Minnesota State University, Mankato SAE Clean Snowmobile Design Using a Semi-Direct Injection Two-Stroke

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ABSTRACT

This paper describes the design strategy of the 2007 Minnesota State University, Mankato Automotive Engineering Technology program's entry into the SAE Clean Snowmobile Challenge (CSC) held in Houghton, MI. The goal for this project is to make a snowmobile more environmentally friendly than production sleds without sacrificing the performance of the vehicle. Mainly, this involves finely tuning the noise and emissions. Included will be the make and model of snowmobile chosen, the fuel delivery system, changes in the electrical, exhaust, suspension, and emission systems. Also included will be rules in the CSC that we had to work around and compromises we had to make.

INTRODUCTION

The SAE Clean Snowmobile Challenge is an intercollegiate competition for students to modify an existing snowmobile to produce less harmful emissions and emit less noise while maintaining stock performance.

The specific challenge was to reengineer an Arctic Cat Sabre Cat 500 engine to produce better emissions and less noise, while maintaining the performance that the engine came with straight from the factory. The 2007 Clean Snowmobile Competition is held on March 19-24. The five day competition includes many events such as the emission test, fuel economy, static display, noise events, as well as many more.

Minnesota State University, Mankato is one of seven state universities in the Minnesota State Colleges and Universities (MnSCU) system. Located in south-central Minnesota, it is attended by over 14,000 students. MSU offers an Automotive Engineering Technology (AET) program as a four-year Baccalaureate degree through the College of Science, Engineering, and Technology. Automotive Engineering Technology is accredited by the Technology Accreditation Commission of the Accreditation Board for Engineering and Technology (TAC-ABET).

ENGINE MODIFICATIONS

FUEL SYSTEM

Semi-direct fuel injection (SDI) has stopped the extinction of the two-stroke cycle engine from snowmobiles and recreational vehicles. When the first four-stroke cycle engines were introduced in snowmobiles, it appeared that the demise of the two-stroke engine seemed inevitable with the quickly approaching 2007 emissions standards.

Bombardier was able to produce a two-stroke cycle engine with comparable emissions and fuel economy to the four-stroke cycle snowmobiles it was competing with in its' class. The semi-direct injection engine allows significantly less short circuiting of fuel as well as metering the fuel more accurately at all engine speeds[1].

The ability to create a compliant two-stroke cycle engine was a large factor in the teams' choice to step away from the four-stroke cycle engines used in the past, and start from the beginning. The team had to first examine the engine positioning in the F- series chassis to see where there was enough room to place the injectors in the engine. Due to the space limitations of the chassis there were only a few choices. In addition to the space requirements for injectors, the team had to research the number of injectors to use per cylinder, as this would increase the space needed drastically. Ski-Doo's 1000cc SDI and Polaris both incorporate two injectors per cylinder. One of which is a smaller injector which is used for idle and low RPM performance. The second is slightly larger and is run together with the smaller one at higher RPM and load. Skidoo's 600 SDI uses two identical injectors per cylinder, however; they maintain staged injection.

The injectors' on-time and injection timing in relation to the piston movement is controlled by the Engine Control Unit (ECU). The earlier SDI models in watercraft, and snowmobiles incorporated one large injector per cylinder. This produces slightly higher emissions and less control at lower RPM due to the lower end stability (See glossary) limitations.

Last year, primarily due to space and time constraints, the single large injector per cylinder design was chosen, sacrificing fuel control accuracy at low RPM. For 2007 two injectors per cylinder were integrated, allowing more accurate control at lower RPM.

The design intent for 2007 was originally to use two SDI injectors per cylinder, with a primary injector on the front side, and a secondary injector in the rear. Figure 1 shows this injector placement.


Figure 1

Due to the flow characteristics of the engine, the only available placement of a secondary SDI injector would have caused the fuel to travel directly into the exhaust port. As a result, the decision

was made to use a set of throttle body injectors as the secondary injectors.
The primary injectors have been placed in the main transfer port of each cylinder.

The team used Siemens Deka Type 36 injectors as primary injectors, the same injectors used in the Ski-Doo 600 SDI snowmobiles. The secondary injectors are a Siemens Deka Type 3, which are a shorter body and have better lower end stability. Ideally we would have liked to use the Type 3 injectors for all 4 injectors; however, a delay in receiving the type 3 injectors would not have allowed sufficient development time.

Wet Flow

Once the general injector location was identified, the team utilized a wet flow system to determine the best injector angle into the transfer port. The wet flow system consists of a SuperFlow SF-1020 flow bench, pressurized liquid tank, OTC Injector Pulse Tool, fluorescent die, a black light, an acrylic cylinder head.

The flow bench supplys air to air inlet opening of the engine as shown in Figure 3. A small amount of water with a fluorescent die is injected into the air stream at possible injector locations to simulate the fuel. The liquid is delivered through a fuel injector into the transfer port as shown in Figure 2. A combustion chamber was machined out of acrylic plastic to the specifications of the stock cylinder head. The acrylic head allowed the team to view the flow patterns and fuel distribution in the combustion chamber using a black light. Figure 3 shows the wet flow bench set up and ready to flow.

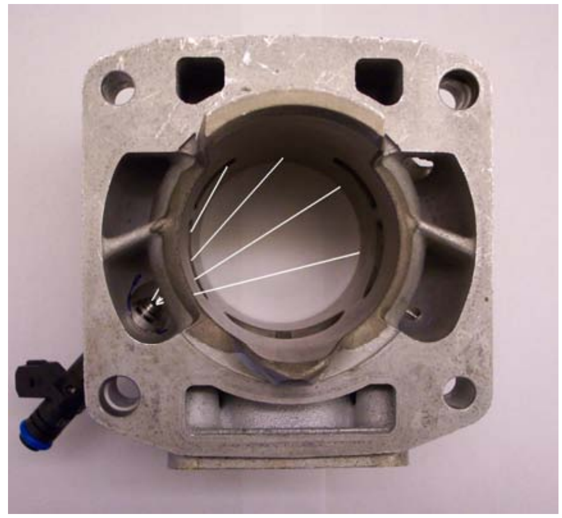
Figure 2 (View from bottom of cylinder)

Figure 3

The team tested the flow at 30, 35 and 40 degrees into the side of the cylinder; Figure 4 shows the placement of the injector at the 30 degree angle into the cylinder.

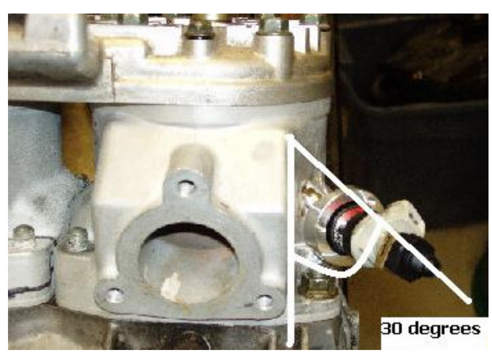

Figure 4

Based on visual dynamic flow characteristics the 40 degree position was chosen over the 30 and 35 degree positions. This was chosen because the 40 degree had an even distribution of fuel and flow through the cylinder didn't promote short circuiting. This was accomplished due to the flow being injected into the cylinder opposite the exhaust port. This placement allowed the movement of fuel to follow the counter clockwise movement of the air entering the cylinder allowing for better fuel atomization. The 40 degree also fit for packaging the injector within the available under hood space. All data was subjective, based on visual observations. Figure 5 shows the concentration of liquid in the cylinder while wet flowing. The neon green in the combustion chamber is the fluorescent dye, and the purple is the black light used to make the dye standout.

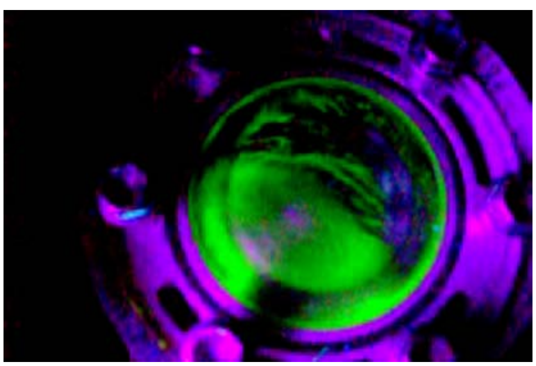

Figure 5

The teams' research concluded that the swirl increases fuel mixture, improving the efficiency of the engine [2].

ENGINE CONTROL UNIT

The team used a MoTeC M48 engine management system. The M48 allowed injection to be controlled sequentially in order to conserve fuel. In addition, the fuel and ignition could be controlled three dimensionally, this allowed precise control over the ignition and fuel delivery, which ensured optimum performance for the full range of operating conditions. The ECU also gave the team an infinite variety of choices for the ignition coil, module, and trigger system. Additional reasons the team chose the M48 include a sensor sampling rate of 480 times per second, low physical weight, low current draw, and compatibility with the sled's relatively high RPM range.

In order to take full advantage of the controllability of the low impedance injectors, a number of inputs were used for ECU compensation. These included:

- 108 kPa Manifold Absolute Pressure (used for barometric pressure)
- Intake air temperature sensor
- Engine temperature sensor
- Stock throttle position sensor

The ECU reads the RPM of the engine by inputting signals from a reference and a synchronization sensor. The reference input allows the ECU to read the RPM of the engine while the synchronization input tells the ECU where the engine is in relation to Top Dead Center of cylinder 1. To achieve these inputs, a trigger wheel with 12 teeth, 30 degrees apart was designed. Using 12 teeth allows for higher resolution of the engine RPM, allowing the ECU to compensate more accurately than with the stock two-tooth design. Figure 6 below shows a CAD drawing of the 12 tooth trigger wheel.

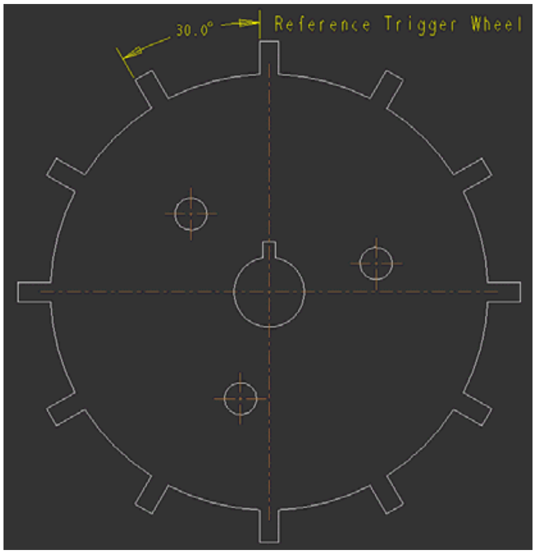

Figure 6

The stock Arctic Cat ignition flywheel trigger system was then modified. The stock flywheel had two teeth, 180 degrees apart and was modified to only have one tooth. The position of this extra tooth was then programmed in the ECU to be used as the synchronization sensor. The trigger wheel was mounted to the flywheel, and a spacer was designed and fabricated to space the recoil starter out the proper distance. The sensors were located using the stock mounting location with minimum modification to the mounting studs.

The ECU's internal drivers were able to trigger the injectors using a small electrical draw while providing an injector pulse width accuracy of 10 microseconds, while keeping heat buildup inside the ECU to a minimum. The sensors combined with the M48 engine management system allowed the team to map the fuel system for peak torque and low emissions using a Land and Sea water brake dynamometer (Figure 7).

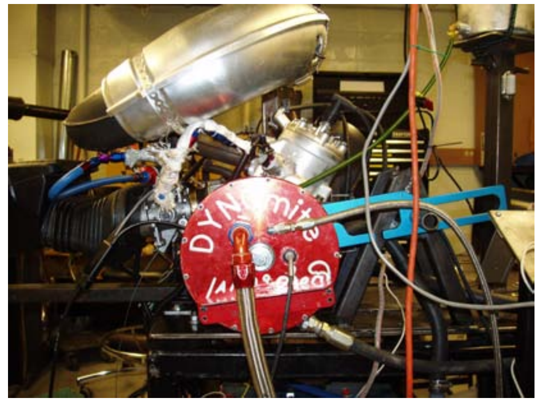
Figure 7

CHASSIS MODIFICATIONS

The competition is geared toward the average trail touring rider. The modifications made for performance and handling such as the traction studs and handlebar riser, along with the race proven F- series chassis sufficiently fulfill the performance for the typical trail snowmobile. In order to accommodate the "non stop all day long" snowmobile enthusiast the team incorporated some aftermarket products to increase the ride ability and comfort.

FUEL TANK

Due to the use of E85, fuel demand is much higher than conventional gasoline. Based on calculations using the brake specific fuel consumption from a carbureted 500cc snowmobile and the lower BTU content of E85, 14 gallons of fuel was determined to be the requirement to drive 100 miles at trail speeds.

Due to the 13 gallon stock fuel tank size, a new fuel tank was needed to fulfill the 14 gallon fuel requirement. As there were no larger replacement fit fuel tanks with the necessary fuel capacity, the decision was made to fabricate a fuel tank from aluminum. Because of the packaging conflicts on the snowmobile, the decision was made to incorporate the fuel under and behind the seat. This allowed the team to have the freedom to design a fuel tank that would meet the capacity needs.

The first challenge in designing a gas tank was making the tank ergonomic. To overcome this challenge, the fuel tank was tapered from 10.5 inches on the bottom to 9 inches at the top. The tank was also designed to maintain a similar seat height as the stock seat.

The second challenge was to design a tank that would keep the fuel from moving excessively inside the tank. Because of the length of the tank, it was apparent that due to acceleration and deceleration, the fuel mass would want slosh. To combat this problem, three baffles were installed to help provide resistance to the movement of the fuel.

A readily available fuel pump was chosen that was mounted in the tank which meant that lines would need to be run to the pump. Steel lines were selected to reduce the risk of fittings coming loose inside the fuel tank when it was sealed. An access cover was incorporated in case the fuel pump would need to be serviced.

Initially the gas tank was also going to serve as the rider's seat; this was determined to be a difficult hurdle. To combat this problem the team chose to build a skeleton frame over the gas tank to support the weight of the rider.

COMFORT MODIFICATIONS

To compliment the new seating position, a handle bar riser one and one-half inches taller than the stock equipment was added to move the bars to a higher position. This position allows the rider to sit comfortably while maintaining better control, and a more aggressive riding position for the performance oriented rider. To compliment raising the handlebars to this new height, a set of Powermadd hand guards were also installed. These guards reduced the amount of cold winter air coming into direct contact with the riders' hands, while protecting them from the unexpected tree branch or track spray from another snowmobile. These additions combine to increase the comfort, control, and assist the "non-stop all day long" snowmobile enthusiast with a comfortable and enjoyable riding experience.

PERFORMANCE MODIFICATIONS

The performance aspects of the competition include acceleration and handling events. The competition purpose clearly states, "the competitors' snowmobiles are to retain or improve upon the stock snowmobiles performance characteristics". In order to accomplish this task the team chose to use the Arctic Cat F5 due to its light weight, crisp power, performance oriented suspension, and chassis. These aspects combined with the ability to use traction products such as studs and carbides will allow the team to keep the modified snowmobile up to par with the stock sled.

The team chose to install 102 Woody's Gold Digger studs in the track using the only standard pattern legal for the competition. In order to compliment this stud pattern on the F5, Woody's suggested the team install six inch Trail

Blazer ski runners. This combination will produce a performance oriented snowmobile, with decreased braking distance and spot on handling for the competition events.

ELECTRICAL

The main issue that needed to be addressed was the inability of the stock charging system to keep up with the added electrical demand. This demand was produced by the more sophisticated engine management system. The team looked at several different reasons why the snowmobile was unable to keep the total system charged.

The first obstacle was to calculate the total amps the system used. The fuel pump, ignition coil & module, lights, and ECU all had their amp usage plotted thru a set RPM range. This allowed the team to approximate what the given electrical load would be at different points. Additional electrical loads such as thumb warmers, brake light, Digitron, were calculated and then added to the total amp draw. After all calculations were completed, a range of 14-16 amps was determined as the required amperage necessary for the snowmobile. Though this was higher than expected, it was not unreasonable to obtain.

After the total system load was determined, voltages were taken before and after the rectifier bridge. At first it appeared that the voltage leaving the rectifier bridge was extremely low, 7.7 volts at 3,000 RPM. To fix this issue the stator was removed from the engine, unwound of its copper wire, and rewound with the same gauge wire with twice the number of turns.

(Stock stator)

(Rewound stator)

In theory this modification would produce twice as many volts at the same RPM, but still maintain its high amp capability.

Once the stator was rewound and installed back into the engine, the voltage reading was taken after the rectifier bridge. First tests proved the theory correct, 14.7 volts were seen at 3,000 rpm, and the charging system was able to exceed system requirements. After time the voltage then appeared to drop off as the rectifier bridge heated. The output voltage of the rectifier dropped from 14.6 volts to 6.4 volts in 10 minutes. Retesting of the voltages before and after the rectifier bridge proved that it was the rectifier that was failing and not the stator. The initial rectifier was replaced with a small 10 amp rectifier. Once installed, the same voltage readings were taken. Testing showed that it was the old rectifier bridge that was at fault. The voltage exiting the rectifier increased excessively. In fear of boiling the battery the rewound stator was taken out and the stock stator was the reinstalled. A custom rectifier bridge was made by mounting four 70 amp diodes on two separate pieces of aluminum. See figure 8.

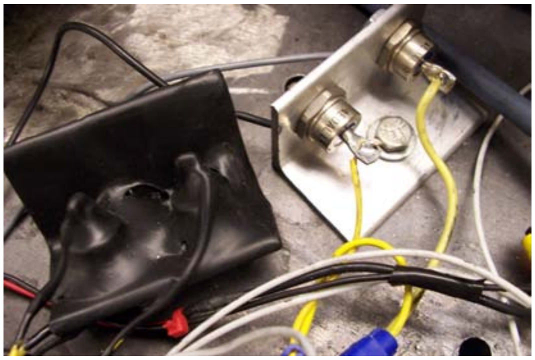

Figure 8

After installing the new rectifier bridge, the team took voltage and amp readings with the full electrical system in use. The stator and rectifier fulfilled the electrical demand, even after simulating a 25 amp load for 2 minutes.

Attention was then set to the creation of the wire harnesses after the charging system was corrected. It was decided that two wire harnesses were to be created. One for the engine testing bench and one for the chassis. Both harnesses would have their own dedicated engine sensors, fuel pump, ignition system, and battery. This would then provide a quick and easy exchange of the ECU from the test bench to the snowmobile. Due to the use of non stock exhaust, fuel tank, and catalyst location, placement of the relays, ECU, fuse block, battery, and wire loom was difficult, but placement was found for all the components.

EMISSIONS

As stated previously, the engine of choice was a Suzuki 500cc two stroke engine. Past CSC competitions have proven that a 4 stroke engine has been more efficient than a two-stroke, however, there are also more drawbacks that it presents. A four-stroke engine is much heavier than a two-stroke, as well as more expensive. Making a snowmobile that is lightweight and cost effective were important factors to take into consideration. Two strokes are much more prevalent in the snowmobile industry; therefore, reengineering a two stroke engine seemed more practical.

With emissions being one of the key focuses in the CSC, significant time and effort were put in to sellecting the correct parameters for this year's snowmobile. Along with the correct catalyst, fuel, engine management system, and secondary air supply, the two stroke engine can be significantly improved.

CATALYST

The emissions goal for the CSC competition is to reduce HC, CO, and NOx levels as much as possible. Heraeus Catalyst Company helped tailor a catalyst that would work the best with a 2-stroke snowmobile. By giving them engine and exhaust parameters, they recommended using a three way honeycomb style catalyst system that was loaded with 50 g/ft^3 of Platinum, Palladium, and Rhodium. [3] Two stroke engines are generally high in HC and CO and lower in NOx, so a two way catalyst would have worked sufficiently, but the 3 way catalyst was donated to the team by the Heraeus Catalyst Company.

The placement of the catalyst proved to be crucial. After looking at many other snowmobiles and other methods of research, it was decided to put our catalyst right after the tuned pipe coming out of the engine. As with every catalytic converter, the generation of heat becomes an issue. To help remedy this, a steel box was built to enclose the converter and keep as much heat away from the under hood area as possible. Along with this, a section of the hood enclosure was removed to allow outside air in to aid in the cooling.

To save as much under hood space as possible, a 60.5mm x 74.5mm catalyst was chosen. Past CSC teams have used catalysts that were 105mm x 90mm. The density of the catalyst is 200 cpsi (cells per square inch). This is a normal density for a catalyst. More cells per square inches results in better oxidation of the Hydrocarbons and Carbon Monoxide, but it also means more restriction in the exhaust system.

AIR PUMP

A secondary air pump was used for the further reduction of the HC and CO emissions. Air is pumped into the exhaust system upstream from the catalytic converter through a port in the exhaust pipe. The oxygen from the pump will help oxidize the unburned HC and CO and turn them into water and carbon dioxide. The equations below show how the secondary air system will how this is performed. [2]

$4HC + 50_2 \Rightarrow 2H_20 + 2CO_2$

$2CO + O_2 \Rightarrow 2CO_2$

Due to packaging issue on the right side of the engine bay, placing the air pump on this side was not an option. Therefore, the clutch side is the only other option besides an electric pump. An electric pump was considered, but the CFM output compared to amperage usage was too high for our application. Therefore, a mechanical drive using a pulley off the primary clutch was utilized as shown in Figure 9.

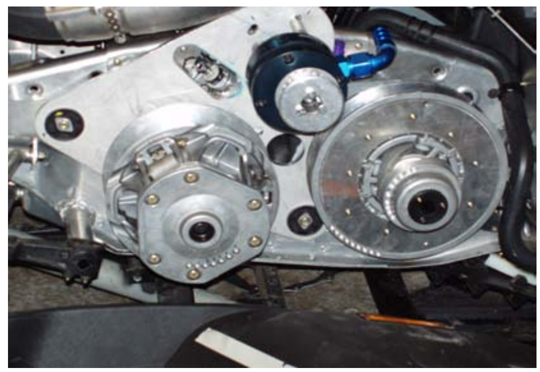

Figure 9

The pump flowed 32 cubic feet of air per minute at 6,000 RPM, and the engine was capable of 8,000 RPM, [4] so a reduced ratio of 1.32:1 was used. [5] A custom bracket was made to accept the pump that mounts in place of the original.

NOISE REDUCTION

With the sound levels of snowmobiles becoming more of an issue for the industry, the team had to consider its' options to reduce the sound levels of the new engine. Due to the base engine being a two-stroke cycle engine, sound levels were an important aspect to improve upon. Specific areas the team focused on in an effort to reduce noise were the incorporation of sound deadening materials to the inside of the hood and the addition of an absorption style silencer.

EXHAUST SYSTEM

A two-inch diameter exhaust tube after the tuned pipe was used to build our exhaust. This tubing, with mandrel bends, was used in addition with a straight through absorption style muffler (figure 10) to keep backpressure to a minimum. Applying the equation for head loss *[Head Loss = f (Lv^2/D)]* where; frictional loss (f), length (L), velocity (v), and diameter (D) are used to show as the diameter increases the head loss in a pipe will decrease. Higher head loss can be compared to adding more restriction [6].


Figure 10

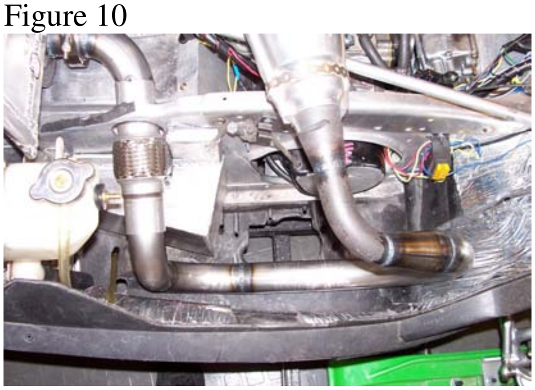
Figure 11

The exhaust pipe was routed through the side of the track tunnel in front of the gas tank and into a silencer that sits on top of the tunnel approximately where the stock gas tank was located. See Figure 11. The inlet and outlet of the silencer are both located on the front side of the silencer. The exhaust tailpipe will be routed through the front of the tunnel and pointed straight down at the ground. This location has several advantages that will further reduce noise levels. The air turbulence that builds up in front of the tunnel due to the spinning track will help to muffle the pressure waves coming out of the exhaust.

The team chose this method as an effective way to maintain adequate ground clearance over a variety of obstacles. Eliminating the stock silencer gave us room under the hood to mount the catalytic converter.

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