2005 SAE Clean Snowmobile Challenge

2004/2005 University of Maine CSC Competition Team
Department of Mechanical Engineering

ABSTRACT

The SAE Clean Snowmobile Challenge was designed to challenge college students from around the country to construct a clean, quiet, and efficient snowmobile. Through collaborative efforts of two UMaine departments, ranging over four years, we are returning this year to Houghton, Michigan. The details of our approach, design process, implementation, and results are given in this paper.

INTRODUCTION

The UMaine CSC team consists of five smaller teams which have all worked collaboratively on the project. These teams include an advanced snowmobile fairing team (construction of cowling, reductions in noise), a modeling and clutching team (development of computer-based modeling), a dynamometer controls team (development of infrastructure for testing), an engine electronics team (whose driving mission was in exhaust reductions), as well as a team of mechanical engineering technology students (aided in construction of the dynamometer mechanical systems and miscellaneous fabrication projects). The 2005 Team used the 2003/04 UMaine team's contributions as a starting point for this current year's design team.

POWERPLANT SELECTION

The first task at hand was to decide whether a two-stroke or four-stroke snowmobile was the best platform to build upon. Two-stroke snowmobiles are known to have great power to weight ratios when compared to similar four-stroke machines. However, two-stroke machines also tend to suffer from poor emissions, fuel economy, and reliability. Furthermore, two-stroke machines generally have higher noise, vibration, and harshness properties than comparable four-stroke machines. The majority of points in the CSC competition are dependent upon the snowmobile being able to finish each event, with most points awarded for low emissions and noise, as well as for fuel efficiency and reliability. As such, a four-stroke snowmobile was decidedly the best platform to build upon. Four-stroke snowmobiles are a relatively new, small market, with only a few models to choose from that met the competition requirements. It was decided to use a model that has been in production long enough to have worked out all or most early production "bugs." The only four-stroke snowmobiles that have been produced relatively unchanged for a number of years, are the Yamaha RX-1, and the Arctic Cat 4-stroke trail sled. Due to the engine displacement limitations of the CSC, the Yamaha, at 1000cc, was ruled out, making the Arctic Cat, at 660cc, the obvious choice. Additionally, it is assumed that using the smaller displacement engine would result in better fuel economy and lower emissions than the larger displacement engine.

APPROACH

ENGINEERING-BASED DESIGN – This year, our focus for modifications made to our snowmobile is in three areas – system modeling utilizing computer software to map the performance of the engine and snowmobile, construction of a custom cowling to maximize sound dampening, and exhaust reductions by use of an engine electronics piggyback.

<u>Modeling</u> – The computer modeling is broken into two groups – engine, and snowmobile systems. By using building-block style computing, the computer models will be able to be adjusted and reconfigured easily to be able to model different engine setups and sleds, quickly and accurately. MatLab, Simulink, and MathCAD were all used to create the models discussed below.

Engine Model – It is common to find horsepower and torque data of virtually any mass-produced vehicle, however, this data, for several reasons, is often of limited value for system optimization. First and foremost, the horsepower and torque curves are frequently based on dynamometer results obtained at the point of the system that transmits the power to the ground. Therefore, this data is actually a measurement of the engine's performance coupled with the various losses throughout the drive train. This means that a low horsepower output could be due to anything from restricted air intake, to inefficiencies in the drivetrain. One of the primary benefits of an accurate system model is the ability to be able to pinpoint the performance of each individual aspect of the system itself, which is not possible with data obtained from the ground. Another problem with using given engine power and torque data in system modeling is that this data is variable, both from production tolerances, and for such variables as fuel type, or environmental operating conditions. Furthermore, modeling of the engine and its response to different modifications is needed to avoid expensive or time-consuming testing.

Snowmobile System Model – After creating an engine model, a more complete snowmobile system model may be developed. A system model is useful for optimizing aspects of the system unrelated to the engine. For example, “How does the chain case ratio affect the ¼ mile performance of our snowmobile?” The system model, once created could answer this question immediately by simply inputting a different chain case ratio and running the model. The new velocity curve can then be compared to the original velocity curve to see if desirable effects are encountered. Simultaneously, other performance changes may be tracked to see their effects. Broader questions also arise, such as in the case of the CSC – “How should the snowmobile be tuned to maximize points gained throughout the competition?” This question involves many trade-offs such as fuel economy versus acceleration. The system model is the key to effective system changes and to the negotiation of any performance trade-offs. The snowmobile model is divided into two groups – a dynamic model, and a steady-state model.

Dynamic System Model – The dynamic model is used to predict acceleration performance. This model allows for the input of engine horse power and torque data, clutch configuration, engagement speeds, gear ratios, shift ratios, shift speeds and efficiencies. Other parameters include aerodynamic drag based on cowling design and sliding friction losses associated with snow conditions. This model allows for the isolation and can show the importance of losses associated with drive train, aerodynamic drag and sliding friction. For example, the model can be used to predict optimum engine shift speed, the RPM at which the CVT operates, to allow the snowmobile to run the 500ft drag within the desired time. At the same time it is necessary to minimize fuel consumption during the 100 mile trail ride.

Steady-State System Model – The steady state model will allow for the prediction of fuel economy during the 100 miles endurance portion of the competition. This model with help determine how the fuel economy is affected by rider and sled mass, aerodynamic drag and sliding friction variables. Using Brake Specific Fuel Consumption, BSFC, data, clutching can also be modified for the endurance run.

<u>Rules</u> – The CSC is the driving force behind the modifications that we are making to our snowmobile. This is analogous to real-world design pressures, such as cost reductions driven by manufacturers, safety and reliability goals set by consumers, performance demanded by racing professionals, or pollution and efficiency issues driven by society.

<u>Clutching</u> – As mentioned above, one of the most important components of a snowmobile is its clutch. Within the clutching system is the potential for many performance variations. The total sled performance is greatly dependent on how the clutch is set up, thus a properly tuned clutch system will ensure the best possible performance for a given operational condition. Most often there is not a unique ‘best’ setup for the clutch, but instead the tuner must consider trade-offs in different areas of performance. Because of the point-weighting in the CSC events, the clutch is currently tuned with fuel economy in mind and tuning for acceleration or top speed deemphasized.

NOISE, VIBRATION, AND HARSHNESS – Designing a custom cowling and installation of a quieter stock track were the two areas where we felt we could effectively reduce noise. The existing custom cowling from last year was decided to be scrapped in favor of a more aesthetic design, as well as to add more sound-deadening material.

<u>Cowling</u> – To reduce noise from the engine a new cowling was constructed. The main design goals were sound dampening, aesthetics, and ample air flow to the engine. The major constraints were that the new cowling had to fit the existing belly pan, and have sufficient engine clearance.

<u>Track</u> – To reduce track noise without modifying the existing track a new Arctic Cat “Quiet Track” was installed. This track is currently used as the stock track for later models. Our four-stroke engines are so quiet, we had to quiet down our tracks, too. They're now whisper quiet, thanks to these bridges that eliminate the rumble as the idler wheels roll between the track’s reinforcement rods.

EMISSIONS CONTROL – The approach for emissions controls was to further enhance results obtained from last year’s team. Last year, the addition of a catalytic converter greatly reduced emissions output, but could these reductions be even further enhanced by adding electronic controls to the engine? This is the objective for exhaust reductions.

EXPERIMENTAL APPROACH FOR TESTING –

<u>Emissions</u> – The Arctic Cat four-stroke engine exhaust emissions were tested using a similar method as in the SAE CSC competition emissions testing. Instead of using the exact percentages of wide open throttle as supplied by SAE CSC Rules (idle, 65%, 75%, 85% and 100%), the microcontroller piggyback for the ECU was tested using an engine speed schedule of idle speed, 3000, 4000, 5000 and 6000 rpm. To control the load on the snowmobile engine, a DYNO-mite Land/Sea water brake dynamometer was used. Testing was completed with at least three dyno runs for each exhaust component (stock or catalyst) and for stock electronics versus modified electronics. A more detailed testing description for the emissions group is given in the Implementation Section of the report, Emissions sub-section.

<u>Performance</u> – A key component in testing this year is to effectively reduce emissions without sacrificing performance. Through dynamometer testing and use of a microcontroller piggyback for the ECU, the Air/Fuel mixture was tuned on the richer side of stoichiometric, based on initial theory and extensive dynamometer testing and exhaust gas sampling.

Noise – This year the cowling group utilized last year's research and sound testing to select the materials used to make a quieter cowling.

AESTHETICS OF DESIGN – The UMaine CSC 2005 team incorporated aesthetics into their design in each of the sub-group projects. The ECU group developed a clean, hard wired piggyback with a microcontroller board packaged in a waterproof Plexiglas case along with the wideband oxygen sensor. The cowling group designed and built an easy to read adjustable gauge cluster with a custom fiberglass cowling.

DESIGN OVERVIEW

ENGINE MODEL – The engine model is modeled in MatLab as an idealized Otto Cycle to determine engine torque and power curves without the losses associated with transmitting the power through the drivetrain.

Otto Cycle – The Otto Cycle shown in Figure 1 idealizes the pressure cycle within the cylinders. The Otto Cycle uses brake mean effective pressure, or BMEP, in calculating the power output of the engine. BMEP is the net work from a pressure cycle on a volume. In the case of a combustion engine the volume is the cylinder. The pressure is exerted on the piston, which through the power stroke, connecting rod and crankshaft, converts this work into rotational mechanical energy. The resulting equation can be seen in Equation 1.[1]

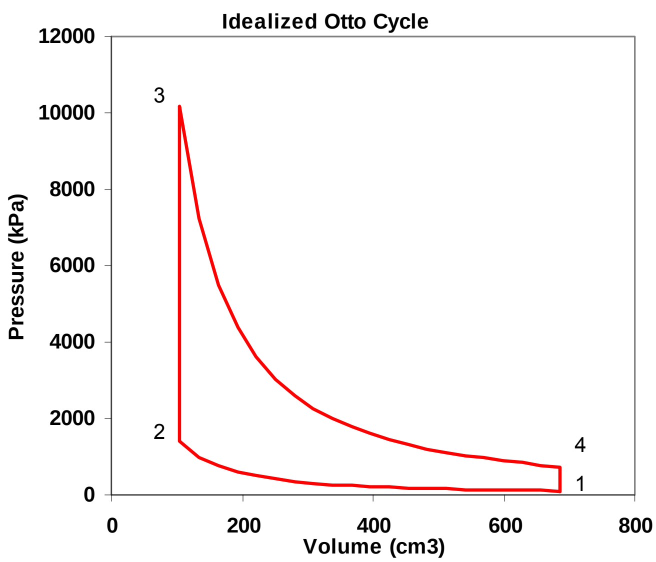

Figure 1. Idealized Otto Cycle; State 1 corresponds to bottom dead center and state 3 corresponds to TDC after combustion.

$$BMEP = P_3 \cdot \frac{1-r^{(1-k)}}{(k-1)(r-1)} + P_1 \cdot \frac{1-r^{k-1}}{(k-1)\left(1-\frac{1}{r}\right)}$$

Equation 1. BMEP from Engine Model

The term r is the compression ratio, k is the specific heat constant, and P_1 and P_3 are the cylinder pressures at states 1 and 3 of the Otto Cycle as seen in Figure 1.

The power produced by the engine is found by multiplying the BMEP by the volume to which the work is done, the number of cylinders, N_c, and the number of cycles or RPM. The volume is the area of the piston, A_p, multiplied by the stroke, S. The number 2 is used for a four-stroke engine which only has a power stroke every other revolution.

$$P_{engine} = N_c \cdot BMEP \cdot S \cdot A_p \cdot \left(\frac{RPM}{60 \cdot 2}\right)$$

Equation 2. Power from Engine Model

Or from the usual definition, power can be found by using Equation 3, where T_{engine} is the torque found by the dyno.

$$P_{engine} = T_{engine} \cdot \frac{RPM}{5252}$$

Equation 3. Power from Engine Dyno

Due to its current simplicity, the engine model produces a flat torque "curve" and a power curve with a constant positive slope and no power peak. See Figure 13

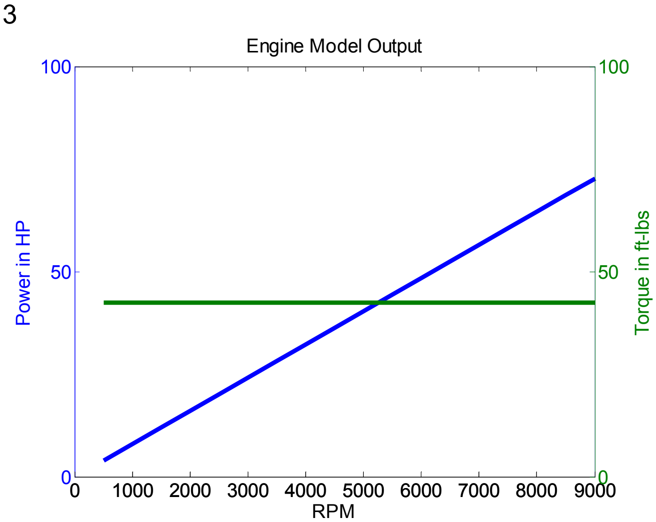

Figure **13** in the Results section. This is due to the model ignoring speed dependent variables such as inertial characteristics both rotational and fluid and thermodynamic losses. Determining the individual losses for items such as intake air drag and rotational inertial components of the engine were deemed outside the scope of this phase of complexity of the engine model. For the current model, the theoretical output is compared to real test data from an engine dynamometer as seen in Figure 2. The theoretical outputs are fitted with correction factors or loss factors so the theoretical curve will mirror the experimental output. From this point, changes to variables that are included in the model such as compression ratio, air to fuel ratio, and fuel type may be changed to determine their affects on performance.

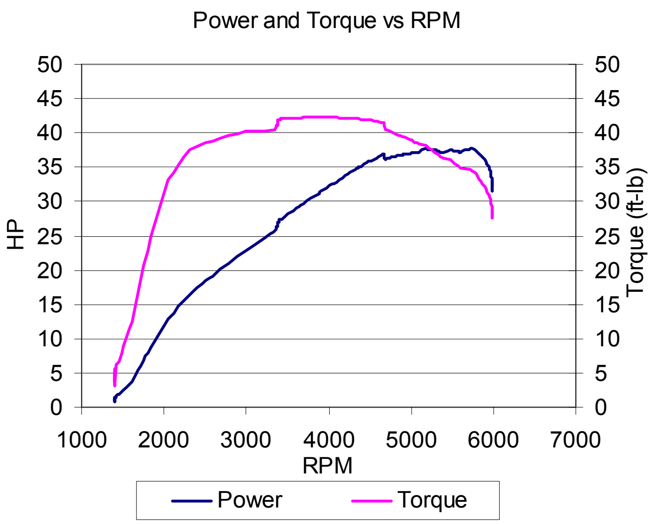

Figure 2. Power and Torque from Engine Dyno.

The design of the dynamic system model allows experimental results from the engine or track dyno to be input instead of the data from the theoretical engine model. This feature affords a more accurate system model necessary for optimizing performance.

DYNAMIC SYSTEM MODEL – For the dynamic model, Simulink was chosen again for its availability, ability to create the cyclical model needed, and compatibility with MatLab. The dynamic model focuses on the acceleration of the snowmobile. The dynamic model incorporates aerodynamic drag, inertial characteristics of the track and sliding friction losses due to snow conditions. The dynamic model calculates the power available for acceleration as a function of velocity. A kinetic track model was developed by the 2004 CSC Team to model the inertial losses due to the track. The kinetic diagram used can be seen in Figure 3.

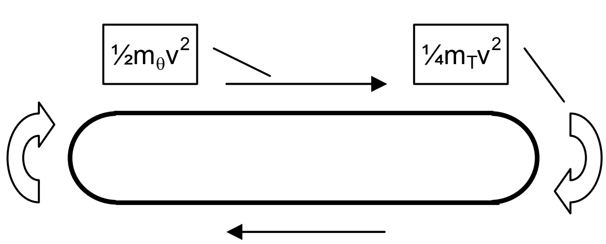

Figure 3. Kinetic Diagram

The two semicircle ends of the track are modeled as a thin walled disc shown in Figure 4.

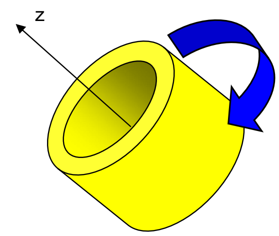

Figure 4. Track Inertia Model

Acceleration – Combining the mass of the rider, m_B, and the masses of the track sections, m_T and m_θ, into the kinetic energy equation and then taking the derivative with respect to time yields the power required to accelerate the snowmobile, see Equation 4.

$$P_{accel} = (m_B + 2 \cdot m_\theta + 2 \cdot m_T) \cdot V \cdot \frac{d}{dt} V$$

Equation 4. Power Needed to Accelerate Snowmobile

Aerodynamic drag and sliding friction losses are subtracted from the available power to give the overall power for acceleration of the snowmobile see Equation 5 and Equation 6 and Equation 7.

$$P_{air} = \frac{(C_D \cdot A \cdot G \cdot V^3)}{2}$$

Equation 5. Aerodynamic Drag on Snowmobile

$$P_{friction} = C_R \cdot (m_B + 2 \cdot m_\theta + 2 \cdot m_T) \cdot g \cdot V$$

Equation 6. Sliding Friction Loss on Snowmobile

$$P_{accel} = P_{engine} - P_{air} - P_{friction}$$

Equation 7. Power Available for Acceleration

Finally, Equation 7 can be rearranged to give acceleration. The acceleration can be integrated to calculate velocity and integrated again to calculate displacement as a function of time. This provides the data needed for determining drag race or acceleration performance for the snowmobile at various distances and conditions such as the 500ft used in the 2005 CSC. The velocity is then used to propagate the loop within Simulink. P_{engine} in Equation 8 is the engine power output from the engine model or engine dynamometer data.

$$\frac{d}{dt}V = \frac{P_{engine}}{V(m_B + 2\cdot m_\theta + 2\cdot m_T)} - C_R g - \frac{(C_D \cdot A \cdot G \cdot V^2)}{2(m_B + 2\cdot m_\theta + 2\cdot m_T)}$$

Equation 8. Acceleration of the Snowmobile

STEADY-STATE SYSTEM MODEL – The steady state model was constructed by making modifications to the dynamic model to allow the user to specify constant velocities or velocity ranges to find the tradeoffs in engine power, aerodynamic drag and sliding friction. The engine power needed to maintain constant velocity is the equal to the sliding and aerodynamic drag power at a given velocity. By rearranging Equation 7, and eliminating the inertia term, or P_{accel} term, the engine power can be calculated using Equation 9:

$$P_{engine} = P_{air} - P_{friction}$$

Equation 9. Power Required to Maintain Constant Velocity

<u>Clutching</u> – In both system models the clutch performance was dictated by an engine shift chart, seen in Figure 16, located in the results section. It basically gives a map of what the clutch is doing at any given engine speed.

<u>Variables</u> – The major mechanical components of the CVT introduce variable parameters influencing the CVT's behavior and the sled in general. Once installed or implemented, these components are no longer variable, however there is a wide range of working parameters, and customizations that can be achieved with just three components—flyweights, springs, and ramps. Figure 5 illustrates the primary clutch components while Figure 6 illustrates the secondary clutch.

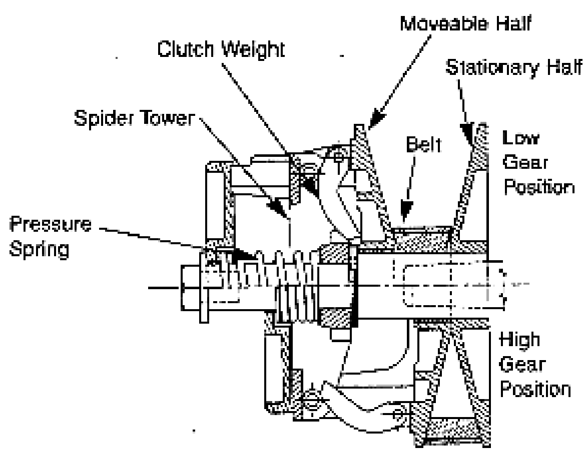

Figure 5. Primary Clutch Schematic.[2]

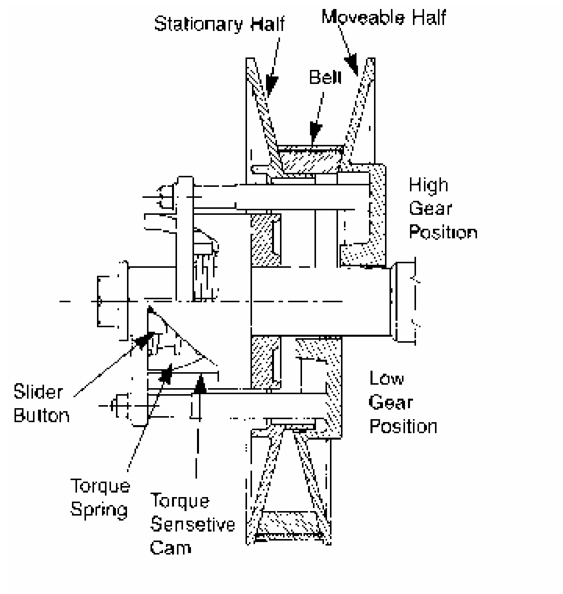

Figure 6. Secondary Clutch Schematic.[2]

<u>Flyweights</u> - The flyweights, or cams, are housed inside the primary clutch and are allowed to swivel on a pin. Cams are shown in situ in Figure 5. For the arctic cat 660 stock clutch there are three cams, spaced equally around the clutch housing. They ride against rollers attached to the spider housing. As the primary clutch rotates directly with the engine, the cams swing outward with a force governed by their mass and a direction based on their geometry. Also factoring into this force are the radius of the cam from its axis of rotation, and the speed at which it is spinning. The latter two contributors to the force are certainly not to be overlooked, but are taken to be constant as they are dependent on the engine itself and the clutch geometry. So, once tuning becomes necessary, only the mass is considered variable, since the other contributors are determined before-hand. In general, the surface of the cam which comes into contact with the spider roller has a curved profile, creating a non-linear and complex interaction with the spider. Essentially, from an idle (while the clutch sheaves are held together by the spring in the spider housing), as the primary clutch spins faster (more engine RPM), the cams exert an increasingly greater force outward against the spider tower. Once the cams' outward force overcomes the spring force, the clutch will engage. It is easy to influence this engagement force by adding or subtracting weight from the cams.[3]

<u>Springs</u> - The two clutch springs are located in the primary and secondary clutch respectively. Springs are shown in situ in Figure 5 and Figure 6. The primary, or pressure spring, as mentioned above, is located with the spider housing and works axially to hold the sheaves of the primary clutch *closed*. The secondary, or torque spring works in twisting to hold the sheaves of the secondary clutch *open*. As one pair of clutch sheaves is made to open or close, the other pair will do the opposite. Since the belt rides between the two sets of sheaves, as they open and close they change the radius

that the belt rides along. As a clutch opens, the belt's riding radius decreases and as it closes, the radius increases.[2]

Ramps – The ramps, also known as torque sensitive cams, are located in the secondary clutch. Ramps are shown in situ in Figure 6. They provide torque-sensing feedback from the track, and are integral in back-shifting. The ramps consist of three ramps which are spaced evenly around a cylinder surface. Each ramp is a surface on which a roller acts against. The governing parameters of the torque ramp are the angle and radius which the ramps are set to. As the ramp angle is decreased (becomes flatter), it creates more side force to act on the belt at the secondary sheaves. The side force, mathematically, is given in Equation 10,

$$force = \frac{T \cdot m_{shift}}{2 \cdot r_{ramp} \cdot \tan\alpha}$$

Equation 10. Side force in sheaves.

where T is torque, m_{shift} is the CVT shift ratio, r_{ramp} is the ramp radius and α is the angle of the ramp measured from the horizontal. This force grabs the belt and is 'felt' at the primary clutch causing the primary sheaves to open, and thus backshift.[3][4]

ENGINE SHIFT CHART – The engine shift chart, included in the appendix, is a road-map of what speed the engine is operating at, for any given sled velocity. There are three subtle, yet powerful, observations that can be made upon examining this chart. One is that the low gear ratio is displayed as the steeper straight line. Two, is that the high gear ratio is displayed as the other straight line. Both these ratios include the entire drive train, from engine to track, but since all components of the drive train other than the CVT are constant ratio, these two lines on the shift ratio chart can be properly taken as the difference between low and high ratio. The third observation is that while the CVT is operating through its variable range, the engine is held at constant speed. This is the essence of why the CVT is utilized; it is an important concept because in order to maximize efficiency, the engine should be operated at its power peak (or as close as possible).

NOISE, VIBRATION, AND HARSHNESS –

Cowling – The first step in the design of the new cowling was to map the coordinates of the belly pan and the necessary engine clearances. These measurements were then imported to solid works to create the model. From here a plug and mold were made. The final lay-up of the part was designed for the previously mentioned objectives and constraints. Then the final part was made.

EMISSION CONTROL SYSTEM –

Catalytic converter – The use of a catalyst on exhaust emissions is well established. The catalyst facilitates chemical reactions that convert oxides of nitrogen, carbon monoxide and unburned hydrocarbons to less detrimental gasses such as carbon dioxide and water. The catalyst increases the rate of a chemical reaction while not going through any changes itself. This often means that reactions requiring heat can occur at lower temperatures. In order for a reaction to occur, reactants must pass through energy barriers to produce the products. A catalyst lowers the amount of energy needed for a chemical reaction to occur by creating intermediate products which are subsequently broken down. Although the initial and final enthalpy of the reactants and products are not changed, a catalyst lowers the energy required to cause the reaction. The more catalyst surface area exposed to the reactants, the more effective it is. A catalytic converter is a piece of hardware installed on the exhaust of a vehicle to expose a catalyst surface to the exhaust gases, allowing the chemical reaction to occur. Use of catalytic converters has been employed in the auto industry to lower exhaust emissions with this type of chemical reaction. When automotive emissions were first recognized as a problem in the late 1960's and early 70's, two-way catalysts were employed. These first generation catalysts used platinum (Pt) and palladium (Pl) in a ratio of 2.5:1 or 5:1 in the catalyst material. These were strictly oxidation catalysts that burned the unburned hydrocarbons and converted carbon monoxide into water and carbon dioxide. The oxidation reactions are shown mathematically in Equation 11.

$$C_yH_n + \left(1 + \frac{n}{4}\right)O_2 \longrightarrow yCO_2 + \left(\frac{n}{2}\right)H_2O$$

$$CO + \left(\frac{1}{2}\right)O_2 \longrightarrow CO_2$$

Equation 11. Oxidation reactions of catalyst.

Since these catalysts used only the oxidation reaction to reduce hydrocarbon emissions, nitrogen oxide emissions (NO_x) were controlled by use of EGR, exhaust gas recirculation. EGR is a method of reintroducing exhaust gases into the engine to dilute the combustion gases and lower the peak flame temperature, thereby lowering the amount of NO_x formed. EGR led to a reduction in engine performance due to combustion gases mixing with fresh charge coming into the engine. EGR is not completely negative though, as it also causes a reduction in pumping losses in an engine, which usually increases fuel economy and is therefore still used in modern engines. In order to fully reduce NO_x emissions without dependence on EGR, companies allowed for a reduction reaction to occur in the catalytic converter in second generation catalysts. This new catalyst, a three-way catalyst, uses an oxidation reaction that reduced hydrocarbon and carbon monoxide emissions and also uses a reduction reaction to reduce

NO_x to Nitrogen. The reduction equations for NO_x are shown mathematically in Equation 12.

$$NO(orNO_2) + CO \longrightarrow \left(\frac{1}{2}\right)N_2 + CO_2$$

$$NO(orNO_2) + H_2 \longrightarrow \left(\frac{1}{2}\right)N_2 + H_2O$$

$$\left(2+\frac{n}{2}\right)NO(orNO_2) + C_yH_n$$

$$\longrightarrow \left(1+\frac{n}{4}\right)N_2 + yCO_2 + \left(\frac{n}{2}\right)H_2O$$

Equation 12. Reduction reactions of NO_x to Nitrogen.

In early systems, the catalysts were impregnated on a ceramic beaded structure due to the abundant supply of beads used in other industrial applications. Unfortunately, these beaded catalysts significantly restricted the flow of exhaust gases and decreased engine performance. To increase exhaust flow within catalytic converters and increase engine performance, a honeycomb style catalyst was developed for second generation catalysts, allowing good catalyst reaction with a large amount of surface area.

Rhodium (Rh) was the first metal used as the reduction catalyst in second generation systems, but it was found that at higher temperatures it could combine with oxygen and volatize. It was then replaced with rubidium (Ru) in third generation catalysts. In these systems, the oxidation reaction takes place downstream from the reduction reaction in the catalytic converter. This allows NO_x to be reduced first, producing excess oxygen. That way, the downstream catalyst causes a reduction reaction where the unburned hydrocarbons and carbon monoxide are burned into carbon dioxide and water using the excess oxygen. While rubidium (Ru) is used in the reduction catalyst, platinum (Pt) and palladium (Pd) were used as an oxidation catalyst. The following illustration notes the flow of exhaust gases and their reduction and oxidation phases within the catalytic converter used in second and third generation catalysts.

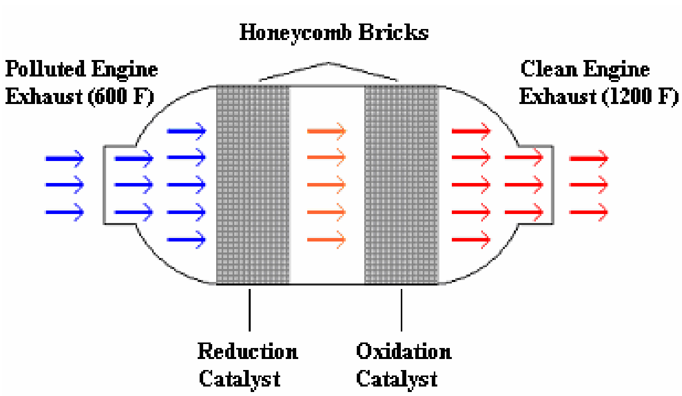

Figure 7. Schematic of Catalytic Converter.

Fourth generation catalysts were aided with the development of tighter control over air fuel ratio mixtures. In order to ensure that the proper air to fuel ratio is maintained, an oxygen sensor is placed in the exhaust upstream of the catalysts. Since the oxygen sensor regulated the “dirtiness” of the exhaust emissions before the catalytic converter, a narrower band of operation could be used so that palladium (Pd) replaced platinum (Pt) and rubidium (Ru). This allowed for a cheaper metal substrate that could be coupled closer to the engine allowing it to reach higher temperature quicker, yielding a longer catalyst life. The engine currently used in Arctic Cat snowmobiles uses an exhaust oxygen sensor to control the air fuel ratio. This allows for modern fourth generation three-way catalysts to be added to the exhaust with no modifications, while potentially realizing significant reduction in emissions.

Optimal mixture for catalytic converter – In order to ensure that the proper air to fuel ratio is maintained, an oxygen sensor is installed in the exhaust, upstream of the catalysts. When implementing a catalyst on a system that does not have one initially, there must be a balance in the design. The catalyst must fit in the space available in the snowmobile, yet it must have enough surface area to react with all the exhaust gases. If the catalyst is too large it will not get hot enough to light off and therefore will not reduce emissions. Also, the use of the oxygen sensor will be detrimental in determining the optimal air/fuel ratio to be used in lighting off the catalytic converter, thus reducing emissions. Three way catalysts must operate in this balanced manner. High reduction of NO_x requires an oxygen lean environment, while the oxidation of CO and hydrocarbons requires oxygen. In order to properly function and not emit an abundance of harmful pollutants, the engine must operate near the stoichiometric air to fuel ratio, around 14.7:1. Figure 8 shows an operating window for engine operation.

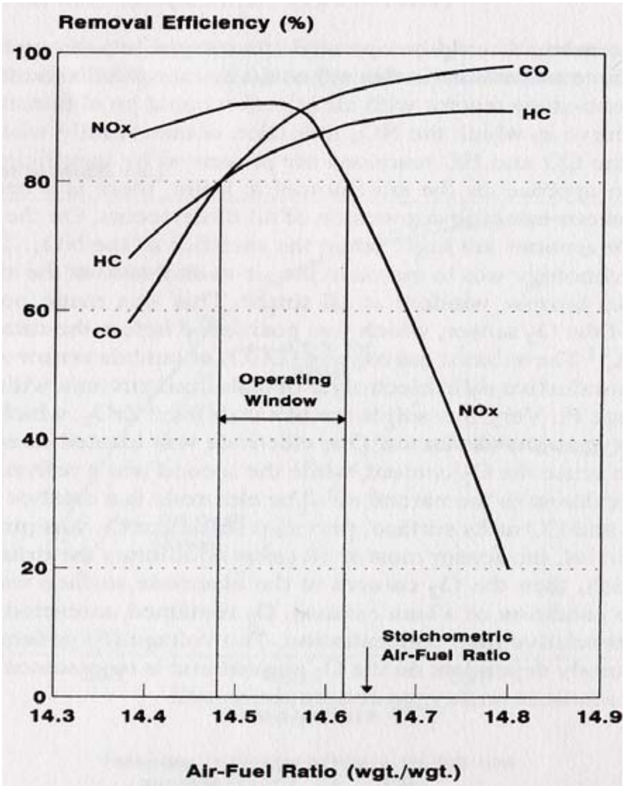

Figure 8. Emissions Gas removal as a function of Fuel Ratio.[5]

In the graph above, the percent of emissions gases removed is plotted as a function of the air-fuel ratio. It shows the ideal mixture for maximum emissions reduction of all three gases is approximately 14.6:1. In order to fully reduce emissions with a catalytic converter, the air/fuel ratio must be controlled so that HC, CO and NO_x emissions are reduced. Testing of our catalytic converter with the use of an ECU-microcontrolled piggyback and oxygen sensor would allow the optimal air/fuel ratio to successfully light off the catalyst and reduce emissions.

<u>Design of ECU piggyback</u> – One way to control the emissions from the engine is to control the air/fuel mixture injected into the engine for combustion. Without using a completely new ECU with a stand alone configuration or remapping the existing ECU, which can take years of experience, the control of the air/fuel mixture can be accomplished through the use of a "piggyback" electronics system with the help of analyzers such as a wideband O_2 sensor, dynamometer, and exhaust gas analyzer. If the stand alone option is desired, electronics products from a company such as Motec would be used, and engineering the fuel maps, timing curves, and ignition curves would have to be done ourselves. Weeks of research went into making the decision between the piggyback and the stand alone system. Background information on the operation of ECUs is a major part of our project and a key element in the decision between a piggyback system and a stand-alone system. The main purpose of the ECU is to determine the pulse width of the fuel injectors. Pulse width is defined as how long the injectors stay on. The pulse width is determined by sensors which act as inputs to the ECU. The ECU looks at the incoming signals, then through programming logic and data tables determines the appropriate pulse width for the situation. Figure 9 shows a block diagram with the inputs and outputs from the ECU.

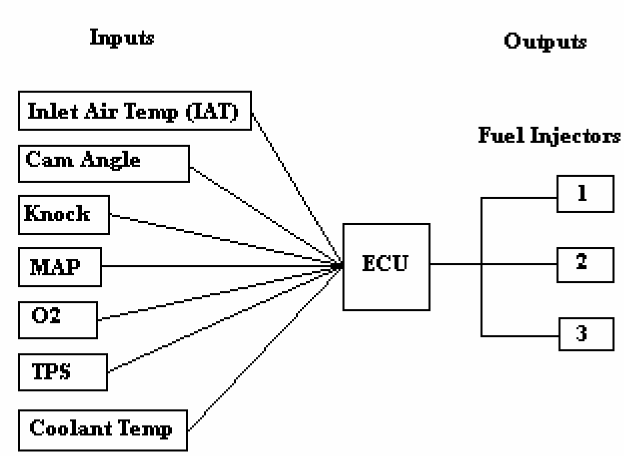

Figure 9. ECU input/output block diagram

Since HC and NO_x are the more important exhaust emissions to reduce, control of the air/fuel ratio via the upstream oxygen sensor must be considered. Since a high reduction in NO_x requires an oxygen lean environment (more fuel, richer air/fuel ratio) and the oxidation of CO and HC requires oxygen (less fuel, leaner air/fuel ratio), finding the optimal air/fuel ratio with the oxygen sensor is needed. However, since Figure 9 does not consider the temperature effects of a catalyst, more consideration needs to be taken when trying to control the air/fuel ratio with an oxygen sensor. If the catalyst does not reach a high enough temperature, less emissions will be burned off. Therefore, lighting off the catalyst is important to lowering all exhaust emissions such as NO_x, CO and HC.

In order to produce high exhaust temperatures, a richer mixture must be used to light off the catalyst. This can be done in one way via the air temperature sensor. Different temperatures yield different preset mixtures from the ECU. By developing a piggyback device that can control the resistance signal, and coupled with the IAT sensor, we are able to control the ECU and effectively change the AFR.

Initial design began with a dial potentiometer wired in series with the IAT sensor. This led to the implementation of our piggyback system that can adjust the resistance read by the ECU, which is in series with the of the IAT sensor.

Figure 10 is a hardware diagram of our piggyback for the snowmobile. It is wired in series with the IAT sensor and uses a basic stamp microcontroller and digital potentiometer to control the various resistances.

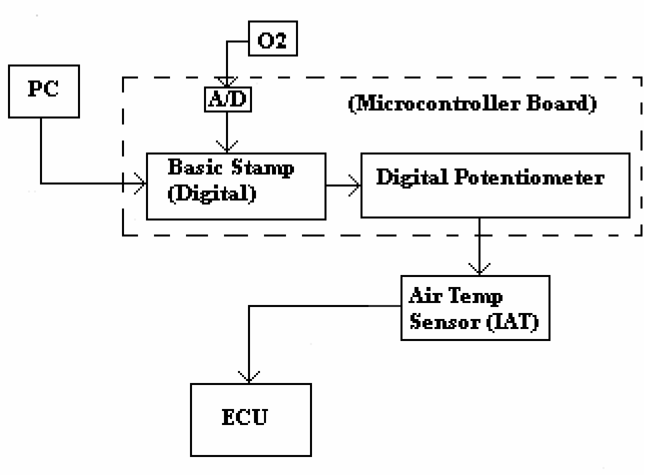

Figure 10. Hardware diagram for digital potentiometer piggyback.

Each component is defined below in more detail.

- PC – A computer used to program the basic stamp
- Basic Stamp – A microcontroller
- A/D – Analog to digital converter
- Digital Potentiometer – Changes the resistance
- ECU – Main computer which operates the snowmobile
- Air Temp Sensor – Measures inlet air temperature on the snowmobile
- O_2 Sensor – Measures the amount of oxygen in the exhaust system

The basic stamp is a microcontroller developed by Parallax, model BS2P24IC. It can easily be programmed using a form of the BASIC programming language, called PBasic. After the program is written, the microcontroller connects to a computer through a serial cable, and the program uploads into the basic stamp's electronically-erasable-programmable-read-only memory (EEPROM). Our design allows different programs to be uploaded onto the microprocessor while the unit is still mounted to the snowmobile. This feature is critical for tuning when adjustments must be made to the logic of the program.

The only input to the microcontroller thus far is a Bosch LSU4.2 wideband O_2 sensor. This sensor is mounted before the catalytic converter in the exhaust system to monitor the AFR. The microcontroller uses a program based on the relationship between the O_2 sensor and the IAT sensor and chooses the best resistance for the current situation.

Once the ECU injects fuel into the cylinders based on the resistance from the IAT sensor, the ECU needs to know if the air/fuel mixture is too rich or too lean for the operating conditions. This determination of rich/lean mixture is determined by an oxygen sensor is placed in the exhaust stream to measure the amount of O_2 in the mixture after combustion. The O_2 sensor is calibrated for O_2 concentration vs. voltage. The voltage signal is sent back to the ECU as feedback to tell the ECU if the mixture has too much O_2 in it or too little, hence if the air/fuel ratio is too lean or too rich. If the mixture is too rich, the ECU will adjust the injector voltage pulse width so that the mixture is leaner, and vice versa.

In order to tune the engine through mixture adjustment with the O_2 sensor, there are two types of O_2 sensors to choose from based on voltage output. A narrow band O_2 sensor uses a 0-1 V range of output, and a wideband O_2 sensor uses a 0-5 V range of outputs. This range of voltage is calibrated for voltage vs. air/fuel ratio, based on voltage and O_2 content in the exhaust stream. Because of the greater range of voltage, a wideband O_2 sensor allows for more fine adjustment of the AFR. This range adjustment can be seen in the O_2 sensor comparison in Figure 11.

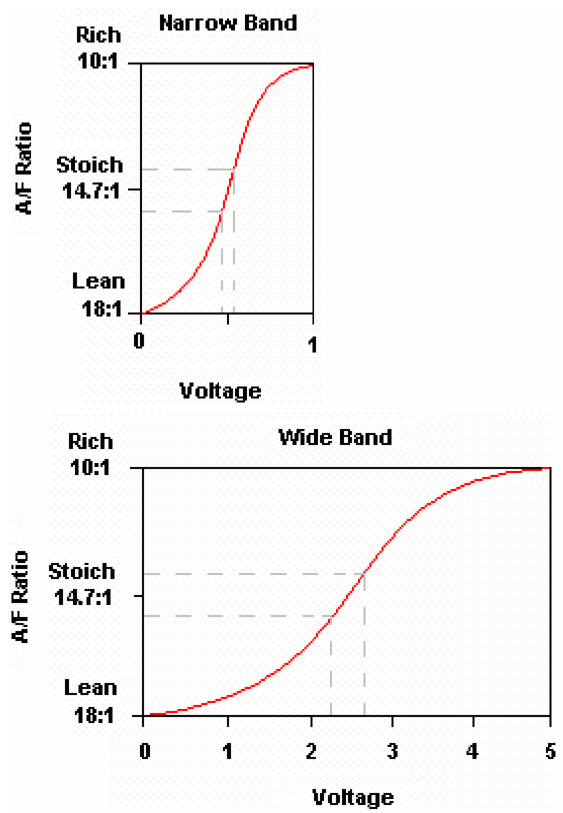

Figure 11. Comparison of narrow and wide band O_2 sensor output.

Once incorporating the Bosch wideband oxygen sensor into the design of the piggyback, several computer programs were written to control the air/fuel mixture. Figure 12, below, depicts a flow diagram of the final PBasic program developed to control the air/fuel ratio of the snowmobile engine. Originally, the program called for a variation in air/fuel ratio throughout the range of voltages supplied by the wideband O_2 sensor. A variation in exhaust gas composition either increased or decreased the resistance on the fly. This type of program worked but due to the complexity in processing for the Basic Stamp, was too complex for our application.

After developing several programs, a very simple one worked effectively. This program makes decisions based on the voltage output from the wideband oxygen sensor in a more defined step pattern. This program gives a firm resistance to a voltage range, rather than allowing the program to vary resistance completely. The output from the oxygen sensor ranges from 0-5 volts, while the microcontroller uses a digital step signal from 0-4095 steps. For example, since stoichiometric air/fuel ratio is approximately 2.35 Volts, this would yield a digital signal step of 1743. In the program, this would yield a resistance of 7.5 kΩ to be sent to the ECU for injector pulse width timing, thus, allowing a richer air/fuel mixture.

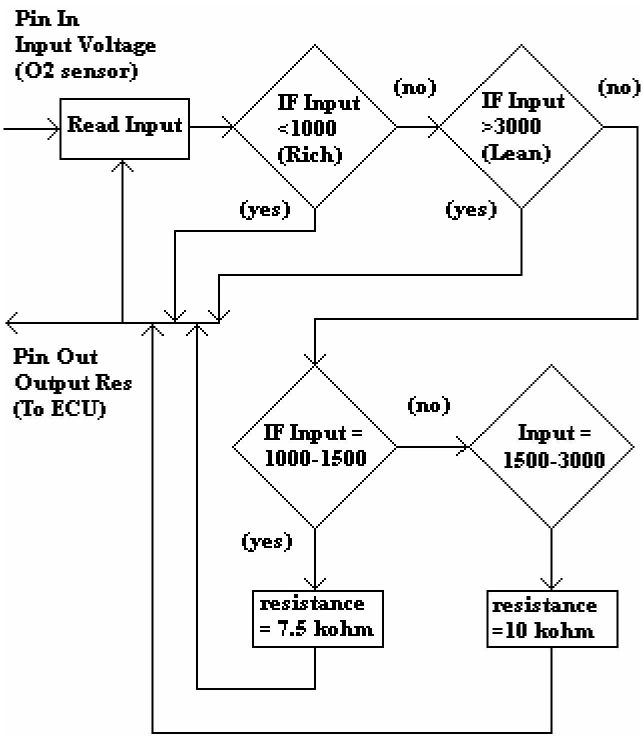

Figure 12. Flow Diagram of piggyback program.

IMPLEMENTATION

EMISSIONS –

Catalytic converter - Emissions tests were conducted in several stages of our project. In order to recognize the gains in using the catalytic converter, tests were conducted on the stock exhaust system and the exhaust system with the catalytic converter. To supply a constant load on the engine, a DYNO-mite land-sea water brake dynamometer was installed on the crankshaft of the engine. Engine coolant temperature was maintained using a small Chrysler radiator and water pump from a supplementary engine testing cart, where all testing was done at a coolant temperature of 180°F. Using an EMS Model 5500 five-gas exhaust gas analyzer; emissions samples were taken using the stock exhaust and the modified exhaust with the catalytic converter at varying engine speeds. A probe located downstream from the muffler allowed gas samples to be taken from the exhaust pipe of the sled. The results of these tests can be noted in the subsequent Results Section.

In order to test the stock exhaust emissions versus the modified exhaust, a test schedule similar to the event testing was followed. The competition specifies testing exhaust emissions at five engine speeds. The first test is at engine idle speed followed by percentages of wide open throttle of 65%, 75%, 85% and then finally a wide open throttle test. In order to ensure the engine's durability during our laboratory testing and to ensure test repeatability, we tested at slightly lower relative ranges. Testing at idle speed as well as intervals of 3000, 4000, 5000 and 6000 rpm were chosen in order to test the baseline emissions of the stock exhaust and the emissions reduction of the catalytic converter. Each RPM interval consisted of a 30 second sampling of exhaust emissions for HC, CO, NO_x, CO_2 and O_2.

ECU – The microcontroller piggyback for the ECU was tested using the same methods as the testing for the catalytic converter. The test engine speed schedule of idle speed, 3000, 4000, 5000 and 6000 rpm was used. Using the stock and modified exhausts, the sled was first tested using a dial potentiometer to vary the resistance seen across the inlet air temperature sensor. With the five gas exhaust analyzer and dynamometer, the sled was tested at stock resistance settings with stock exhaust, then with stock exhaust and 10 kΩ resistance.

Replacing the exhaust system with the catalytic converter, the sled was tested again at stock resistance settings, then at 10 kΩ resistance. This initial testing was done to determine the maximum affect on emissions due to the maximum amount of resistance the microcontroller would ever see in operation. After initial testing, the microcontroller was tested in a similar manner, with the exception of not testing the microcontroller with the stock exhaust. This testing would be redundant for the fact that we are not looking for stock exhaust emissions reduction with the microcontroller; we are not using it in the competition. The objective lies with reducing emissions with the microcontroller and catalytic converter. However, testing was completed with the stock exhaust to obtain baseline emissions readings. This would give a direct comparison to the microcontroller effects with the catalytic converter on that day, giving accurate data due to ambient air conditions.

NOISE, VIBRATION, AND HARSHNESS –

Cowling – Once the model was complete in solid woks the group was able to start construction of the cowling. Due to a lack of experience with composites a quarter scale model would be made first. After gaining a little experience, the full-scale plug was made. The plug started with a sturdy plywood backbone that was filled with foam. The plug was shaped the fit the mapped points and to look good. Bondo was applied and sanded to a smooth finish. The last steps of the plug were painting and waxing for a smooth mold release. The mold was created using whiteboard and two layers of medium weight fiberglass. The final part consisted of a layer of 2 oz. glass, Divinycell strips for stability, and a layer of 7 oz. glass. Only two NACA air vents were used in the final lay-up to reduce noise and still provide enough airflow. A layer of Tedlar-faced acoustical foam was then added to the inside of the cowling.

RESULTS

ENGINE MODEL – The engine model is modeled in MatLab as an idealized Otto Cycle to determine engine torque and power curves without the losses associated with transmitting the power through the drivetrain.

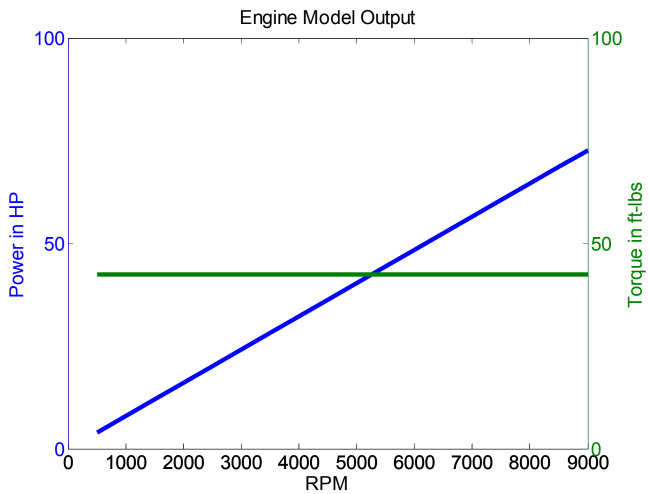

Figure 13. Power and torque vs. RPM from the four-stroke 660 engine model.

Notice the power curve has a constant slope and the torque curve is flat in Figure 13. No engine losses are included. Figure 14 compares the engine output from the Two-Stroke model. The constant slope is above the actual dyno data because no losses are included.

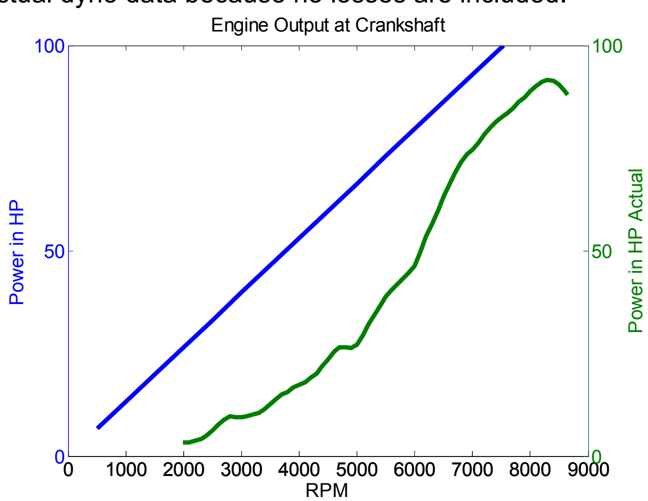

Figure 14. Two-stroke 580 output vs. engine model for Pantera 580 without engine losses.

The torque curves in Figure 15 show the model output adjusted for losses and has slightly higher output. This higher output is due to leaning out the fuel mixture. This may or may not be a good move, but it demonstrates the capabilities of the model.

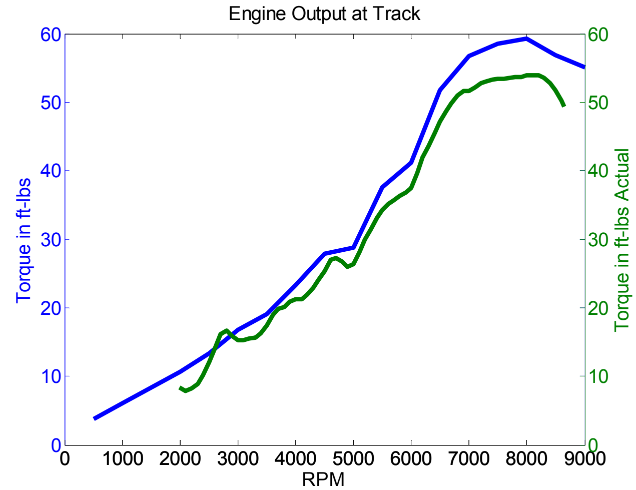

Figure 15. Two-stroke 580 output versus engine model for Pantera 580 with engine losses.

DYNAMIC SYSTEM MODEL – The Speed Diagram or Shift Chart is a powerful tool that can be used to visualize the function of the CVT in delivering power to the ground and how it translate into velocity. The Speed Diagram in Figure 16 show the engagement speed, shift speed and high and low ratios. This chart is used in the dynamic system model to create the relation between the velocity of the snowmobile and the engine RPM.

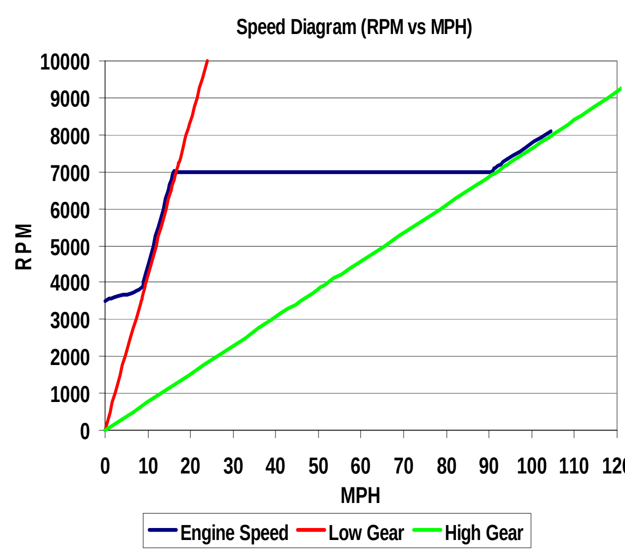

Figure 16. CVT speed diagram based on the Arctic Cat 660 four-stroke.

Running the dynamic system model, with configurations set for the Arctic Cat 660 four-stroke, and for operational parameters consistent with those at the actual CSC 500-foot drag race, a time prediction is estimated at approximately 8.3 seconds. Figure 17 shows the snowmobile position versus time. Note that the graph also predicts our time of roughly 18 seconds for last year's quarter-mile (1320 feet) drag event.

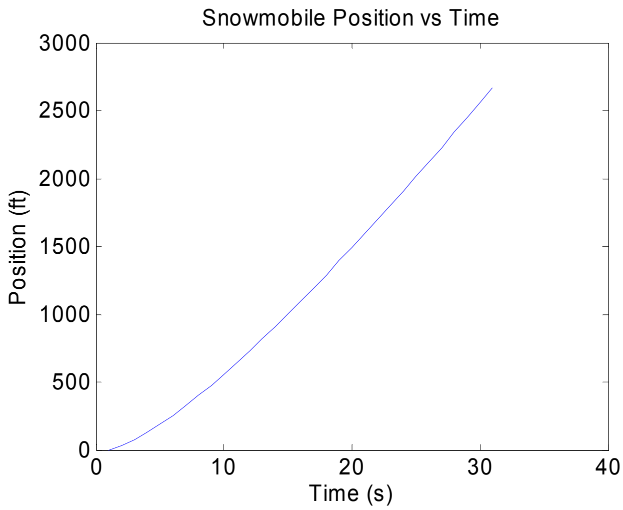

Figure 17. Snowmobile position vs. time.

STEADY STATE SYSTEM MODEL – The steady state model will allow for the prediction of fuel economy during the 100 miles endurance portion of the competition. This model with help determine how the fuel economy is affected by rider and sled mass, aerodynamic drag and sliding friction variables. Figure 18 shows the relative affect of aerodynamic drag and frictional losses at various velocities.

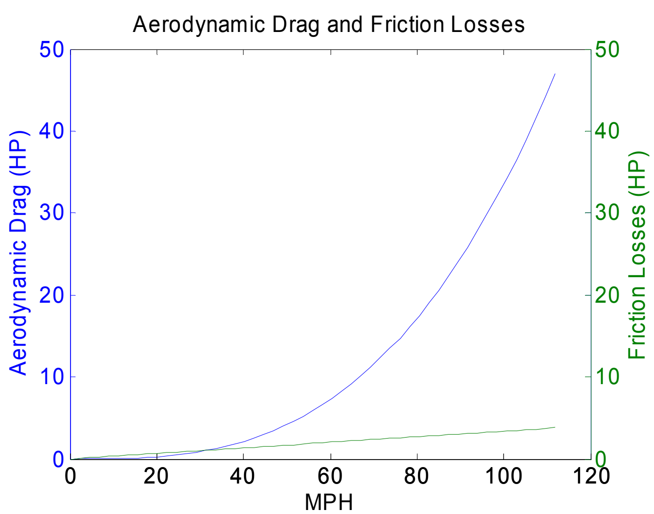

Figure 18. Aerodynamic drag and sliding friction as a function of velocity.

Adding the aerodynamic drag and the frictional losses together give the total power required at the ground to maintain constant velocity. This can be used to find fuel consumption at various velocities and help determine optimum running speeds for best fuel economy. See Figure 19.

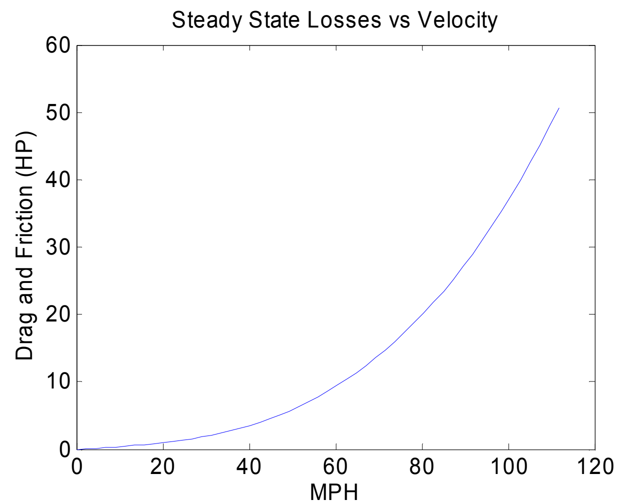

Figure 19. Power needed by engine.

Fuel Economy – BSFC in general is minimized at peak torque when the engine is most efficient.[6] The CVT is most efficient when the shift ratio is 1:1. The optimum steady-state speed for the 100 mi endurance should be in this range.

CATALYTIC CONVERTER – To determine the gains in using the microcontroller and wideband oxygen sensor with the catalytic converter, data for HC, CO, and NO_x emissions were plotted as a function of time. This was initially tested with the dial potentiometer and catalytic converter to determine if the variance in resistance across the inlet air temperature sensor would govern the air/fuel ratio significantly. Testing of the digital potentiometer and microcontroller yielded similar results with a maximum 10kΩ resistance supplied by the digital potentiometer. In order to obtain good data, each engine speed range was tested at 30 second intervals, idle speed was equivalent to the 0-30 second range, 3000 RPM was the 30-60 second range, 4000 RPM was the 60-90 RPM range, and so forth. The three following graphs plot these emissions versus the time interval, and essentially versus RPM. Since there was some lag time between the exhaust directly out of the engine and the sampling probe, the graphs display output approximately 10 seconds late of actual operation. Thus, when looking at hydrocarbons emitted in Figure 20, the 3000 RPM interval starts at approximately 40 seconds, indicated by the downward sloping plot. This is where the air/fuel mixture leaned from approximately 13:1 at idle to approximately 14.6:1 at 3000 RPM. This mixture continued to stay fairly constant up through the end of the 6000 rpm test.

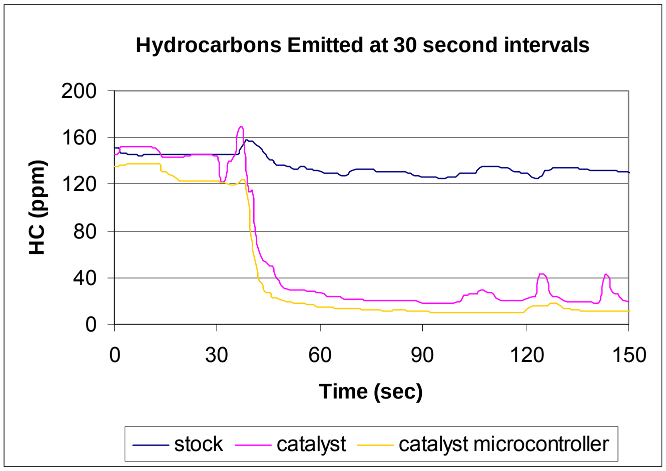

Figure 20. Hydrocarbon (HC) emissions data.

It is clear when observing Figure 20 that the catalyst gave a vast reduction in the hydrocarbon emissions above 40 seconds (3000 RPM). This indicates that the catalyst was very effective in reducing emissions, just by bolting it on without tuning of the air/fuel ratio. When taking into consideration the 10kΩ resistance supplied by the dial potentiometer, which is the maximum resistance the microcontroller will ever supply to the ECU, emissions decreased further as indicated in Figure 20. Figure 21 and Figure 22 relay similar emissions data for both carbon monoxide and nitrogen oxides. The catalyst alone proved to reduce emissions, while use of the microcontroller reduced emissions even further. Nitrogen oxide emissions in Figure 22 display the greatest reduction from stock configuration to the catalyst with microcontroller.

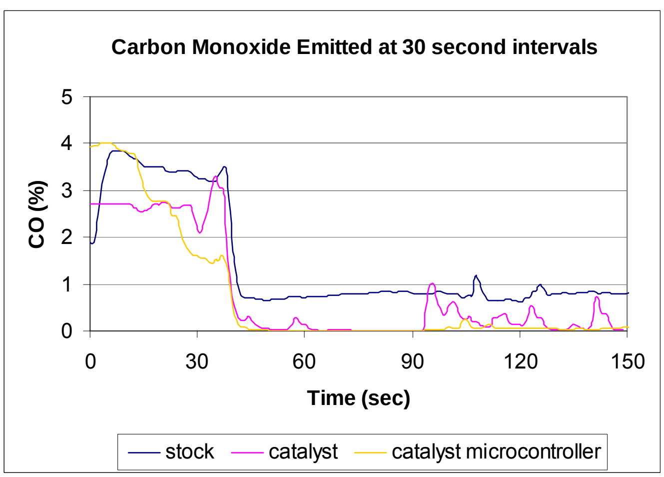

Figure 21. Carbon monoxide (CO) emissions data.

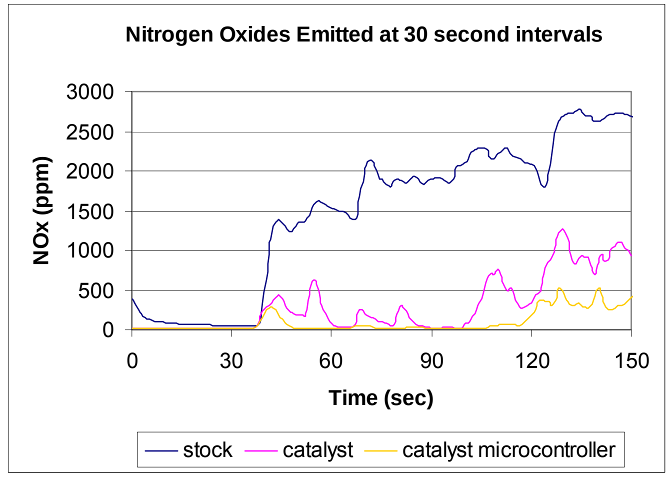

Figure 22. Nitrogen oxides (NO_x) data.

Figure 23 compares the average total reduction in emission for all three pollutants over the engine speed range. In order to fully compare reduction numbers, a comparison is made between the catalyst and microcontroller configuration with the stock configuration. It is clear that most reduction in all three types of pollutants occurs at engine speeds above 3000 RPM. This is a good monitor for snowmobile emissions due to the fact that these machines will be operating in these upper rev ranges on the trail, limiting pollutants all around.

The 4000 RPM range gives the greatest percentage reduction in emissions for both CO and NO_x, while the 5000 RPM range reduces HC the most. Idle speeds do not have as much of an effect on emissions because light off is not occurring due to a rich mixture of approximately 13:1. NO_x proves to be reduced at this range, this goes back to the fact that NO_x reduces chemically to nitrogen and either carbon dioxide or water, or both depending on the molar amounts. The mixture is too rich at this engine speed for HC and CO to oxidize, but when engine speed increases, the mixture leans to approximately 14.6:1, just rich of stoichiometric, where HC and CO oxidize into carbon dioxide and water.

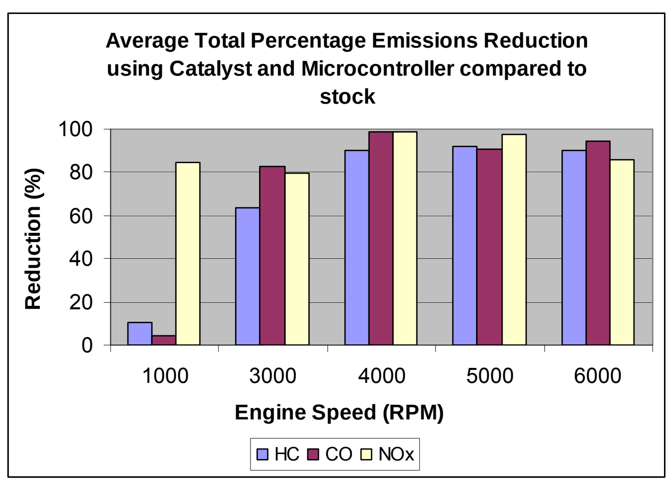

Figure 23. Emissions reduction using the catalyst and microcontroller, compared to stock.

Figure 24 relays overall percentage reduction in emissions using just the catalyst as compared to stock configuration. NO_x is reduced the most, which can be related back to Figure 22 which gives the actual data recorded for NO_x emissions. Similarly, CO and HC are reduced greatly from stock configuration.

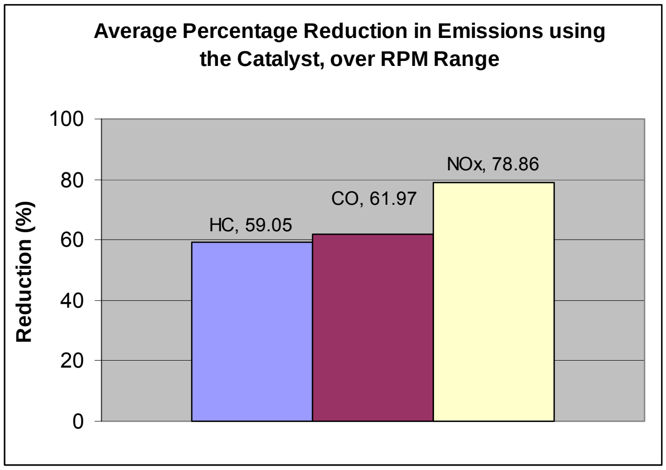

Figure 24. Emissions Reduction using the catalyst, compared to stock, over RPM range.

These reduction numbers in Figure 24 are somewhat higher in magnitude than Figure 25, which compares the effects when the microcontroller is installed. The microcontroller adjusts the mixture further giving approximately 30% reductions in HC and CO compared to just using the catalyst, and a 53% reduction in NO_x from just using the catalyst. Thus, the total reduction in all three exhaust emissions can be relayed in Figure 26, where the microcontroller and catalyst configuration is compared to stock configuration over the engine speed range tested. This displays the overall gains from the stock engine configuration over the RPM range.

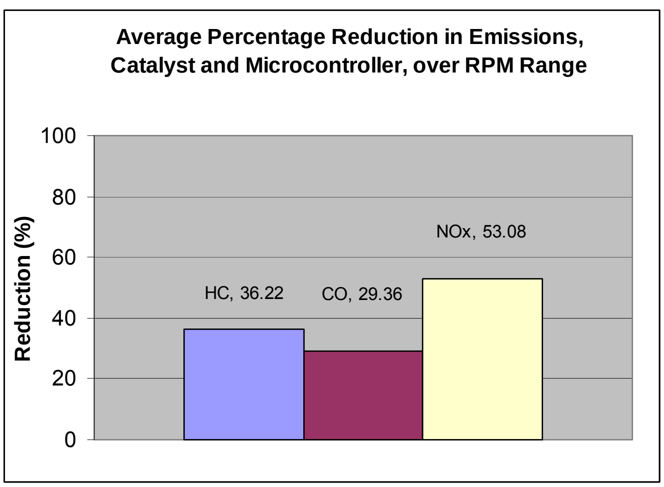

Figure 25. Emissions Reduction using the Catalyst and Microcontroller, compared to catalyst alone, over the RPM range.

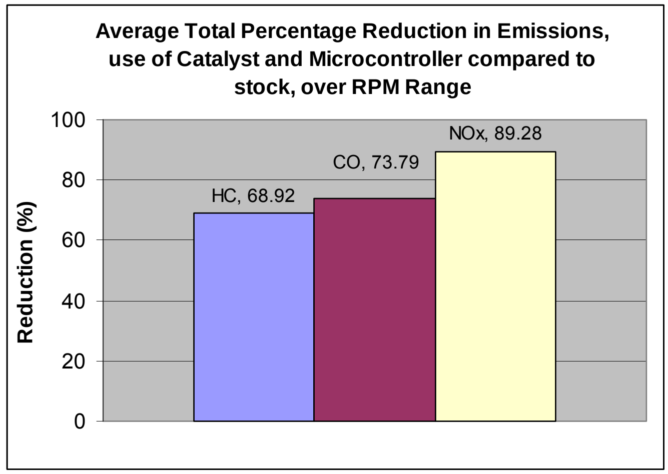

Figure 26. Emissions Reduction using the Catalyst and Microcontroller compared to stock configuration, over the RPM range.

Considering the entire operating range of the snowmobile is good for testing, but the emissions test administered by SAE Clean Snowmobile Challenge uses high percentages of wide open throttle to test emissions other than at idle speed. This testing would be in consideration of emissions at trail operating conditions. Thus, one would not be operating the snowmobile below the clutch engagement RPM on the trail, or approximately 4000 RPM. Operation from this speed to wide open throttle of approximately 7000 RPM would be given regularly. Figure 27 displays overall gains from the microcontroller and catalytic converter in this range, normal trail engine operating conditions. This is where emissions reduction is most important.

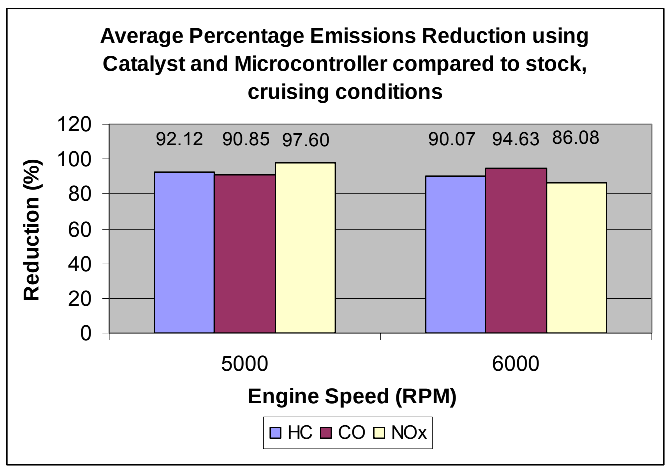

Figure 27. Emissions Reduction using Catalyst and Microcontroller compared to stock, at cruising conditions.

COSTS – Costs for the piggyback package were \$580.07. The microcontroller part of the piggyback cost \$251.07 and the wideband oxygen sensor cost \$329.00. The new cowling cost \$170.61. Details on component costs for the microcontroller can be referenced in the University of Maine Technology Implementation Cost Assessment sheets.

CONCLUSIONS

CATALYTIC CONVERTER/MICROCONTROLLER – When implementing a catalytic converter and piggyback microcontroller with wideband oxygen sensor, emissions were reduced overall for hydrocarbons, carbon monoxide and nitrogen oxides. Over the entire engine speed range of testing (refer to Figure 26), hydrocarbons were reduced by 68.9% from stock configuration, carbon monoxide was reduced by 73.8% from stock, and nitrogen oxides were reduced by 89.3% from stock. At normal operation on the trail from 5000-6000 RPM, average percentage emissions reduction using the catalyst and microcontroller will range from approximately 90-95%, according to the data in Figure 27.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

AFR: Air Fuel Ratio

BSFC: Brake Specific Fuel Consumption

CVT: Continuously Variable Transmission

ECU: Engine or Electronic Control Unit

EGR: Exhaust Gas Recirculation

IAT: Inlet Air Temperature

Microcontroller: A device consisting of a basic stamp (processor) that is programmed by a PC in Basic programming language. The microcontroller developed by the UMaine team also consists of an Analog to Digital Converter to convert the wideband oxygen sensor output to a digital signal, a digital potentiometer to vary the resistance across the inlet air temperature sensor read by the ECU, and a DC to DC converter to reduce the voltage input to the Basic Stamp.

Piggyback: A device used to override or supplement the Electronic Control Unit of an engine, or to cause the ECU to make decisions based on the piggyback input to the ECU. The piggyback developed by the UMaine team consists of a wideband oxygen sensor and microcontroller.

Wideband Oxygen Sensor: Produces a 0-5 Volt signal as opposed to a 0-1 Volt signal for better resolution on the signal sent to the ECU, in this case sent to the microcontroller, for air/fuel ratio readings.

APPENDIX

INFRASTRUCTURE FOR DESIGN – All designs and modifications need testing at some stage in development. The UMaine CSC team has integrated a sub-team who has enabled us to use an engine dynamometer. This team was implemented simultaneously to other current

Engine Dynamometer – A DYNO-MITE Land-Sea water brake dynamometer was used in obtaining experimental horsepower and torque curves for the Arctic Cat 660 engine. The water brake dyno was also used in testing the emissions reduction capability of the piggyback with catalytic converter. The dynamometer bolts onto the crankshaft of the sled and uses water pressure to load the engine and a load cell attached to the countershaft to measure force exerted on the moment arm. The relative ease of setup, and user-friendly computer interface make engine diagnostics much simpler to execute and understand. Currently the University of Maine Team uses a track dynamometer with an eddy current resistance unit to determine the amount of horsepower delivered to the ground. Combining information from the two dynos allows for approximation of losses due to drivetrain. Another parameter captured by the new dynamometer acquisition system that is important for us is the Exhaust Gas Temperatures. This information tells us how rich or lean the engine must be run in order for the catalytic converter to run at its maximum efficiency. The working torque and power curves for the Arctic Cat 660 four-stroke, created by the engine dyno, is shown in Figure 2.

Exhaust gas analyzer – A 5-gas automotive exhaust gas analyzer from EMS, model 5500, was used to measure HC, CO, and NO_x, as well as O_2 and CO_2 levels in the snowmobile exhaust stream. Computer diagnostic equipment was used with the analyzer to record emissions percentages and parts per million for analysis.

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[6] http://www.westechperformance.com/pages/Tech_Library/Understanding/bsfc.html