# TABLE OF CONTENTS

EXECUTIVE SUMMARY ................................................................................................ 1  
DESCRIPTION OF PROBLEM ......................................................................................... 2  
APPROACH AND METHODOLOGY .............................................................................. 4  
  DESIGN GOALS ............................................................................................................ 4  
  DESIGN STRATEGY .................................................................................................... 5  
   Two-Stroke Operation ................................................................................................ 7  
   Direct Injection Theory ............................................................................................... 9  
DESIGN OF A GDI ENGINE ...................................................................................... 10  
BENCHMARKING/MODELING ............................................................................... 12  
   Combustion Chamber Design ................................................................................ 15  
   Engine Management System ................................................................................. 18  
   12 Volt and 45 Volt Power Supply ........................................................................ 19  
   Tuned Exhaust .......................................................................................................... 20  
   Exhaust Aftertreatment ............................................................................................. 23  
   Oil Poisoning ............................................................................................................ 24  
   Noise Reduction ........................................................................................................ 24  
   Intake and Exhaust Noise .......................................................................................... 25  
   Mechanical Noise ..................................................................................................... 27  
CHASSIS MODIFICATIONS ...................................................................................... 29  
COMFORT/SAFETY ................................................................................................... 30  
COST OF PRODUCTION ............................................................................................. 31  
TESTING AND RESULTS ........................................................................................... 31  
   Engine Power and Emissions ................................................................................. 31  
CONCLUSION ................................................................................................................. 33  
ACKNOWLEDGEMENTS .............................................................................................. 34  
REFERENCES ................................................................................................................. 35
EXECUTIVE SUMMARY

The University of Idaho’s entry into the 2004 SAE Clean Snowmobile Challenge was a proof-of-concept gasoline direct-injection (DI) two-stroke powered snowmobile. The direct injection system was designed to decrease exhaust emissions and improve fuel economy without reducing the power output of the engine. An oxidation catalyst was used to further reduce the emissions. Engine noise was reduced by using two exhaust silencers and sound absorbing materials. Chassis noise was reduced using a spray on material that absorbs vibrations transferred through the chassis. The final design was a lightweight, fuel efficient, clean, quiet, and fun-to-ride snowmobile.
DESCRIPTION OF PROBLEM

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

The NPS later published a revised alternative to the “Snowcoach Rule” in 2003, allowing a set number of snowmobiles to enter National Parks. The snowmobiles allowed to enter the Parks would be required to conform to the best available technology (BAT) standards, an “adaptive management” program, and 80 percent of the snowmobiles would have to be guided through the Parks [1]. To meet the BAT standards for emissions, snowmobiles must have unburned hydrocarbon emissions less than 15 g/kW-hr and carbon monoxide emissions less than 120 g/kW-hr [2].

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

On February 10, 2004 U.S. District Court Judge Clarence A. Brimmer stated that the January 2001 Rule is not valid, and required the NPS to provide temporary rules for the 2004 snowmobile season that are “fair and equitable” to all parties [3].

In response to this ruling, the NPS produced a compendium amendment describing the temporary rules [4]. The temporary rules allow for 780 snowmobiles, rather than the previous 493, to enter Yellowstone each day. The additional snowmobiles allowed into the park must be BAT. Furthermore, all snowmobiles must be commercially guided. In addition to the exhaust emissions standard for BAT, the snowmobiles must also produce less than 73 dBA sound pressure measured at full throttle according to the SAE J192 test procedure.

The Society of Automotive Engineers, along with many others concerned with the impact of snowmobiles on environmentally sensitive areas, began the SAE Clean Snowmobile Challenge (CSC) Student Design Competition in 2000. This competition encourages the development of touring snowmobiles that can be used in environmentally sensitive areas [5]. Competing snowmobiles are expected to produce less unburned hydrocarbons (UHC) and carbon monoxide (CO) without significantly increasing the levels of oxides of nitrogen (NOx). The snowmobiles are also expected to be quieter than the currently available technology.

If snowmobiles are to be allowed back into Yellowstone and other National Parks they must have a reduced impact on the environment. With these design goals in mind, the 2004 University of Idaho Clean Snowmobile Challenge Team (UI CSC) developed a fuel efficient, clean, and quiet snowmobile.
APPRAOCH AND METHODOLOGY

DESIGN GOALS

One goal of the CSC was to reduce CO and UHC emissions, without significantly increasing NOx, when compared to a standard consumer model four-stroke touring snowmobile. The control snowmobile for the 2004 competition is a 2003 Arctic Cat 660 non-turbo two-seater [5]. Reducing the noise emitted from the snowmobile was also a large priority for the competition. To receive points for sound reduction, the snowmobiles had to produce a sound intensity 0.5 dBA less than the control snowmobile when measured at a steady speed [5].

Another CSC goal was to improve fuel efficiency beyond that of conventional touring snowmobiles. The target range for the competition endurance event was 100 mi (161 km). Each snowmobile must complete the endurance event while following a trail judge pacing them at an average speed of 45 mph (72 km/h) [5]. This ensured that the fuel consumption for all the snowmobiles would be based on the same duty cycle.

To quantify performance and handling characteristics, the student-designed snowmobiles compete in an acceleration and a handling event. The acceleration event is based on the time it takes to travel 500 ft (152 m) starting from a stop. To pass the event, the competition snowmobile had to complete the course in less than 12 seconds. To assess handling, each of the snow machines was ridden through a slalom course. The snowmobiles were allowed to complete three laps; the shortest time of the three laps was recorded for scoring. The snowmobiles were also subjected to a morning cold start, requiring them to start within 20 seconds without starting fluids [5].

Students submitted technical design papers describing the approaches taken and the challenges met during the design and building of the snowmobiles. The teams also completed oral design presentations and presented static displays. These presentations focused on how the teams’ snowmobiles accomplished the goals of the competition.


DESIGN STRATEGY

The University of Idaho design started with a 2003 Polaris Pro-X chassis. The team chose this chassis for several reasons: It is lightweight, durable, comfortable to ride, and has a short track. All of these characteristics make it ideal for use as a trail snowmobile chassis. The chassis benefits from lightweight aluminum radius rods and chrome molybdenum trailing arms, both of which feature improved strength. Finally, this chassis was the choice because it offered a large underhood volume necessary for adapting a new power plant.

Walker Evans Racing Shocks reduced weight and are tunable and very durable. The front suspension was lightened by 2.7 lbs. by using aluminum spindles. The independent front suspension (IFS) featured lightweight, dual-rate single coil springs. The dual-piston liquid-cooled “Phantom” brake caliper is the lightest in the industry and has an improved brake rotor and long lasting brake pads. The phantom brakes required 50 percent less hand effort than standard brake systems. Further durability was gained by using a hollow jackshaft with more reinforcement and a revised chain-case cover [6].

The team improved driver ergonomics by positioning of the steering post forward, allowing for better driver control. The race seat provided for an easy transition from sitting to standing position due to a three-inch higher lift and the more forward position. The combination of the chassis improvements and the ergonomic improvements reduced driver fatigue and improved overall vehicle control [6].

The team next needed to select an engine. The University of Idaho has proved in the past that using four-stroke engines in snowmobile designs produces a fuel efficient, clean, and quiet snowmobile. However, avid snowmobile riders still prefer the lighter and more powerful two-stroke engine. The major downfalls to two-stroke engines are their high exhaust emissions and poor fuel economy. Results from experiments at Southwest
Research Institute (SwRI) shown in Table 1 clearly demonstrate the difference in exhaust emissions between two and four-stroke engines.

**Table 1: Four-Stroke and Two-Stroke Five-Mode Engine Brake-Specific Emissions and Fuel Consumption Running on 10 Percent Ethanol Fuel [7]**

<table>
<thead>
<tr>
<th>Engine</th>
<th>HC g/hp-hr</th>
<th>CO g/hp-hr</th>
<th>NOx g/hp-hr</th>
<th>BSFC lb/hp-hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four-Stroke</td>
<td>3.50</td>
<td>59.3</td>
<td>6.57</td>
<td>0.65</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two-Stroke</td>
<td>140.7</td>
<td>385.1</td>
<td>0.54</td>
<td>1.08</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 illustrates the results of fuel economy tests conducted by the 2003 UI CSC team. Both of the tables express the downfalls of current two-stroke engines.

**Table 2: Four-Stroke and Two-Stroke Snowmobile Fuel Efficiency [8]**

<table>
<thead>
<tr>
<th>Snowmobile</th>
<th>Fuel Economy (mil/gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002 U of I Competition 749cc 4-Stroke</td>
<td>16.0</td>
</tr>
<tr>
<td>2003 U of I Competition 833cc 4-Stroke</td>
<td>18.3</td>
</tr>
<tr>
<td>2003 Arctic Cat Mountain Cat 600cc EFI 2-Stroke</td>
<td>7.5</td>
</tr>
</tbody>
</table>

While standard two-stroke engines are very fuel inefficient, they have a simple mechanical design compared to their four-stroke counterparts. After considering all options available and the larger potential for improvement over current gasoline two-stroke engines, the University of Idaho decided to design and build a gasoline direct-injection (GDI) two-stroke engine.
The team also worked to improve other systems on the snowmobile. While direct-injection can reduce significantly emissions on its own, an exhaust after treatment system was designed to reach the low emissions standards of this competition. The team also designed and built an exhaust silencing system. Other areas of focus were the transfer of noise through the chassis and hood, and using lightweight components wherever possible.

**Two-Stroke Operation**

The characteristics that make two-stroke engines mechanically simple also cause poor fuel economy, poor low load operation, and high exhaust emissions. This occurs because of the way the air/fuel mixture is introduced into the combustion chamber. Unlike the four-stroke engine that has four distinct cycles- intake, compression, power, and exhaust, the two-stroke engine does all of these operations in just two cycles.

Emptying the cylinder of burned gases and replacing them with a fresh mixture (or air) is called scavenging [9]. During the scavenging process, the intake and exhaust ports are open at the same time and some of the fresh air/fuel charge is lost out the exhaust pipe. This loss of fresh fuel is called short-circuiting. Towards the end of the scavenging process, there can be a back flow of fresh charge and exhaust gas residuals into the combustion chamber due to the ramming effect of tuned exhaust pipes [10].

Stone [11] points out two very undesirable side effects of the two-stroke cycle: The short-circuiting of the fresh charge and the mixing of the fresh fuel/air mixture with the exhaust gas residuals. Tests performed at the University of Idaho show that as much as 50 percent of the fresh charge can be short-circuited (Fig. 1). The range of throttle and engine speed that matches the 50 percent short-circuited fuel is an operating zone that never actually occurs in snowmobile operation. The clutches used to transfer power from the crankshaft to the track do not engage until well above 4000 rpm. Normal snowmobile two-stroke engine operating ranges see short-circuiting of fuel ranging between 20 percent and 35 percent.
The literature states that the largest percentage of unburned hydrocarbon emissions (UHC) can be expected at low engine rpm with small throttle openings [12]. This is due to incomplete combustion, low scavenging efficiency, misfire and fuel short-circuiting [13]. The poor combustion and misfire are attributed to air-intake throttling. The restriction on the intake side of the scavenging reduces the scavenging efficiency and leaves excessive residual exhaust gases in the cylinder. The large amounts of exhaust gases present in the chamber lead to incomplete combustion and high emissions. Incomplete combustion is also responsible for poor idle quality and light load operation [14]. As engine speed increases, the scavenging process becomes more efficient, less residual exhaust gases are present, and combustion is more complete. Short-circuited fuel is by far the greatest contributor to UHC emissions.

Improving the idle quality and light load operation would have a large positive effect on fuel economy and emissions. Figure 1 shows that short-circuiting is a problem for the entire operating range of a two-stroke engine. By eliminating the short-circuited fuel, a
drastic improvement in fuel economy and a reduction in exhaust gas emissions could also be realized. Direct injection can lessen or eliminate of these negative characteristics.

Direct Injection Theory

Direct injection can lessen the effects of charge and exhaust gas mixing, and significantly reduce, if not eliminate, short-circuiting. Direct injection can also improve cold start reliability and efficiency [14]. In a GDI two-stroke, fuel is injected into the cylinder when the exhaust ports are nearly or completely closed. Air-assisted or high-pressure fuel injectors are used to ensure the fuel atomizes quickly for combustion. Two modes of combustion are used for GDI engines: homogenous and stratified.

Homogenous combustion occurs when fuel is mixed with the air before it enters the combustion chamber as in a standard spark ignition engine. For the GDI engine, the fuel is injected early in the cycle when there is plenty of time for the fuel to completely mix with the freshly scavenged air. The homogenous mixture is then ignited and the power stroke begins. As stated earlier, at low engine speeds residual exhaust gases cause incomplete combustion in a homogeneously charged two-stroke engine. It is suggested to use homogenous operation only during part load to high load operation [15].

Stratified combustion occurs when the injection event is late in the cycle and ignition is timed to occur when there is a fuel rich mixture surrounding the spark plug. With the rich condition occurring at the onset of the combustion, a reaction rate high enough to sustain stable combustion will occur [14]. The flame front moves out from the spark plug gap, burning the even leaner mixture until combustion can no longer be sustained. Stratified combustion can eliminate poor idle quality and poor low load operation [14]. Strauss [15] suggests stratified charge combustion should be used during idle and light load operation.

One potential disadvantage to this type of combustion is a potential for an increased production of NOx from the lean combustion occurring at the outer edges of the flame front [14]. This can be combated with the use of a catalyst designed for a GDI two-stroke
and the natural exhaust gas recirculation (EGR) effect of two-stroke engines with tuned exhaust pipes. For stratified combustion to occur, the injector/spark plug relationship as well as the geometry of the combustion chamber plays a significant role in combustion stability.

Although direct-injection is considered the best technology available to reduce emissions from two-stroke engines, there are many obstacles that need to be overcome for a GDI system to be successful. The injectors need to be able to atomize the fuel quickly and completely to ensure UHC emissions are kept to a minimum. The shape of the combustion chamber needs to change significantly in order to have a combustible mixture near the spark plug during ignition. Additionally, it is recommended that the engine have a multiple spark discharge system to ensure a spark event occurs when a rich mixture is near the spark plug during stratified operation [15].

Another factor limiting the development of GDI two-stroke engines is the fact that two-stroke engines operate at high engine speeds. As engine speed increases, the amount of time available to inject the fuel decreases. Coupled with the fact that the compression part of the cycle is very short, designing injectors that can atomize the fuel quickly and completely have limited the production of high power output GDI two-strokes.

**DESIGN OF A GDI ENGINE**

The UI CSC Team chose to adapt FICHT electro-mechanical direct fuel injectors from a Genesis series Polaris personal watercraft to an Arctic Cat 600 cc two-stroke engine. The injectors consisted of an accelerating pump and a fuel-retarding device that, when activated, “convert the kinetic energy of the accelerated fuel abruptly to a pressure shock wave which causes the fuel to be sprayed through the injection nozzle” [16]. Figure 2 shows a cross section of a FICHT injector.
According to Heimberg, the pump is intermittently operated during the injection pulse so the injector can be “operated with very little, optimally utilized energy and can inject fuel in a precisely controllable manner” [16]. The injectors operate on 45 volts with a peak current draw of 17 amps to increase a standard EFI fuel pressure of 35 psi (241 kPa) to over 720 psi (4.96 MPa) [15].

The team originally hoped that the power source and electronic control unit (ECU) from the watercraft could be adapted to the Arctic Cat engine. However, neither the power source nor the ECU could be adapted to the snowmobile engine. The ECU was designed for a three-cylinder engine with no options to change the programming to operate a two-cylinder engine. Along with this discovery, the team found that the injector driver was located in the watercraft ECU and it could not be adapted to the 600cc engine.

After considerable time spent researching patents, the team decided to develop an injector drive circuit. Before the UI CSC team could move forward with the project, it was necessary to determine if an injector drive circuit could be developed. As stated earlier, the basic operating principle for the injectors was understood. The FICHT injectors were designed to operate intermittently during the injection pulse (see Fig. 3).
The high frequency switching signal allows the fuel to be “hammered” in the cylinder at very high pressures.

![Graph of 45 volt signal sent to the injectors from the injector driver and 12 volt signal sent to the injector driver from the ECU]

Figure 3: Injector driver signal and ECU signal.

Standard injectors operate using a square wave signal sent from the ECU (also shown in Fig. 3). While the square wave signal sent from the ECU is high, the injectors are on; when the signal is low, the injectors are off. The team needed to develop a circuit that could convert the standard low voltage square wave sent by the ECU into the high voltage signal required by the FICHT injectors.

**BENCHMARKING/MODELING**

To develop the injector drive circuit the team worked closely with Joe Plummer, a staff electrical engineer. The only information available to the team was the patent material, the operating voltage and the maximum supply current.

The team encountered several problems during the development of the injector driver. They learned that if a particular duty cycle were exceeded, the injectors would heat up and the internal windings would short to ground, making the injector inoperable. Another major problem with the injectors occurred when the signal was quickly turned off. When the current supplied to an inductor is turned off quickly, a large voltage spike is
produced. The voltage spikes occurring from the switching of the injectors was reaching over 1200 V. The high voltage spikes were breaking down the transistors used to switch the injectors on and off. The transistors would short close allowing the 45V and 17 A power source to power the injectors at 100 percent duty cycle. The injectors would heat up and fail. A solution was finally developed that used high voltage transistors, capacitors, and high power resistors to shed the power of the voltage spikes in the form of heat.

After four iterations and three failed injectors, an injector driver was developed that allowed the injectors to flow enough fuel for the 600cc engine. Figure 4 shows the amount of fuel the injectors can supply with the latest generation circuit. The figure clearly shows the injectors are exceeding the expected potential based on information from Polaris [17].

![Prototype circuit fuel flow vs. Polaris fuel flow](image)

**Figure 4: Fuel flow of the FICHT injectors with the UI CSC injector driver and the fuel flow of the FICHT injectors while on the watercraft.**

Along with the amount of fuel supplied, the shape and velocity of the fuel cone is necessary information for the design of the combustion chamber. The FICHT injectors used in this design have an exiting sheet velocity around 50 m/s [15]. Testing at the
University of Idaho determined that the included angle of the fuel cone is approximately 14 degrees.

While the injector drive circuit and high voltage power source were being developed the stock Arctic Cat engine fuel consumption, emissions and power output were measured for future comparisons to the GDI engine. The fuel consumption measurements also allowed the team to develop preliminary full maps for the GDI engine. A nine-inch Dyno-MITE® water brake engine dynamometer, a Max Machinery 710 Fuel Measurement System, and an EMS Model 5001 5-gas emissions analyzer were used to collect the data.

The measured items were:

- Hydrocarbons (ppm)
- Carbon Monoxide (percent)
- Oxides of Nitrogen (ppm)
- Carbon Dioxide (percent)
- Oxygen (percent)
- Fuel consumption (kg/hr)
- Engine Torque (ft-lbs.)
- Engine Speed (rpm)

All of the measurements were taken versus engine speed and throttle position (percent). The testing was performed over an engine speed range from 1600 to 8500 rpm. The throttle positions were set in 10 percent increments from fully closed to fully opened.

The team wanted to use the measured emissions, power and fuel consumption data of the stock Arctic Cat engine to develop a model that could describe the projected fuel consumption of the GDI engine. The fuel consumption data collected for the stock engine included the short-circuited fuel. The GDI engine will have little to no short-circuited fuel. To calculate a projected fuel consumption curve for the GDI engine, the short-circuited fuel of the stock engine needed to be subtracted from the measured fuel flow. The calculation of the short-circuited fuel started with two assumptions:
1. There is approximately 82 percent carbon by weight in E-10 fuel [7].
2. Incomplete combustion accounts for an approximate 2 percent of UHC to be present in the exhaust stream [11].

Using these two assumptions, partial pressures and mol fractions the team was able to perform a mass balance on the carbon entering the engine and the carbon exiting the engine. After the carbon balance was performed, the amount of UHC emissions due to short-circuiting was calculated. The predicted short-circuited fuel was then subtracted from the fuel consumption and the predicted GDI fuel consumption curve was created (Fig. 5). The figure also shows that the injector driver circuit can command enough fuel flow from the injectors to supply the 600 cc engine at wide-open throttle (WOT).

![Graph showing fuel consumption and available flow](image)

**Figure 5: Injector available fuel flow, stock engine fuel consumption and predicted GDI fuel consumption at WOT.**

**Combustion Chamber Design**

The combustion chamber shape is the most critical component of a GDI system. The combustion chamber is defined by the geometry of the dome in the head and the piston surface when the piston is at top dead center (TDC). Several design factors must be
Considered in GDI combustion chamber in order to achieve low emissions operation [14]:

- Location and angle of the injector
- Location of the spark plug
- Squish area used to induce turbulence
- Shape of the dish in the piston surface
- Height of the combustion chamber

Strauss [15] shows that wall impingement of the fuel spray onto the surface of the piston is a major source of hydrocarbon emissions. He also shows that near-nozzle geometry and the distance of the fuel cone from the cylinder wall are critical for optimal fuel spray development and mixture preparation. Strauss lists design criteria that can be used to decrease the amount of fuel impingement:

1. Contain the wall fill by creating a boundary layer to avoid spreading the fuel on the piston surface (dished piston).
2. Shield the residual UHC and wall films from scavenging flow (dished piston).
3. Increase the vaporization rates by using high surface temperatures, large surface areas, and with intensive mixing (shape of dish in piston, squish band, and high pressure injectors).
4. Maximize the re-entrainment of the fuel vapor (dished piston).
5. Control the droplet rebound direction and keep them away from walls. Keep the fuel vapor contained to minimize over mixing (dished piston).

The UI CSC combustion chamber was designed with all of these considerations in mind. Because of the high sheet velocity and narrow angle of the fuel cone, the team developed a tall, offset, narrow-spacing, spray-guided combustion chamber [14]. The injectors are angled at 11 degrees towards the intake ports, with the fuel cone centered in the tall conical chamber to limit the amount of impinging fuel. The spark plug is located very near the top and center of the chamber. The near-central location of the spark plug helps obtain a symmetric flame propagation, maximizes the burn rate and specific power and decreases the heat losses [8]. The squish band around the lower portion of the chamber is shallow and provides more swirl that aides in the mixing of the fuel as well as guiding the mixture toward the spark plug [14]. Figure 6 is a cross section of the UI CSC GDI head design.
Figure 6: Cross section of the UI CSC offset and narrow-spacing head showing the injector and spark plug orientation.

The top of the piston completes the combustion chamber shape and plays a significant role in emissions characteristics of a GDI engine. Using a splash bowl aides in re-entrainment of impinging fuel, shields residual UHCs from being scavenged out, and increases surface area. Finally, the raised tip in the center of the dish is considerably hotter and helps to quickly evaporate impinging fuel [15]. The shape of the splash bowl was designed based on the splash bowl proposed by Strauss to meet the California Air Recourses Board (CARB) 3-Star emissions standards [15]. It is designed to help maintain the spray induced flow structures and improves mixing. Figure 7 shows the shape of the splash bowl in the UI CSC pistons.

Figure 7: UI CSC piston with splash bowl designed to match the fuel cone angle and diameter.
Engine Management System

There are several electronic components used to control the GDI engine. The main component is the ECU. The ECU used for this engine offers the wide range of programming options necessary for direct-injection operation. Namely, it allows the user to define when the fuel injection event and the spark event occur independent of each other, and it allows for each cylinder to be tuned individually. The ECU also compensates for altitude, air temperature, engine temperature, acceleration, and cold starts by referring to user-defined tables that adjust the fuel and ignition maps.

As stated earlier, it is important for a GDI engine to use a multiple spark discharge system (MSD). This is especially important during stratified combustion when a high-energy spark is required to ignite the mixture in the chamber. The MSD controller adapted to the UI CSC engine was initially a stand-alone system designed for snowmobiles. However, it did not offer the precise timing adjustments or the large timing advance required for the GDI engine. To make the MSD system work, the team designed a signal interrupter circuit that allowed the ECU to operate the MSD and allowed the ignition timing to be controlled precisely.

Figure 8: The final iteration of the injector driver circuit.
The last major electronic component used to control the engine was the injector driver circuit, described earlier. The final iteration injector driver circuit gave the team the ability to have precise control over the amount of fuel delivered to the engine. Figure 8 shows the final iteration of the injector driver circuit.

12 Volt and 45 Volt Power Supply

One of the largest problems the UI CSC team faced was developing a charging system that would supply both 12-volt power for the standard snowmobile items and the 45-volt power required to operate the injectors. Initially there were three options available to the team. The first idea was to adapt the stator windings from the permanent magnet alternator in the Polaris watercraft and use it in conjunction with the Arctic Cat permanent magnet alternator. However, the 45-volt watercraft stator would not fit inside the crankcase of the engine. Further, the regulator circuit used to control the output and maintain the 45 volt is located in the watercraft ECU. This option was ruled out early in the design process.

The second option the team considered was to purchase or build a 45-volt automotive alternator and use the Arctic Cat permanent magnet alternator to supply the 12-volt power as it normally does. While there are several alternators currently in development that supply 45 volts, there are none available for purchase. To build an alternator, the team purchased a standard automotive 12-volt alternator and had the stator rewound with more turns. The team then modified an automotive voltage regulator to regulate the new alternator to 45 volts. While this system worked, it was not the most desirable solution. In order to start the engine, it needs stored energy at 45 volts to operate the injectors. A battery system that could store 45 volts is heavy and expensive. An alternate solution to a battery was to use capacitors to store energy for initial start-up. While capacitors are lighter than batteries, two 2.5 F capacitors used to store the energy would only allow for 30 seconds of power to start the engine. If for some reason the engine did not start in those 30 seconds, it could not be started without the use of a 45 volt jumper battery. This solution proved to be impractical and the team continued to look for another solution. While building the 45-volt alternator, the team also developed a 12 volt to 45 volt power
converter. A power converter would allow the snowmobile to have a standard 12 volt charging system, and the 45 volts required to operate the injectors would be converted from the 12 volt system. The team found a company that was willing to build a converter but it would have cost over $5000. Joe Plummer again helped the team find a solution. A standard 1600 W 12 volt DC to 120-volt AC power converter was modified to convert 12 volt DC to 45 volt DC. The converter was modified for a cost of just over $100. This solution allowed the engine to have a standard 12-volt charging system and a standard 12-volt battery for initial startup.

The 12-volt permanent magnet alternator on the Arctic Cat engine did not produce enough electrical power to operate the ECU, MSD, injector driver and the power converter. To assist the Arctic Cat charging system, the team adapted an automotive alternator to produce the electrical power required to run all the electric systems on the snowmobile. The automotive alternator was connected to the engine block with aluminum brackets and is driven by the crankshaft with a standard v-belt pulley.

**Tuned Exhaust**

The performance characteristics of crankcase scavenged two-stroke engines depend on the ratio of the displaced volume inside the cylinder with the fresh mixture (or air); this ratio is called the charging efficiency [18]. To improve the charging efficiency and the scavenging process, the team used tuned exhaust pipes. Tuned pipes allow for an increased charging efficiency by making use of the pressure wave motion of the exhaust process and retain a larger mass of fresh charge in the cylinder [10].

Initially when the exhaust port opens the in-cylinder pressure is much greater than the pressure in the exhaust system. The higher pressures inside the cylinder coupled with an increasing diameter of the pipe creates a condition that pulls the exhaust gases out of the combustion chamber. The gases continue to expand and scavenge the combustion chamber until the pressure inside the combustion chamber is equal to ambient conditions. The gases then reach the decreasing diameter section of the pipe, where a positive pressure wave pushes some of the freshly scavenged air and some residual gases back
into the chamber just as the piston covers the exhaust port [10].

The effect of the tuned pipe is determined by the length of the pipe sections and the rate at which the cross-sectional area changes in those sections. The length of the sections determines the timing of the pressure waves while the rate of change in the area determines the intensity of the reflected waves. Using the physical geometry of the height and area of the exhaust port, pipe sections can be designed to increase the charging efficiency for a certain rpm range of an engine [10].

Because of the countless combinations of exhaust pipe geometries, the team used the engine simulation software Virtual Two-Stroke supplied by Optimum Power Technologies and equations developed by Blair [10] to aid in the design process of the tuned exhaust system. The team decided to develop two different exhaust systems and compare them to determine which would be better for the competition. One exhaust system would be a twin-pipe design developed from modeling and testing. The second system would incorporate the original Arctic Cat single pipe, re-shaped to fit into the smaller Polaris chassis.

The development of the twin pipes was based on the empirical exhaust design as explained by Blair [10]. This model uses exhaust port timing, desired peak operating speed, average exhaust temperature, and exhaust port area to develop diameters and lengths for seven sections of the exhaust pipe. Three coefficients can be changed to vary the pipe diameters depending whether it is an enduro-tuned engine or a road-racing style engine. Virtual Two-Stroke indicated that the road racing coefficients should be used.

After the modeling was completed, the team began building the twin pipes. Each section of the pipes was designed using solid modeling software. The sections were then cut from 18-gauge steel and rolled; then the seams were welded together. All the sections were then welded together, resulting in two straight pipes. The pipes were left straight until testing was performed. If the pipes performed as expected, the team knew they would
have been cut in several places, rotated, and welded back together until they fit in the chassis. Figure 9 illustrates the first construction of the first twin pipes.

Figure 9: Dual Pipe exhaust.

Because of the extended time developing the DI system and building fuel and ignition maps, the team decided there was not enough time to thoroughly test the twin pipe system. The modified stock Arctic Cat tuned pipe was used in the competition because the effect on power was already known from previous testing. The modified stock exhaust system is shown in Fig. 10.

Figure 10: The stock Arctic Cat tuned exhaust pipe modified to fit into the Polaris chassis.
Exhaust Aftertreatment

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

The effectiveness of the oxidation catalyst depends upon the wash-coat selected, the substrate structure and the location of the catalyst. The wash-coat selected was a ceria based 1:1 platinum/rhodium catalyst. This is a composition particular to two-stroke applications. Ceria based wash-coats are proven to have greater oxidation efficiencies than contending two-stroke wash-coat bases [19]. A metallic substrate was chosen over a ceramic substrate to provide for more durability. The location of the two-stroke catalysts is very important because it is more susceptible to thermal degradation and oil poisoning than conventional four-stroke catalysts [20]. The oxidation catalyst is located directly behind the expansion chamber to ensure maximum exhaust temperatures with less oil fouling.

The catalyst was constructed with an oversized substrate (2 inch diameter by 3½ inch length—5.1 cm x 8.9 cm) compared to other catalysts used in snowmobile two-stroke prototype applications. The larger size ensured a long lifetime and high activation levels. The catalyst substrate was solidly loaded into a durable structure custom fit to the exhaust system (Fig. 11).
Oil Poisoning

The total loss oil system used by the GDI engine can provide a severe threat to the operation of the catalyst. The entire oil supply including its additives and base-stock components, ultimately reaches the catalyst in either a vapor or liquid phase. This can possibly cause catalyst poisoning through losses in micro-porosity or sulfur layering [18]. Additionally, under oil fouling conditions of light loading and low temperatures, a major concern is that heavy oil oxidation could cause localized thermal deactivation. The selection of engine lubricant plays a vital role in catalyst operation and life expectancy. McCullough [18] has shown that lubrication oils with minimal levels of sulfur, calcium, and phosphorus should be strictly used in two-stroke catalyst applications. The SAE competition is sponsored by an oil company and the team used this oil at competition.

Noise Reduction

The noise event at the competition measures sound pressure weighted against the A-scale. The A-scale mimics the threshold of human hearing, which is approximately 2 KHz to 20 KHz [10]. For the UI CSC snowmobile to be competitive in the noise event, the team needed to address the entire range of noise.
There are three sources of noise in a snowmobile: air intake noise, engine exhaust noise, and mechanical noise emitted from the engine and track. To effectively reduce the overall noise of a snowmobile all three of these sources must be addressed.

**Intake and Exhaust Noise**

High pressure pulses are created in the intake and exhaust ducting of a crank-case scavenged two-stroke engine when the piston opens the ports in the engine. These pressure pulses travel through the exhaust and intake ducting at the local speed of sound until a change in area is encountered, where they are reflected. A reduction in area reflects a positive pressure pulse back towards the source while an increase in area reflects a negative pressure pulse back towards the source. By developing a system that can take advantage of this phenomenon, the sound pressure energy can be used to cancel itself out over a wide frequency range [10].

**Intake Noise**

In the case of the intake system, it is common for stock snowmobiles to be equipped with baffled air-boxes designed specifically for the sound frequencies emanating from the intake system. However, the air-box adapted from the racing chassis did not have a baffle. In order to address the noise from the intake system the interior of the air-box was lined with a dense sound absorbing material. This increased the level of acoustical energy require to make the box resonate, limiting the noise that could pass through [21].

**Exhaust Noise**

It is important to limit the amount of backpressure in a two-stroke exhaust system to allow the tuned pipe to work properly [10]. Any addition of components, such as a catalytic converter or silencer, will add backpressure and affect the ability of the tuned pipe to scavenge the engine. Because a catalyst and two silencers were used in this design, this concern was even more relevant to the design of the silencers.

To balance the performance of the silencer and the performance of the engine, the silencers were tailored to the specific acoustic output of the engine. This option allowed
for an efficient use of the available space under the hood while maintaining the high levels of noise reduction and engine performance.

The first silencer has two diffusing chambers tuned to dissipate the lower frequencies on the A-scale with most sound energy. The amount of sound attenuation was modeled using a variable geometry resonator placed on a 440 cc two-stroke. Because development of the engine prevented sound testing in an appropriate environment, the team used an analytical method using SolidWorks FlowWorks to determine the optimal internal geometry (Fig.12). The final design has low backpressure and still offers the desired level of sound attenuation (Fig. 13).

![Silencer backpressure](image)

**Figure 12:** Results of the SolidWorks FlowWorks program used to determine silencer design.

![Solid model cross-section](image)

**Figure 13:** Solid model cross-section of the diffusing silencer used on the UI CSC snowmobile.

Because the diffusing silencer only attenuated the lower frequencies, an absorption silencer was used to address the higher frequencies of noise. Absorptive silencers work
by converting sound energy into heat and are especially well suited for frequencies above four KHz. Smith describes a simple absorptive silencer as “a duct with walls lined with sound-absorbing material” [14]. However, if the sound absorbing material is packed between two concentric pipes, greater sound attenuation can be realized. The inner pipe should be perforated to allow the passage of pressure waves into the packing [10]. Figure 14 shows the final design of the silencing system with the catalytic converter attached.

![Figure 14: Silencer system with catalytic converter used in the UI CSC snowmobile.](image)

**Mechanical Noise**

The last source of noise the team addressed was the mechanical noise from the engine and the chassis. This mechanical noise is generated from the engine, clutches and track, and can be difficult to attenuate since they are not caused by pressure pulses that can be tuned and reflected. Limiting the paths that the noise can exit the snowmobile and using vibration absorbing materials are the two methods the team used to combat these noises. Using experience from past competitions, the team used several different types of sound insulation to reduce mechanical noise. One material that was used based on previous years’ experience is an insulation commonly found in the engine compartments of boats. This insulation served a double purpose by also protecting the hood and belly pan from...
the heat of the engine and exhaust system. Dynamat, another material used in previous competitions, is a dense vibration absorbing material, was placed on the surface of the clutch cover to absorb the sound energy produced by the clutches.

The last material used to reduce mechanical noise was a dense spray on pickup bed liner. It was applied to all large metal surfaces to prevent them from resonating (Fig. 15). The bed liner material is 1/16\textsuperscript{th} inch thick and added approximately 6 lbs. (2.7 kg.) to the snowmobile.

![Spray-on liner applied to the bulkhead and underside of the tunnel used to absorb mechanical sound energy transferred through the chassis.](image)

To gain the most benefit from the sound insulation in the engine compartment, a Lexan\textsuperscript{TM} hood was used (Fig. 16). The hood is completely sealed, allowing more sound insulating material to be applied as well as eliminating holes in the hood that allow sound to escape. The hood was also significantly lighter than its plastic counterpart. An added feature of this hood is that it is slightly taller than the stock hood, giving more room for the exhaust system.
CHASSIS MODIFICATIONS

The team made several modifications to adapt the Arctic Cat engine to the Polaris chassis. Modifications were also made to improve the efficiency of the chassis. The team designed and manufactured engine mounts similar to the original engine mounts that would allow the Arctic Cat engine to be bolted to the chassis. Figure 17 shows the orientation of the engine in the snowmobile chassis. The engine mounts incorporate rubber vibration dampers used to isolate engine noise and vibration from the chassis. When designing the engine mounts, the team was careful to maintain the original center-to-center distance of the crankshaft and the secondary clutch. This allowed the team to continue to use the same clutch belt.

To improve the efficiency of the snowmobile the team made several changes. The stock Hyfax was replaced with Teflon impregnated Hyperfax to decrease the friction between the track and the slides of the suspension. To decrease the weight of the snowmobile, aluminum spindles were used.
COMFORT/SAFETY

Because this snowmobile was designed for touring use, it needed to be comfortable and easy to operate. It also needed to be safe and reliable. These goals were accomplished by using an ergonomically superior chassis and adopting other design strategies. The rider position was higher and more forward than most snowmobiles. This position reduced rider fatigue and improved the drivability of the snowmobile. As with most snowmobiles, this design included hand-warmers and a thumb warmer on the throttle.

The team included several other features to improve the safety and reliability of the snowmobile. For safety, the snowmobile has three methods to turn off the engine. The rider can either turn the ignition key or use the run kill switch mounted on the handle bars. Additionally, if the rider falls from the machine, a tether switch connected to the rider will shut the engine off. A second safety feature was the isolated spill proof battery used on the snowmobile. The battery is contained in a non-conductive battery box located on top of the tunnel behind the rider. Another added safety feature is the addition of a clutch cover that extends to the centerline of the clutches. The clutch cover has woven belting riveted to the top of it to protect the rider in the unlikely event the clutches fail.
To ensure the engine life, the ECU controls the rev limit of the engine and an exhaust gas temperature (EGT) warning display is used. The ECU rev limit ensures the engine speed remains below a set level. The rider can read the EGT in real time and warning lights appear if the EGT reaches a user-defined point.

COST OF PRODUCTION

The cost of producing this snowmobile would be very similar to that of the current four-stroke, touring sleds. The only components that would increase the cost of manufacture are the high-pressure injectors, 45-volt power source, MSD, exhaust catalyst and the sound insulating materials. The injector driver and the MSD circuit can easily be manufactured inside an ECU so one unit could control the entire system. Dual voltage alternators are being developed that produce both 12 and 45 volts. After comparing the Technology Implementation Cost Assessments (TICA) for both the Arctic Cat 660 touring snowmobile used as the base snowmobile, and the UI CSC GDI snowmobile, the team found the added manufacturer’s cost for implementing the technologies found in the UI CSC snowmobile would be only $507.

TESTING AND RESULTS

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

Engine Power and Emissions

Before the competition, the team was only able to operate the engine up to 5500 rpm. Data collected at rpm and load points at or below the 5500 rpm showed that the GDI engine was making nearly as much power as the stock engine and that the fuel consumption was considerably reduced. The fuel consumption of the stock engine at idle was 1.50 kg/hr and the GDI fuel consumption at idle was 0.65 kg/hr. Figure 18 shows the torque measured for three engine rpm values. The UHC emissions were not reduced as
much as the team was hoping. A reason for this has not yet been found.

![Figure 18: Measured stock EFI torque and UI CSC GDI torque.](image-url)
CONCLUSION

The University of Idaho has developed a cost-effective, direct-injection, two-stroke engine that does not require an external high pressure fuel pump or air pump. The overall design was a success, although the full potential of the system has not yet been reached. The fuel and ignition maps were programmed to ensure the snowmobile would survive competition but they were not aimed at the low emission the team was hoping for. Further testing and engine tuning will bring the engine to its full potential.

The research conducted throughout the project showed that a GDI two-stroke engine can produce significant power while significantly reducing pollution emissions. In many cases GDI two-strokes have brake-specific emissions better than many four-stroke engines while maintaining the mechanical simplicity and low weight snowmobile riders enjoy. With continued work and development, the University of Idaho is confident that a solution for an environmentally friendly snowmobile is at hand.
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ADDITIONAL SOURCES


