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Minnesota State University

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ABSTRACT

Illustrated within this paper is Minnesota State University, Mankato Automotive Engineering Technology program's entry to the 2003 Clean Snowmobile Challenge held in Houghton, Michigan. Encompassed in this report are the criteria of performance, emissions, chassis, noise control, and results. Characterized in these criteria are the engine modifications and reasoning for the changes implemented.

The 2003 Clean Snowmobile Challenge (CSC) allowed the MSU students to concentrate on a thorough comparison of a two-stroke cycle engine vs. a four-stroke cycle engine in the areas listed. Extensive modifications and tests were performed on these two engines in order to provide significant data for performance, emissions and noise.

INTRODUCTION

The Society of Automotive Engineers (SAE) created the Clean Snowmobile Challenge to respond to the concerns of snowmobiling impacts on environmentally sensitive areas. The performance, emission, and noise levels of snowmobiles, affect the well being of people, wildlife, and the environment. The objective of this competition was to challenge engineering students to effectively decrease the emissions and noise pollutions that a snowmobile produces, while maintaining performance and cost effectiveness. This competition allows engineering students to generate ideas for existing production snowmobiles that can be applied to the future of the snowmobiling industry, which will help our environment.

Minnesota State University, Mankato (MSU) was one of 14 colleges and universities approved by SAE for the 2003 competition. The entrants were selected by an evaluation of each school's submitted design proposal. The competition was conducted on March 19-24, 2003 at Michigan Technological University (MTU) in Houghton, MI.

Minnesota State University, Mankato is one of seven Universities in the Minnesota State Colleges and Universities (MnSCU) system. Located in south-central Minnesota, it is attended by over 13,000 students. MSU offers an Automotive Engineering Technology (AET) program as a four-year Baccalaureate Degree of Science through the College of Science, Engineering, and Technology.

The AET program consists of 182 Students pursuing a degree in the field, with 39 of those students scheduled for graduation during the 2002-2003 academic year. The Technology Accreditation Commission and the Accreditation Board for Engineering Technology (TAC-ABET) accredit this program.

Each student in the AET Baccalaureate Degree must complete a comprehensive senior design project; 10 seniors selected the 2003 Clean Snowmobile Challenge to satisfy this requirement. These 10 seniors, along with 9 underclass students joined together to form the MSU Mavericks Clean Snowmobile Team, Figure 1. The 2002 entry for this competition influenced modifications and improvements for the CSC 2003. The team was guided by SAE rules and regulations, which needed to be met to succeed in developing the best snowmobile for the competition.

Figure 1, Minnesota State University, Mankato Mavericks Clean Snowmobile Challenge Team 2003

The students worked together and organized an analysis of the two most commonly used power plants of today's snowmobiles; a two-stroke cycle snowmobile engine and a four-stroke cycle all terrain vehicles (ATV) engine. These were chosen and modified to participate in the competition. Both engines were evaluated for their strengths and weaknesses in the eight judging criteria, and both engines were compared for best performance, emissions, and noise results.

The MSU Maverick's snowmobile teams were divided into five design and development groups to efficiently design and manufacture a competitive snowmobile entry. Senior members chose an area, which best suited there interests and experience.

These groups specialized in:

- Two–stroke Cycle Direct Injection Development
- Four–Stroke Cycle E85 Engine
- Exhaust
- Noise
- Chassis.

The two-stroke cycle engine team decided to use a high pressure spark direct injection system, which uses a computer controlled engine management system that enables the control of components such as fuel injectors, electronic sensors, and emission controls. The four–stroke cycle engine team designed a fuel injection system to replace the stock carburetor, and tuned the engine to run on E85 blend of 85% ethanol and 15% gasoline.

The exhaust team researched the control of emissions and noise. Options considered by the team included the use of a catalytic converter and electronically controlled exhaust valves.

The chassis team implemented improvements on the suspension, braking, clutching, and appearance to insure the best handling abilities as well as drive train efficiency.

The MSU Mavericks gathered weekly for open discussion of ideas and made decisions for further development. The weekly meetings provided an insight to any problems or improvements and determined the next course of action. This allowed time for the project to be a well-developed competitive entry.

Two – Stroke Cycle and Four – Stroke Cycle Engine Comparison

Two – Stroke Cycle Engine

The use of the two–stroke cycle engine was an ideal application for a snowmobile. The lubrication capabilities are adequate for sub-zero temperatures and the power to weight ratio is optimal for snowmobile performance. The two–stroke cycle engine has greater power output compared to a four-stroke cycle engine of the same displacement mainly because the two-stoke cycle engine has twice as many power strokes per revolution. Conversely, this engine creates higher emissions, and is less efficient than a four-stroke cycle engine. These emissions and efficiency problems are mainly caused by the increase of short-circuiting during the scavenging process. These effects are what have given rise to environmental concerns that need to be addressed.

Base Engine

The objective of the competition was to re-design a snowmobile to improve performance, emissions, and noise while meeting the requirements within the SAE rules. Since a stock two-stroke cycle engine creates high emissions and has poor fuel economy, it seemed to be the best choice to re-design for the competition.

To address these technical challenges the two-stroke cycle engine team developed upgrades to a Polaris 500-cc, variable exhaust, twin cylinder engine. The baseline engine carries some of the advances of modern technology, but demonstrated room for improvements.

Stock Mechanical System

The base two-stroke cycle engine consisted of a readily available Polaris 500 cc power plant. The engine was manufactured with exhaust power valves, which are fully closed under 5300 RPM, and fully open above 5300 RPM. The increase of cylinder pressure physically opens the valves, which increases the size of the exhaust ports.

The increase in port size allows more exhaust flow. With a variable exhaust ports, at low engine RPM; the ports will be smaller which will produce a higher torque band.

When engines pressures rise, the power valves open and create a higher power band.

The combustion chamber design of the stock head was a hemispherical dome with the spark plug in a central location. A centralized spark plug in the combustion chamber reduces the need for timing advance because the flame front has less distance to travel. The shorter distance the flame front has to travel, the lower chance detonation occurring. [Stone] (2)

Stock Electrical System

The two-stroke cycle engine utilized a half sine wave, 285-watt stator running into a two-wire voltage regulator/rectifier. This system was adequate for the electrical requirements of the stock 500 cc engine.

Stock Fuel system

The fuel and air induction system on the stock 500 cc engine consisted of two 38mm Mikuni™ carburetors. Fuel was provided by a gravity fed, mechanically driven diaphragm style fuel pump.

Engine Modifications

In order to improve on today's technology; engineering technology students were able to modify the Polaris 500-cc two-stroke cycle engine to achieve competitive results. Modifications were made to the stock mechanical, electrical, and fuel systems to incorporate a high-pressure spark ignition direct injection system (SIDI). All modifications took into account durability, noise, emissions, and performance.

The internal mechanical system of the engine was kept near stock to control the cost and retain the durability of the snowmobile. The engine utilized stock Polaris pistons, crank, cylinders, and crankcase.

The following table displays the differences between the two-stroke cycle stock and modified engine. (Table 1-A)

Combustion Chamber Modifications

The creation of the combustion chamber involved consideration of the surface-to-volume ratio, combustion control, and thermal loading. These factors where first addressed by last years team and have been improved for this year's design of MSU's two-stroke cycle SIDI engine.

The decrease of the surface-to-volume ratio reduces hydrocarbon (HC) emissions. This is due to the fact that with lower surface area there is less cylinder wall wetting. As a result, more fuel remains atomized in the burn mixture resulting in more efficient, overall operation.

	STOCK ENGINE	MODIFIED ENGINE
COMPRESSION RATIO (TRAPPED)	6.07:1	6.57:1
COMPRESSION RATIO (FULL-STROKE)	10.91:1	13.44:1
BORE	70.5 MM (2.776 IN)	70.5 MM (2.776 IN)
STROKE	64 MM (2.520IN)	64 MM (2.520IN)
HEAD VOLUME (UNINSTALLED)	26.5 CC	24.4 CC
HEAD VOLUME (INSTALLED)	25.2 CC	23.7 CC
SQUISH CLEARANCE	1.65 MM	1.27 MM
SQUISH AREA RATIO	42.8%	39.8%
SQUISH VELOCITY	17.2 M/S @ 12° BTDC	34.2 M/S @ 9° BTDC
PEAK POWER RPM	7700	7800
CRANKING PRESSURE	133 PSI	165 PSI
EXHAUST PORT OPEN	77° A&B TDC	77° A&B TDC
PUMP OCTANE	85	92
FUEL DELIVERY SYSTEM	2 MIKUNI TM 38 MM FLAT SLIDE CARB	MOTEC CONTROLLED SIEMENS HPDI
CHARGING SYSTEM	280 WATTS	1224 WATTS
SPARK PLUG/GAP	CHAMPION RN57YC/ 0.028"	NGK R CR9E/0.035"
POWER SAE	67.86kW (97HP)	59.66kW (102 HP)

Table 1

The combustion chamber was also designed for maximum squish velocity. By designing for maximum squish velocity, the air/fuel charge is forced from the squish area towards the centrally located spark plug. When the fresh air/fuel charge is forced around the spark plug, the fuel stays atomized and a stratified charge is induced in the combustion chamber. This design allows for a leaner air/fuel ratio, which in turn improves performance and emission characteristics.

The fuel injector was placed in a central location to eliminate cylinder wall wetting. To obtain a stratified charge, the fuel is sprayed at 7584 kPa (1100 psi) with a 30-degree cone angle directly onto the incoming piston. The spark plug was placed at a 30° angle with respect to the fuel injector. The 30° angle was chosen to keep the spark plug in a centralized location and provide a compact design. (See Figure 2)

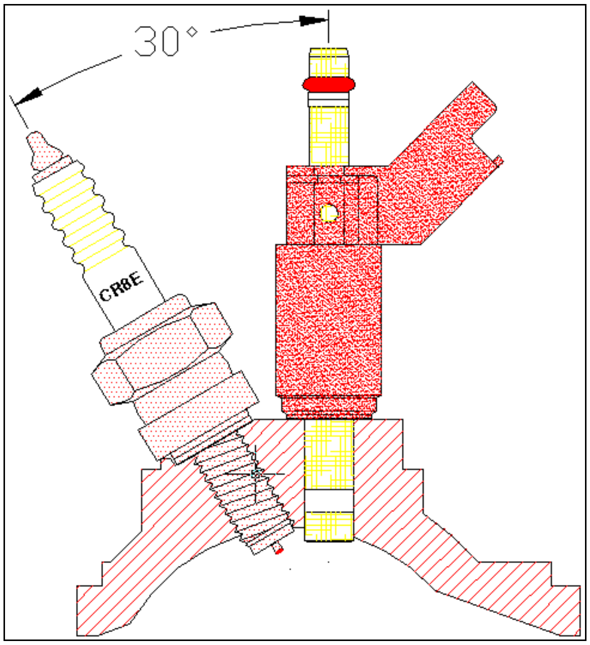


Figure 2, Two-Stroke Cycle's Fuel Injector Location

An electric servo was installed to control the exhaust valve timing pneumatically. Outside factors caused the stock exhaust valves to not operate as the manufacturer intended. The stock exhaust valves were controlled by a spring that pushed the valves toward the piston. By only using a spring, hysteresis in the metal was inevitable and caused many inconsistencies in the exhaust port timing.

Fuel System Modifications

Fuel system modifications were a significant and major focus of the group. Modifications were made to the fuel delivery, fuel pressure, and the fuel tank to accommodate the SIDI system.

The fuel pressure was increased with the assistance of a belt drive, three piston, and radial fuel pump. This type of fuel pump was implemented to create the optimum fuel flow for proper fuel injector operation. The fuel pump delivers 0.6 cc/rev of fuel at 7584 kPa (1100 psi). An aluminum case was manufactured to house the pump assembly. The main fuel pump was fed by an electric 241 kPa (20psi) in-tank fuel pump. (Fig 3)

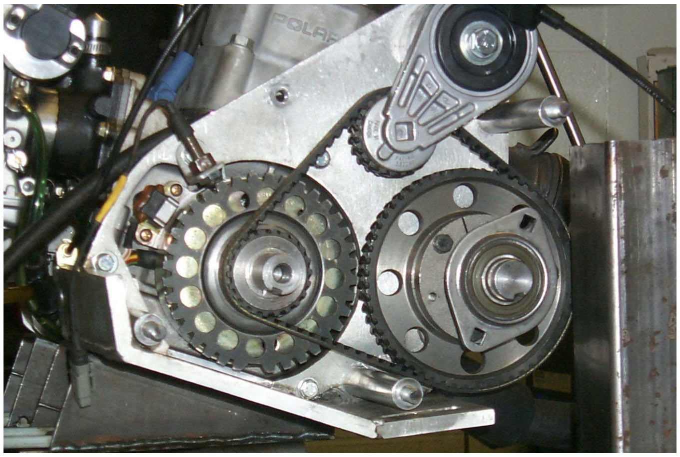


Figure 3, Main Fuel Pump Assembly

The main fuel pump housing consists of two parallel aluminum plates, bolted to the magneto side of the engine. The system utilizes a Goodyear Eagle Pd quiet belt drive system with matching herringbone gears. The belt drive arrangement is made up of a pulley driven from the crankshaft that powers the fuel pump, and a belt tensioner.

The Siemens injector driver used a 0.5-volt reference signal from the ECU. This reference signal activates the Siemens Driver, which then releases a 100-volt pulse to the injectors. This power boost was required, in order to drive the high-pressure fuel injectors.

The stock carburetors were left as a part of the intake system. However, the carburetors serve only as throttle bodies and facilitate the stock system. More economical implementations could be applied, if the system was redesigned. These modifications would reduce cost, weight, and maintenance.

An aluminum fuel tank (Figure 4) was constructed with a cavity to allow the exhaust pipe to be directed under the tank.

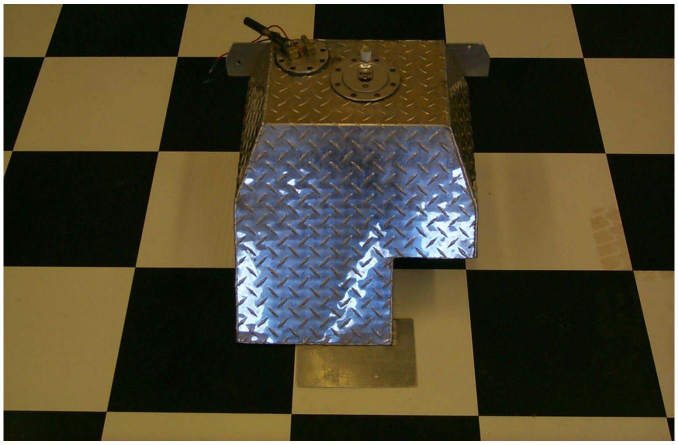


Figure 4, Aluminum Gas Tank

Electrical System Modifications

The MoTeC M48 Engine Control Unit (ECU) and Siemens Injector Driver were used to control the fuel injection process. The following sensors were used as inputs to the ECU

- Coolant Temperature
- Intake Air Temperature
- Barometric Pressure
- Crankshaft Position
- Throttle Position

These sensors were used to gather data for constant updates of changing engine conditions. The ECU uses the data from these sensors to continuously adjust injection properties for optimal performance.

A supplementary power source was required for these additional accessories. A Nippon Denso 90 amp, 14-volt automotive alternator was used to compensate for the additional amperage draw. The additional current provided by the alternator was enough to successfully power the ECU, Siemens Injector Driver, and other electrical devices on the snowmobile.

The ECU was also used to control the electric servo exhaust valves. When the engine reached 5300 RPM, a signal was sent form the ECU to energize the electric servo and in turn, open the exhaust power valves. Consistency in performance and efficiency were gained when the valve timing was controlled. Exhaust valve maintenance was also reduced.

SIDI Development

The major barrier in SIDI two-stroke cycle engines is not the construction of the physical engine, but the development of the SIDI system and fuel mapping. Mapping was the most time consuming process. It involved finding the proper injection timing and pulse width to ensure the proper amount of fuel entered the cylinder.

The utilization of SIDI on any engine would be to increase fuel economy and power while reducing emissions. A two-stroke cycle engine's air/lubrication mixture comes into the cylinder from both the air intake ports, transfer ports and also from the scavenging of the raw fuel in the tuned pipe. About 20% of the charge for each power stroke is brought back into the cylinder through the scavenging effect. [Heywood & Sher] The main reason for high HC emissions is due to the short-circuiting effect. In order for a two-stroke cycle engine to work more efficiently and have lower emissions, the scavenging and short-circuiting effects must be improved. Improving the scavenging effect will result in less dilution of the fresh air/fuel mixture by spent exhaust gases.

Short-circuiting is the flow of the fresh incoming charge directly through the cylinder and out the exhaust ports. This phenomenon occurs because the intake and exhaust ports are exposed at the same time. In conventional carbureted or port fuel injected engine this fresh charge contains fully atomized gas that can readily escape to the exhaust. In DI engines, the fuel is injected later during the cycle to limit the amount of short-circuiting. Therefore, raw emissions were decreased and the scavenging effect inducts a leaner air/fuel mixture back into combustion.

Engine Mapping Procedure

In order to map a two-stroke cycle or four-stroke cycle engine, several steps are required. The following steps need to be taken to effectively map each engine:

a) The engine must be started and warmed to proper operating temperature.
b) The dynamometer must be engaged to hold the engine at a specific RPM while maintaining a constant load.
c) Set the engine throttle position to a specific 10% increment.
d) The injector on time and injection timing must be modified to find the highest torque.
e) The injector on time and injection timing were fine tuned with comparison to EGT's.
f) The final step in engine mapping consisted of using a raw gas analyzer to make final adjustments that is compared to the emissions data

.

Engine Mapping

A two-stroke cycle engine cannot effectively use a lambda sensor because the exhausting emissions are too dirty and will foul the sensor. This means that the engine may or may not be running at a stoichiometric air/fuel ratio or at its highest performance and efficiency.

The mapping and tuning procedure consisted of coupling the engine to a Land and Sea Dynomite water break dynamometer, which measured the engine under full load at a specific RPM and throttle position. The fuel injector on-time was modified to achieve the highest torque while maintaining correct exhaust gas temperature (EGT).

Monitoring EGT's was achieved by the use of thermal couples in the y-pipe of the exhaust. These thermocouples were linked to a Digitron Model DT-33 monitoring system. The Digitron allowed the programmer the ability to read the exhaust temperature. Tuning for correct exhaust temperatures provided correct injection properties for a close to stoichiometric mixture.

The next major step in mapping was the use of a service grade exhaust gas analyzer. This analyzer detects actual engine emissions including hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2) oxygen (O_2), and oxides of nitrogen (NOx). The fuel map was modified to lower excessive HC emissions without any major horsepower loss.

Emissions

The harmful problems with two-stroke cycle engine emissions are the CO and unburned HC gases. Sher and Heywood stated that, "First, charging losses are inevitable. Under normal operating conditions in a typical two-stroke cycle engine, about 20% of the fresh charge entering the cylinder is lost due to short-circuiting to the exhaust. In carbureted spark ignition engines, this process results in very high HC emissions and poor fuel economy." (3)

An alternate way to reduce HC and CO emissions in the exhaust is to add a catalytic converter along with oxygen to create an oxidization reaction, changing HC and CO to H_2O and CO_2.

Exhaust Modifications

The engine has two exhaust ports, which are joined by a Y shaped manifold. The manifold directs exhaust flow to a "J" shaped tuned pipe downstream. Within the tuned pipe the hot and cold exhaust gases are separated. The cooler exhaust, which is still quite volatile, contains many unburned HC's. Some of these volatile exhaust gases are forced back into the cylinder because of backpressure created by the tuned pipe. By forcing some of the unburned HC's back into the cylinder, emissions were reduced and performance was improved.

To further improve emissions, MSU students chose to use a catalytic converter and an air pump. The team contacted Environmental Solutions Worldwide Incorporated, and worked with them to select the best catalyst for the two-stroke cycle SIDI engine. The MSU students acquired an electric vane air pump from a 1999 Chevrolet Silverado. The vane air pump was a part of the air injection system that was originally added to the Chevrolet when it was required to pass emissions standards in the state of California. This was the most efficient way to reduce HC and CO emissions without taking away any engine power. The electric vane air pump gave improvements by adding O_2. This was effectively routed into the exhaust system directly in front of the catalyst.

The two-stroke cycle engine was tested with two different catalysts to find the best emission improvements. One substrate was a Rhodium coated catalyst used to reduce NO_x; this catalyst consisted of 7.0 g-ft^3 of the Rhodium coating. It performed as a slower oxidizer when compared to the Palladium substrate. The slower oxidation was beneficial when there was too many HC's in the stream, thus preventing the catalyst from overheating and deactivating completely.

The second catalyst tested in the exhaust stream was the more common Palladium substrate. This catalyst was modestly loaded to a concentration of 18 g-ft^3 of Palladium.

After the tuned pipe, oxygen was added by means of an air injection system. The most efficient way to reduce emissions without taking away any engine power is by use of an air pump. The electric vane air pump gave improvements on HC and CO emissions by adding O_2. This was directed into the exhaust system directly in front of the catalyst.

Performance and Testing Results

The modified two-stroke cycle engine was tested and compared to the stock two-stroke cycle engine. The modified engine shows significant improvements considering these results.

Test Description	Stock 500cc			SIDI 500cc		
Emissions	HC (ppm)	CO(%)	NOx (ppm)	HC (ppm)	CO	NOx
Mode 1	35520	6.5	400	18246	5.9	401
Mode 2	52800	7.7	270	15452	7.7	265
Mode 3	52800	6.2	425	10569	6.1	420
Mode 4	38400	7.6	475	7241	7.6	468
Mode 5	84480	3.3	430	4021	3.2	427

Table 2-A

Cost Analysis

The two-stroke SIDI engine will add a small upfront cost to a manufactured snowmobile, but over its serviceable lifespan a savings will return to the owner. The high performance of the two-stroke cycle engine can be taken advantage of by running the snowmobile at the best fuel trim for the conditions. The sensors aboard the machine will compensate for air temperature, engine temperature and altitude. Maintenance and tuning issues are eliminated because rejetting and adjustments to the carburetors due to changing conditions will be eliminated. As attitude increases or decreases, the manifold absolute pressure (MAP) sensor will compensate for changes and deliver optimal performance. The DI system reduces short-circuiting; therefore the fuel that would have otherwise escaped out of the exhaust port will remain in the combustion chamber to power the engine. When a SIDI system is applied to a snowmobile, performance is increased, while emissions levels are significantly decreased as compared to today's snowmobiles. (See Table 3)

Sub-System	Subtotal
Induction System	0.00
Fuel System	$250.00
Engine	$350.00
Exhaust After treatment	$63.00
Electronics	$268.00
Noise Treatment	$89.00
Total Modification Costs	$1020.00

Table 3, Two-Stroke Cycle Engine DI Cost Analysis

Four – Stroke Cycle Engine

A four-stroke cycle engine has several advantages over a two-stroke cycle engine. A four-stroke cycle engine will typically produce fewer emissions, be more fuel efficient, and will perform at a much lower sound level than a typical two-stroke cycle engine. Some snowmobiles along with other two-stroke recreational vehicles are slowly making a change to four-stroke cycle engines.

Although a two-stroke cycle engine will produce more power than a four-stroke cycle engine of the same displacement, it is becoming more and more difficult for two-stroke cycle engines to meet proposed laws regulating emissions. The reason a two-stroke cycle engine will typically produce higher emissions than a four-stroke cycle engine is due to the intake and exhaust stroke occurring at the same time. A four-stroke cycle engine will overcome this flaw by using separate intake and exhaust strokes, thus having a very small overlap of the intake and exhaust valves.

Base Engine

The base engine chosen for modification was from a Polaris 700 Sportsman ATV. This even-firing parallel four-stroke cycle twin cylinder engine is the largest displacement engine that has been used in a production ATV.

This engine is more expensive than a simple two-stroke cycle engine, but it makes up for the extra expense with lowered emissions, quieter exhaust, and better fuel economy. Other four-stroke cycle engines were considered for this project. However, they were not chosen due to concerns of cost of development for snowmobile use.

The engine is liquid cooled which allows a constant operating temperature and enables more accurate tuning. This results in better engine performance and exhaust emissions. (See Figure 5)

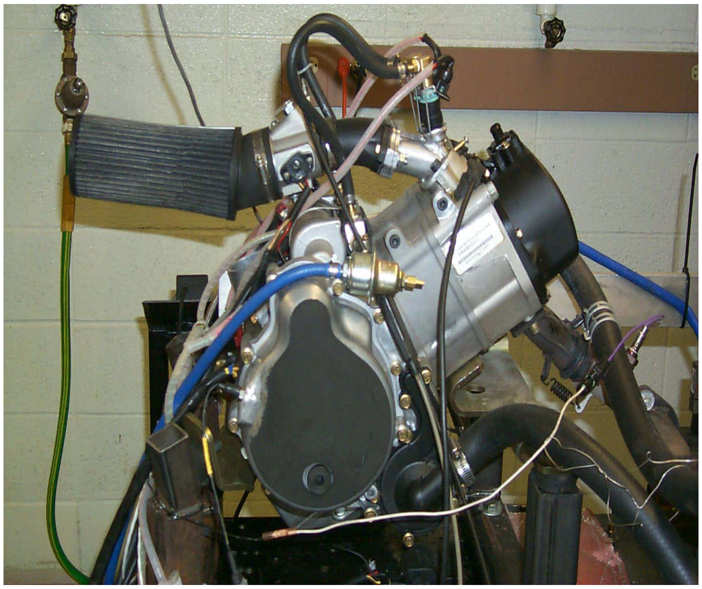


Figure 5, Polaris 700 cc Sportsman Twin

Stock Mechanical Systems

The engine that was used for testing contained several unique designs. The engine used a balance shaft to provide for a smoother running engine. The stock engine is adapted to couple a contentiously variable transmission (CVT). This feature decreased the mass of the drive train, simplified the manufacturing process, and made the engine more cost effective.

The stock mechanical systems of the four-stroke cycle engine were evaluated to determine what modifications, if any, would be desired to increase performance, and reduce emissions. Both the static and dynamic compression ratios were measured. The static compression ratio compares the volume of the full stroke to the volume of the combustion chamber, (Equation 1), and the dynamic compression ratio compares the volume of the stroke from the time the intake valve closes until the piston reaches top dead center to the volume of the combustion chamber (Equation 2). In order to do this, measurements of the bore, stroke, piston dish volume, head volume, and squish clearance were taken.

Equation 1

$$\mathrm{SCR} = \frac{\mathrm{Disp} + \mathrm{CCV} + \mathrm{HGV} + \mathrm{DHV} + \mathrm{PDV}}{\mathrm{CCV} + \mathrm{HGV} + \mathrm{DHV} + \mathrm{PDV}}$$

Equation 2

$$\mathrm{DCR} = \frac{\mathrm{EFFECTIVE\ DISPLACEMENT}}{\mathrm{CCV} + \mathrm{HGV} + \mathrm{DHV} + \mathrm{PDV}}$$

Displacement per cylinder (DISP)
Combustion Chamber Volume (CCV)
Head Gasket Volume (HGV)
Deck Height Volume (DHV)
Piston Dish Volume (PDV)
Static Compression Ratio (SCR)
Dynamic Compression Ratio (DCR).

Equation Abbreviations

Four-Stroke Cycle Engine Specifications

Stock Electrical System

Stock electrical system was comprised of a stator, rotor, and a voltage regulator, in conjunction with a capacitated discharge ignition (CDI) box. This stock electrical system is standard on most recreational vehicles. This system provides sufficient energy to power all electrical accessories.

Stock Fuel System

The fuel delivery system on this engine consisted of a single 34 mm Minkuni™ carburetor. The stock fuel system used 87-octane, non-oxygenated gasoline, or 89 octane-oxygenated gasolines.

Engine Modifications

The Sportsman 700 cc engine was modified to for E85 fuel. In order to effectively operate the engine using E85, modifications had to be made to the mechanical, electrical, and fuel delivery systems.

Mechanical System Modifications

The mechanical system of the stock engine was modified to improve performance and emissions. One method was to increase the compression ratio for additional power. Increasing compression was possible because E85 has a higher-octane value then standard pump gasoline.

Another modification would be to install a forced induction system, so the engine could produce more power. The idea, such as a turbo charger would be implemented. However, minimal modifications were made in order to keep the implementation costs to a minimum for this year's competition. The table listed below displays current modifications. (See table 4)

		MODIFIED ENGINE
DISPLACEMENT		683 CC
COMPRESSION RATIO (STATIC)		9.78:1
COMPRESSION RATIO (DYNAMIC)		7.19:1
BORE		80MM (3.149 IN)
STROKE		68MM (2.67 IN)
HEAD VOLUME (UNINSTALLED)		8.2 CC
PEAK POWER RPM		6300RPM
CRANKING PRESSURE		150-170 PSI +/- 15%
INTAKE VALVE OPEN		25 DEGREES BTDC
FUEL		E-85
FUEL DELIVERY SYSTEM		BOSCH FUEL INJECTORS
SPARK PLUG/GAP		CHAMPION RC7YC/0.036" (0.9 MM)
POWER SAE		(48 HP)
AIR INTAKE		40MM (XXIN)

Table 4

Fuel System Modifications

The 34mm Mikuni carburetor was eliminated and a 40 mm throttle body was introduced allowing for the addition of electronically controlled fuel injection system. The fuel injection system was implemented to decrease emissions, increase performance, and improve tuning accuracy. (See figure 6)

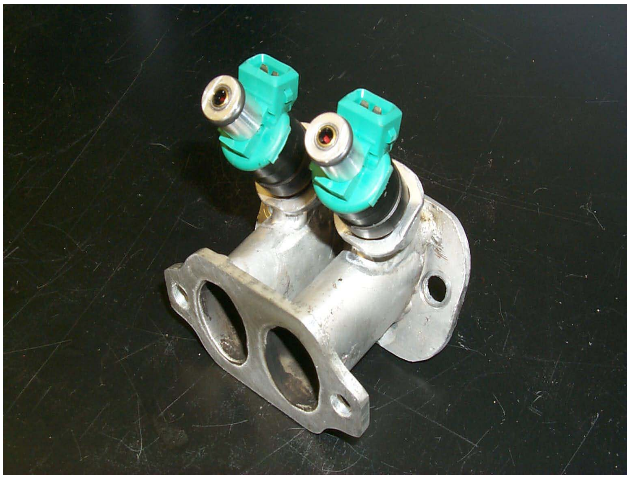


Figure 6, Intake Manifold with Injectors

To increase performance and decrease emissions the four-stroke cycle engine used E85 as its fuel. Using E85 will decrease emissions because alcohols contain more oxygen then gasoline. Stone (2) states, "E85 has a much faster burn rate than pump gas, therefore a more complete burn. Spark timing can be retarded which also decrease emissions." Performance is enhanced with the use of alcohol-based fuels, although this is done at the expense of fuel economy, Stone also states, "the increased oxygen content of alcohol-based fuels gives them a lower stoichiometric air/fuel ratio than gas. The lower air/fuel ratio of E85 means the chemical energy released per kilogram of stoichiometric mixture burnt during combustion is greater than for pump gasoline, despite the lower specific enthalpy of combustion."

The required flow rate of E85 was calculated from equation 3. The resulting values were used to determine proper injector size based on expected horsepower.

$$\frac{\text{Expected HP x BSFC}}{\text{\# Of injectors (.8)}} = \text{Flow Rate}$$

Equation 3

Electrical System Modifications

A MoTeC M48 engine management system was chosen to tune the engine. The data gathered from the sensors below were used by the ECU to control the fuel injection system.

- Coolant Temperature
- Intake Air Temperature
- Barometric Pressure
- Camshaft Position
- Throttle Position
- Crankshaft Position
- Oxygen Sensor

Engine Mapping / Four-Stroke Cycle Engine

The procedure for mapping the four-stroke cycle engine was similar to the procedure used on the two-stroke cycle engine with the addition of a lambda sensor. The lambda sensor provided values of exhaust gas oxygen levels. The engine operator uses these values to determine if the engine is running at a stoichiometric air/fuel ratio. Tuning for a stoichiometric air/fuel ratio maximized engine performance while minimizing emissions.

The four-stroke cycle engine was mapped by holding throttle position increments of 10% for each 500-RPM level. At each increment, the injector on time and injector timing were adjusted to provide maximum torque. The fuel map was adjusted until the engine seemed to be operating close to a stoichiometric ratio. Next, the lambda sensor was turned on. Readings from the lambda sensor allowed further fuel map adjustments to get the engine running as close to stoichiometric as possible. This provided the Maverick's with a baseline fuel map for the engine.

The final step in the four-stroke cycle engine mapping was to utilize an exhaust gas analyzer. The analyzer determined emission levels produced by the engine. The fuel map was richened or leaned according to the emission readings. Exhaust gas analyzer and dynamometer readings were combined to produce the lowest emissions, yet maintain increased performance levels.

Exhaust Modifications

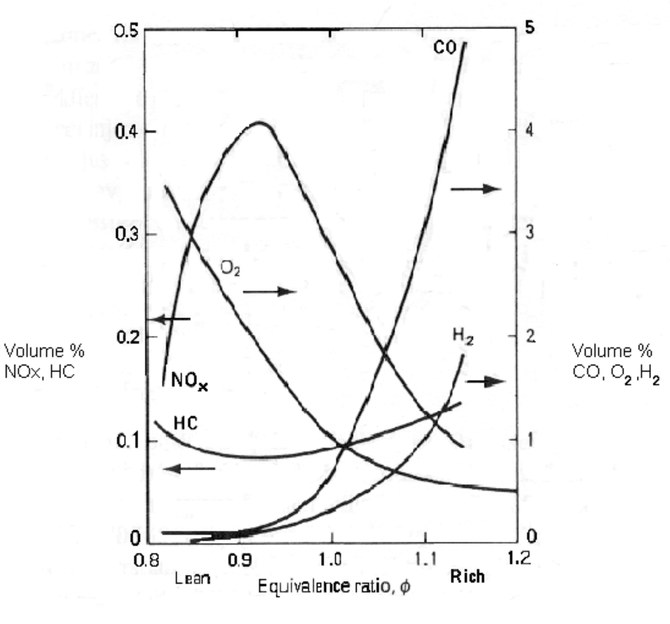
The four-stroke cycle engine had greater exhaust efficiency than a two-stroke cycle engine. Scavenging is controlled by the lift duration of the individual exhaust valves. The greater the valves overlap, the more exhaust scavenging will occur. HC's are reduced in a four-stroke cycle engine by minimizing the scavenging effect. The correct amount of scavenging from the intake port to the exhaust port increased the volumetric efficiency of the engine by inducing a vacuum in the intake manifold.

The high compression ratio of a four-stroke cycle engine compared to a two–stroke cycle engine creates a higher temperature of combustion, therefore increasing NO_x. With higher combustion temperatures HC and CO levels were theoretically decreased. This was done because of a more complete combustion reaction of the air and injected fuel. The air/fuel mixture entering the cylinder controlled the levels of HC's and CO's. The leaner the mixture, the more NOx was produced. The equation below shows how a richened or leaned out mixture will affect emission levels.

$$\mathbf{C\,H\,O\,N} + \lambda\,(\ +\ /4-\ /2)\ \{O_2+3.77(N_2)\} \bullet$$
$$n_1CO_2+n_2CO+n_3H_2O+n_4H_2+n_5O_2+n_7N_2$$

Equation 4

With a stoichiometric mixture, (λ=1) the values of n_2, n_4 and n_5 will be eliminated from the equation. If λ was greater than 1 (rich air/fuel mixture), then n_5 approached zero. When λ was less than 1, (lean air/fuel mixture) then n_2 and n_4 approached zero. (See equation 4). Graph 1 below gives a more visual approach to the equation. When λ veers off of stoichiometric you can see what happens to each component in the exhaust.



Graph1, Air/Fuel Emissions Curves

Performance and Testing Results

The modified four-stroke cycle engine was tested and compared to the stock four-stroke cycle engine. The modified engine showed improvements as the results in table 5 provides.

mode	1	2	3	4	5
RPM(%)	100	85	75	65	Idle
Torque(%)	100	51	33	19	0
RPM	6300	5355	4725	4095	1400
Torque.lb/ft	48	24.5	15.8	9.1	0
EMISSIONS	g/kwhr	g/kwhr	g/kwhr	g/kwhr	g/kwhr
HC	.286	1.72	.331	.626	25.7
NO_x	.526	0	.155	1.438	.580
CO	.006	.037	.001	0	.001
CO_2	844.6	1151.4	1053.9	873.4	3452
O_2	654.4	1163.6	725.8	1566.1	18310.8

Table 5, Four-Stroke Cycle Engine and Testing Results

Cost Analysis

One of the largest factors in converting a snowmobile to use four-stroke cycle engine is the cost of manufacturing. Most people interested in snowmobiling do not purchase a snowmobile solely based upon emissions. The goal of MSU's was to successfully implement a four-stroke cycle engine into a snowmobile, maintain performance, and keep the cost economical. (See table 6)

Fuel System	Subtotal
Fuel Injectors	$100
Throttle Body	$40
Fuel Rail	$10
Intake Manifold	$20
Fuel Heaters	$30
Exhaust After Treatment	$120
Noise Treatment	$45
Total Modification Costs	$365

Table 6, Four-Stroke Cycle Engines Cost Analysis

Noise

Exhaust System

The team realized that many factors were contributed to noise. The factors were determined through testing that the track, chain-drive system, CVT and exhaust cause considerable noise. The team quickly realized that a majority of the time needed to be dedicated to reducing the exhaust noise.

Noise Control of Chassis Functions

Much noise can be contributed from the performance of the chassis in motion. Noise was decreased through the use of the chain-less drive system. Figure 11-A shows the comparison of the stock chain case to the new belt drive assembly. This was tested with the hood opened and closed, and with the use of a noise dampening material. The belt noise was also decreased further by the use of a shroud surrounding the belt drive.

Exhaust Noise Modifications

The majority of the noise form a "traditional" two-stroke cycle snowmobile comes from the exhaust. This is from the need to have a highly unrestricted path for the exhaust to flow, and because the exhaust port is open when the mixture is still burning. MSU dealt with this problem by incorporating additional components to the stock exhaust system. Noise was also decreased further with the use of a catalytic converter. The addition to the system consisted of a glass packed silencer and an automotive type muffler. Many bends were configured while attaching the systems together that further reduce noise. The bends in the exhaust pipe needed to be added for compensation of the allowable room on the chassis.

The glass packed silencer is a hollow tube with holes drilled in for sound absorption. The muffler was chosen to be a compact design that would readily bolt on and fit under the seat. The seat was lined with Nextel™ fabric to insulate the rider form the hot exhaust temperatures.

Chassis

A 2001 Polaris Edge Chassis was used for the Clean Snowmobile Challenge. The features of the Edge chassis and drive train received improvements.

Suspension

The snowmobile chassis's rear suspension incorporated Fox® Position Sensitive shocks with 10" of travel for a wide variety of performance conditions. The front suspension features Polaris Controlled Roll Center (CRC) design, Fox® Shocks, preload springs, and Independent Front Suspension (IFS). The IFS trailing arms were pulled towards the center of the chassis' bulkhead. By pulling the IFS arms closer to the bulkhead, Polaris achieved a lower center of gravity. The center of gravity is lower, because the weight bearing on the IFS arms was drawn closer to the central axis of the snowmobile. A lower center of gravity meant a less top-heavy snowmobile for more all around control.

Track

A 307 cm (121inch) Predator Track with 3.175 cm (1.25inch) Lugs was decided to be used during the competition. The track weighs 16.3 kg (36 pounds), which is 3.6 kg (8 pounds) more than the stock short-track. This weight increase is due to having deeper lugs and rubber-molded studs on the track, which provided better acceleration and braking.

To increase track speed and efficiency, 20.3 cm (8 inch) idler wheels were included. These wheels added .54 kg (1.2 pounds) of weight to the undercarriage; however they allow a less restricted return of the track by not requiring as much bending of the track at the rear. The lower restriction allows for 1.3-2.2 meters per second (3-5 mph) more track speed. [Performance Engineering and Machine]

Chainless Drive

To reduce noise and inertia, the stock chain drive was replaced with a lighter, quieter, toothed belt chain-less drive system. "Belt drives have increased in popularity due to the much lighter rotating mass, durability, and power efficiency, as compared to the "traditional" chain drives of today's sleds." [Performance Engineering and Machine]

The chain-less drive decreased .95 kg (2.1 pounds) of mass from the drive system. The chainless drive allowed for a better movement of power to the track. (Table 7) Without running a metal-on-metal system, (chain on sprocket) no oil was needed; there was less routine maintenance, performance was increased and less environmental concerns.

Testing Procedures

The tests were conduced using starter motor. The procedures for both drive systems were as follows:

a) The track and suspension was removed.
b) The starter motor was coupled to the jackshaft.
c) The jackshaft was spun to produce a track speed of 8.94 meters per second (20 mph).
d) Sound was measured with an audiometer placed at a distance of 1.5 meters (4.9 feet) perpendicular to the drive system.
e) Voltage and Amperes were measured using a volt/ohm meter.

	Belt Drive	Chain Drive
Hood Open	95 dB	96 dB
Hood Closed	89 dB	88 dB
Dynamat (open)	91 dB	89 dB
Dynamat (closed)	84 dB	86 dB
With Guard	82 dB	
Energy Drawn	9.6 Volts	11.4 Volts
Current Drawn	211 Amps	195 Amps
Power Calculated	2025.6 Watts (2.71 HP)	2223 Watts (2.98 HP)

Table 7, Chain Drive vs. Belt Drive

Braking

The MSU Mavericks used a jackshaft and drive shaft mounted brake system to control the snowmobile. When the stock chain drive was replaced with a belt driven system, the belt's designer recommended that a secondary brake rotor and caliper be applied to the drive shaft. The secondary brake system was needed to reduce the chance of belt failure. As the belt went from positive tension (driving) to negative tension (braking) the belt was prone to a higher failure rate due to the inertia of the rotating drive train applying a shear force to the belt teeth. See table 8 for Brake specifications and calculations.

Brake Specifications and Calculations

Fluid Displacement	
Stock Master Cylinder	2.15ml / .131 cu.in.
Stock / Primary Caliper Bore	4.122cm(1.623") (as measured)
Stock / Primary Caliper Stroke	.043cm(.017") (as measured)
Stock / Primary Piston Area	2.069cu.in.
Stock / Primary Displacement	.574 cu cm.035 cu.in.

Table 8, Brake Specifications

To find the remaining fluid volume of a given master cylinder the following equation was derived.

Remaining Fluid Volume = (Master Cylinder Displaced Volume) – (Primary Caliper Displacement)

0.131cu.in. – 0.035cu.in. = 0.096cu.in.

In assuming the secondary caliper has the same stroke as the primary caliper the radius can be equated.

.096cu.in. / .017in. = $5.647in^2$

$5.647in.^2 / 2 = 1.798in.^2$

$11.6\ cm^2 (1.798inches.^2)$=3.40 cm (1.341in.) Radius

2.282in. for the Maximum Bore of the Secondary Caliper

Conclusions

Throughout the design and implementation of the two engine choices, many factors were considered for the competition. The guiding principle of the competition stated that the design should be realistic, cost effective, and resilient.

Both engine choices could be effectively implemented into the snowmobile industry; however an engine choice of the four-stroke cycle engine was made. The two-stroke cycle SIDI had the best performance for the rider, while the four-stroke cycle engine proved to have lower emissions and better fuel economy. Although each engine has its place in the snowmobile industry, the four-stroke cycle engine was chosen due to the fact that it better fulfills the objectives of the clean snowmobile challenge.

Competition Results

The four-stroke cycle engine was the best over all choice for the competition. This engine had lower emissions and comparable fuel economy when compared to the two-stroke cycle engine snowmobile. However, the four-stroke cycle engine lacked acceleration and power when compared to the two-stroke cycle engine.

During emissions testing the four-stroke cycle engine performed well in two of the five modes. This differed from earlier testing where the engine performed well in all modes. The increased emissions were due to the dynamic tuning performed on the engine after installed in the chassis.

The snowmobile proved its durability by completing the 60 mile endurance run without any problems. It also proved itself by winning the braking completion and placing fourth in the handling event.

Overall Minnesota State University, Mankato placed 10th at the 2003 Clean Snowmobile Challenge. This placement was unexpected, but the unseen value of the competition was the experience and knowledge the students gained.

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  Polaris Industries
  Sandlin Heating & Cooling
  Siemens VDO Automotive
  Total Construction
  Vetter's Sales and Service
  Williams

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4) Chris Iverson - Performance Engineering and Machine 14800 James road. Rogers, MN 55374

5) Scott McKinster Polaris Industries 301 5th avenue south west. Roseau, MN 56751

Acronyms

ATV – All Terrain Vehicles

CO – Carbon Monoxide

CRC- Controlled Rolled Center

CVT - Continuously Variable Transmission

E85 - 85% Ethanol Fuel

ECU – Engine Control Unit

HC – Hydrocarbon

IFS - Independent Front Suspension

NOx – Oxides of Nitrogen

SIDI – Spark Ignition Direct Injection