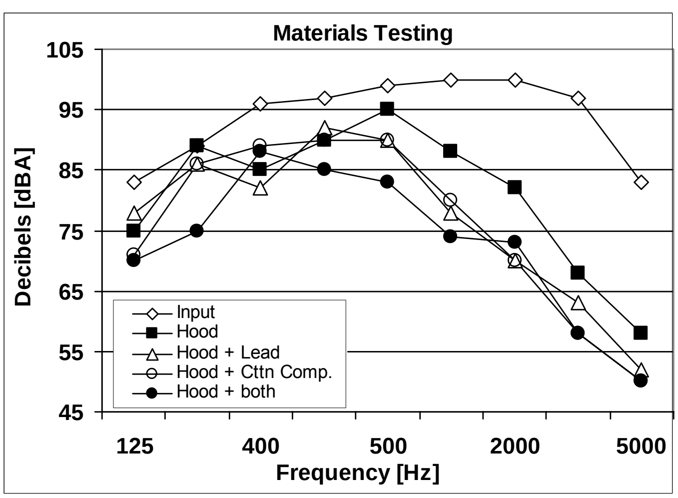

Figure 17: Cotton composite and lead impregnated foam provided the most noise attenuation.

As Figure 17 shows, the cotton composite paired with the lead impregnated foam provided the best solution for sound attenuation. This combination was used everywhere in the chassis where clearances would allow its installation. In all, three materials were used in the engine compartment. In the belly-pan and on any open metal surface, a vibration-absorbing layer was installed. On the underside of the hood, lead impregnated foam was installed to serve as a sound barrier and cotton composite material installed over the lead impregnated foam providing further noise attenuation.

An additional material used to reduce mechanical noise was a dense spray on pickup bed liner. It was applied to the underside of the tunnel. The bed liner absorbs vibrations that are transmitted from the engine to the tunnel. The bed liner material is 1/4 inch (0.65 cm) thick.

All hood vents, other than those necessary for sufficient heat dissipation, were closed off in an attempt to limit direct noise emission from the engine compartment. The air intake vents on the dash were covered with foam to muffle any sound waves that escape out of the air box.

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

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

COST - The cost of producing this snowmobile would be very similar to that of the current two-stroke touring snowmobiles. The only components that increased the cost of manufacture are the high-pressure injectors and the sound insulating materials. The Technology Implementation Cost Assessments (TICA) for the UICSC GDI snowmobile was less than $965. The final design is shown in Figure 18.

Figure 18: Final design of the UICSC GDI snowmobile.

TESTING AND RESULTS - Testing is required to determine the improvement a new design over an existing design. For the UICSC GDI snowmobile to be considered a success it needed to have better fuel economy, improved emissions, and reduced noise levels. In the previous sections, results of noise testing were presented, showing the effectiveness of noise emissions reduction.

Engine power and emissions – The emissions data provided are from preliminary testing, with no catalyst in the exhaust system. For these data, peak power output was 100 hp (75 kW) at 8000 rpm. Figures 19 and 20 compare the UHC+NOx and CO emissions (respectively) of the GDI engine to the stock carbureted engine. The GDI engine has significantly reduced emissions for all of the mode points except mode point 4 on CO emissions. Results showed the need for further tuning at Mode 4.

Figure 21 illustrates the percent reduction in fuel consumption of the GDI engine over the carbureted engine. The largest reduction was at Mode 3 with over 70% less fuel being used.

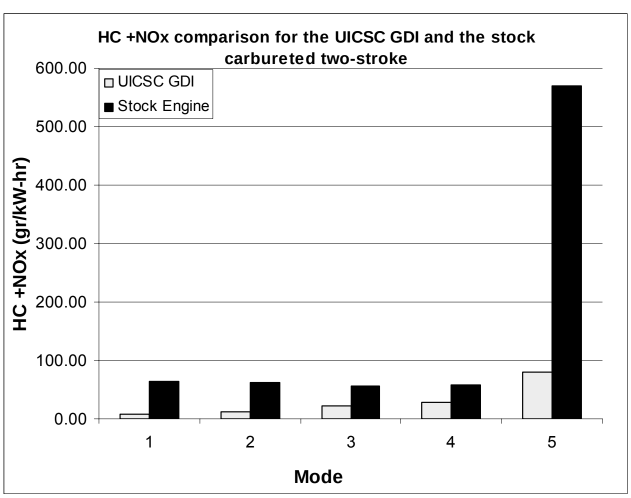

Figure 19: Five-mode HC + NO_x emissions for the UICSC GDI and the stock carbureted engine.

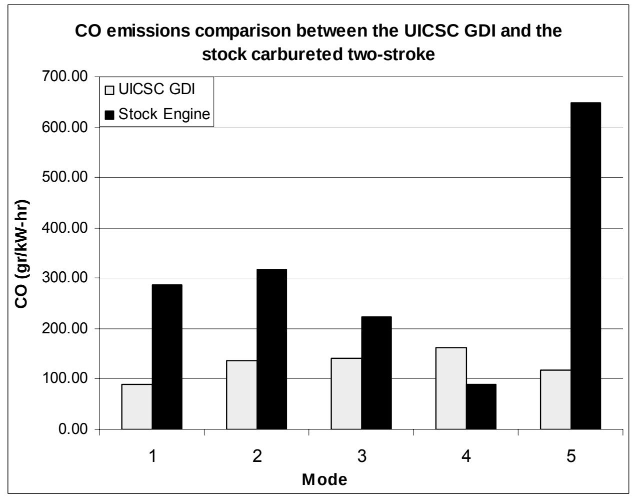

Figure 20: Five-mode CO emissions for the UICSC GDI and stock engine

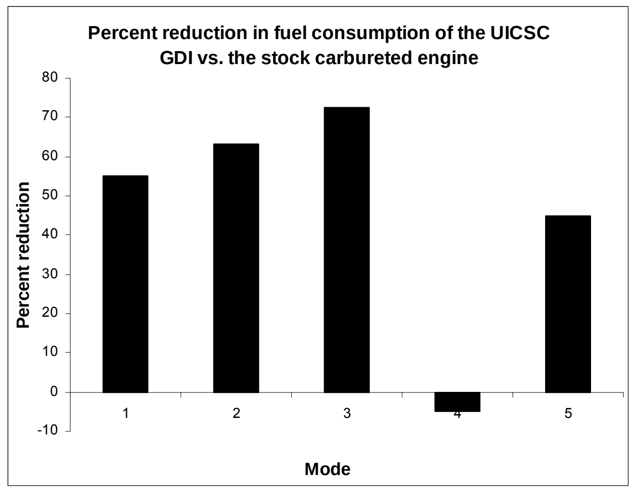

Figure 21: Five-mode percent reduction in fuel consumption of the UICSC GDI compared to the stock engine.

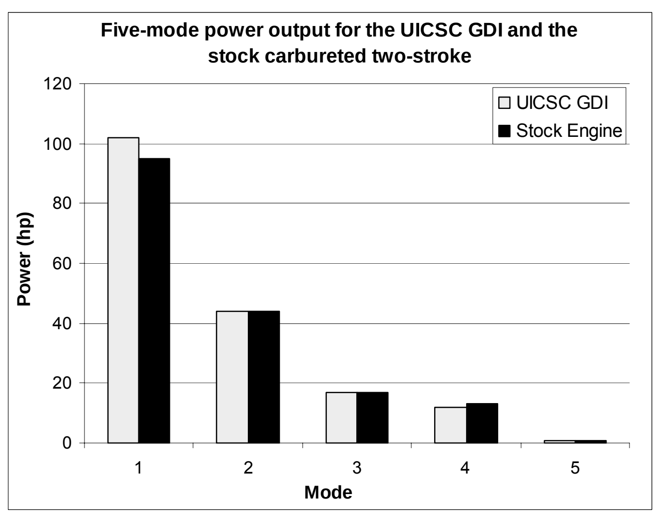

Figure 22: Five-mode power output of the UICSC GDI engine and the stock engine.

Figure 22 compares power output at each of the mode points for the GDI engine and the stock engine. Power output was comparable at all mode points showing that GDI is capable of retaining the power output of a carbureted engine.

CONCLUSION

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

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