Development of Clean Snowmobile Technology for the 2007 SAE Clean Snowmobile Challenge

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ABSTRACT

The Kettering University entry into the 2007 Clean Snowmobile Challenge is a 2006 Polaris FST Switchback. Building upon the success of the conversion to ethanol (E85) from the 2006 competition, the team chose to focus efforts on overall vehicle refinement. The Bosch controller has been recalibrated to improve engine tuning for running E85. The stock 144-inch track has been replaced in favor of a shorter 121-inch track. For noise reduction the muffler system was redesigned for better air flow and sound quality. The team has also focused on weight reduction by installing a lighter chaincase, a revised suspension, a specially designed catalytic converter, and the use of aluminum bits where applicable.

INTRODUCTION

The first snowmobile was developed in 1935 and was capable of carrying 12 people. The snowmobile meant that doctors, veterinarians, and ambulance drivers could get to those in need of medical care even during heavy snowfall. This often meant the difference between life and death. Snowmobiling as a recreation did not catch on until the late-1950's. The development of smaller gasoline engines meant that manufacturers could offer smaller and lighter one or two passenger snowmobiles. Within ten years, dozens of manufacturers produced snowmobiles. Only four manufacturers remain today, with global industry sales of around 200,000 snowmobiles annually. [1]

During President Nixon's term, the snowmobile came under scrutiny for environmental hazards. The executive order from the president was that snowmobile use in national parks was permitted such that use did not harm the ecology or aesthetics of the park. This meant snowmobiling was restricted to designated trails in areas where accumulated snow would allow travel without harming underlying vegetation, soil and wildlife. [2]

The International Snowmobile Manufacturers Association (ISMA) estimates that snowmobiling generates over 27 billion dollars of economic activity annually. New snowmobile sales account for about 1.2 billion dollars while the remainder is accounted for in apparel and accessories, registrations, permits, tourism and spare parts. The snowmobiling industry also accounts for nearly 95,000 fulltime jobs, and 3,000 dealerships. Approximately 10% of this 27 billion dollars is collected directly by the state as taxes. [3]

Taking into account the economic impact alone, a blanket ban on snowmobiling is not a feasible option. However, as snowmobiles are used in the winter season the environmental impacts are the greatest due to colder denser air. Further, cold fuel does not combust as easily nor does it completely convert to heat energy. As a result there is a greater amount of unprocessed emissions passed through the tailpipe into a cold dense ambient air medium which cannot disperse the toxins as quickly.

In an effort to reduce emissions, the Environmental Protection Agency (EPA) has mandated the following strategy for emission reduction:

- 30% reduction by 2006
- 50% reduction by 2010
- 70% reduction by 2012

The shift for manufacturers has been to use a four-stroke engine in place of the historically typical two-stroke engine. While the two-stroke engine offered the advantage in terms of weight and power output compared to a four-stroke engine, the disadvantage was that it sent unburned fuel and lubricating oil directly into the exhaust line. In addition to being cleaner burning the four-stroke engine is also quieter.

The function of this paper is to therefore document the effort of the student design team in building a cleaner and quieter snowmobile with minimal impact to cost using technologies and innovative methods applicable to the real world. This is the goal behind the Clean Snowmobile Challenge (CSC) organized by the Society of Automotive Engineers (SAE).

DESIGN OBJECTIVES

Building upon the success of the Polaris FST used in the 2006 competition, the Kettering University team chose to focus efforts on overall vehicle refinement to meet the stringent 2012 EPA regulations. These foci include:

- Emissions Reduction
- Noise Reduction
- Ethanol Performance Refinement
- Weight Reduction
- Durability
- Rider Safety
- Cost Effectiveness
- Rider Comfort

PERFORMANCE MODIFICATIONS

The starting point for the 2007 competition is the 2006 Polaris FST used by the team in the previous year's competition. The team focused on reducing emissions, noise, and weight while maintaining the performance and durability of the sled.

ENGINE

The Polaris FST is factory equipped with a 749cc four-stroke turbocharged two-cylinder engine (see Table 1). Given the robust, lightweight design of this engine and the limited space in the engine compartment, the team chose to utilize the stock engine and modify it for use with E85 to improve power and emissions.

POWER

In stock form the Polaris FST was rated to produce 135 hp (100 kW) at 7500 rpm. Initial dynamometer testing revealed a peak power output of only 110 hp (82 kW), which was attributed to this snowmobile's preproduction nature. The engine had not been calibrated to the manufacturer's final production specifications before it was received because of an issue with spring preload on the waste gate. The Polaris FST also has a built in power limiter which engages at a lower engine speed when the track is not moving as part of a limp home mode safety system. Therefore during initial testing the engine never produced peak power.

Table 1. Polaris FST Specifications. [4]

Displacement:	749 CC
Configuration:	Twin Cylinder
Block Material:	Aluminum
Cam system:	8 Valve-SOHC
Ignition:	Coil on plug
Valves per cylinder:	Four
Compression ratio:	9.0:1
Bore in/mm:	3.45/85
Stroke in/mm:	2.60/66
Aspiration:	Turbocharged
Engine Control System:	Bosch M7.4.4
Snowmobile Weight:	268 kg (590 lb)
Front Suspension Travel	254 mm (10 in)
Rear Suspension Travel	353 mm (13.9 in)
Track Length	3070 mm (121 in)

FUEL SELECTION

With the instability of petroleum prices, the demand for alternative fuels has greatly increased. Most of the major automobile manufacturers have been offering flex fuel vehicles (FFV) that have the ability to run on gasoline or ethanol blended fuels up to 85% (E85). Ethanol blend fuels have a number of advantages over gasoline in terms of power output and emission production. With this in mind the team chose to convert the snowmobile to run on E85.

Ethanol blend fuels are made from a renewable resource such as corn or sugarcane. The alcohol derived is mixed with a hydrocarbon for denaturing, typically gasoline. As federal law requires that all fuel sold in the United States must contain an oxygenated component, nearly all pump gasoline contains 10% ethanol by volume. While this low percentage of ethanol content does not present compatibility issues with vehicles produced today, vehicle must be modified in order to use with E85. Many of the standard fuel components must be upgraded. Compared to pump gasoline, E85 is also safer to transport as the alcohol is water soluble and biodegradable.

While E85 has a lower Lower Heating Value than gasoline (see Table 2), operating an engine at the proper stoichiometric value will produce an increase in power. E85 has a stoichiometric air to fuel ratio of about 10 to 1, whereas stoichiometric for gasoline is 14.7 to 1. Therefore, to run on E85 more fuel must be delivered to the combustion chamber for proper air to fuel mixing and combustion. For the same amount of air, an engine operating on E85 will use approximately 1.48 times more fuel, while only 1.4 times as much fuel by volume is required to release the same amount of energy. This increases the mean effective pressure on the piston resulting in an increase in power and torque output. [5]

Table 2. Fuel Properties. [5]

Physical Fuel Properties			
	Gasoline - Regular Unleaded	**Ethanol**	**E-85**
Formulation	C_4 TO C_{12} H/C-chains	C_2H_5OH	85% ethanol (by volume) 15% gasoline (by volume)
Average Analysis (%mass)	C: 85-88 H: 12-15	C: 52 H: 13 O: 35	C: 57 H: 13 O: 30
Octane - R+M/2	87	98-100	96
Lower Heating Value KJ/Kg (Btu/lb$_m$)	43,000 (18,500)	26,750 (11,500)	29,080 (12,500)
Lower Heating Value - KJ/liter (Btu/gal)	32,250 (115,700)	21,240 (76,200)	22,830 (81,900)
Heat of Vaporization - KJ/Kg (Btu/ lb$_m$)	330-400 (140-170)	842-930 (362-400)	812 (349)
Stoichiometric A/F (mass)	14.7	9	10
Conductivity - mhos/cm	$1x10^{-14}$	$1.35x10^{-9}$	$1.4x10^{-9}$

FUEL SYSTEM MODIFICATIONS

Because of the corrosive nature of ethanol, before E85 could be used in the snowmobile many of the standard fuel system components had to be upgraded.

For ease of testing the team fitted quick disconnects to the supply and return fuel lines. In addition, the in-tank fuel pump was replaced with an inline external fuel pump. However, the team was unable to procure an off-the-shelf external inline pump compatible with E85. As ethanol is approximately 135,000 times more conductive than gasoline, an issue arose with the inline pump because it passes the fuel through the motor and circuitry. To resolve the issue the internal components of the inline fuel pump were replaced with those of an in-tank fuel pump which was E85 compatible.

The stock paper fuel filter was replaced in favor of a 35 micron sintered bronze filter as shown in figure 1 to accommodate the required increase in fuel flow. An E85 compatible adjustable fuel pressure regulator with gauge was installed. Fuel lines were replaced with a synthetic rubber hose reinforced by a full coverage interior braided fabric sheath as show in figure 2. Specialized Army Navy (AN) pressure fittings made specific to the synthetic hose were utilized to connect various fuel components. [6] To compensate for the increase in fuel consumption and ensure completion of the endurance event a 10.2 gallon tank was installed to replace the stock 9.2 gallon tank.

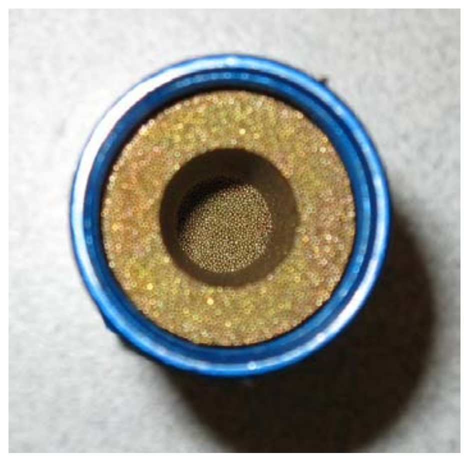

Figure 1. Sintered Bronze Fuel Filter

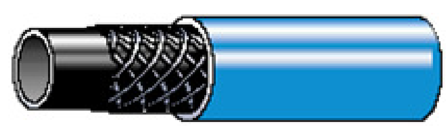

Figure 2. Synthetic Rubber Fuel Line [6]

To ensure the remaining stock fuel system components E85 compatibility, samples were taken from injector seals, the fuel rail, fuel tank, and in-tank pickup. The condition of the samples was recorded and then the samples were placed in a solution of E85 and sealed. For the 2006 competition, the samples were examined after a two week soak with no visual effects of degradation recorded. For the 2007 competition, the samples were soaked for a year with no visual change compared to the 2006 results.

To increase the fuel delivery to compensate for the increased fuel volume requirement, the stock injectors were replaced with larger units. The new injector size (453 g/min; 60 lb/hr) allowed for a more reasonable fuel line pressure (441 kPa, 64 psi) and only minor modifications to the fuel rail to accommodate the increased length. Because the stock injectors were running at the upper limit of their pulse-width duty cycle increasing pulse-width was not an option.

While running the engine on the dynamometer the team tested a variety of air to fuel mixtures and spark timing to find the optimal operating points for best brake specific fuel consumption, engine out emissions, as well as a reasonable exhaust gas temperature. Since the octane rating of E85 (96) is higher than that of regular pump gasoline (87), spark timing could be safely advanced without encountering a knock condition.

ENGINE CONTROL UNIT (ECU)

The snowmobile was factory equipped with a Bosch M7.4.4 engine control unit (ECU) with closed loop wide band oxygen sensor feedback. Closed loop engine control allows the ECU to monitor oxygen content of the exhaust gases and adjust the air/fuel mixture. Using Bosch supplied calibration tools, the Bosch ECU/ETK, ETAS ES-690, and Inca Version 5.4 software, the team was able to adjust the ECU to avoid excessively rich mixtures in an effort to curb emissions and maintain fuel economy based on speed and load conditions. To calculate appropriate spark timing and fuel injector pulse-width the ECU reads manifold absolute pressure (MAP), rather than throttle position, verses engine speed. This allowed greater accuracy and adjustability to match actual intake manifold conditions.

Where this type of fuel injection system proved most useful was in the selection of the exhaust system design. The team designed multiple systems in an effort to reduce backpressure for improved performance but at the same time reduce overall noise emission. Backpressure in the exhaust system affects how quickly exhaust gases are expelled from the cylinder after the combustion stroke. Excess backpressure will reduce the amount of exhaust expelled leaving more exhaust gas residual in the system. As the residual fluctuates the amount of air and fuel the engine is able to consume fluctuates. As the ECU utilizes a MAP sensor to calculate volumetric efficiency it did not require recalibration each time a different exhaust system was installed.

GUAGES

To make accurate adjustments to the ECU, engine oil temperature, engine oil pressure, intake boost pressure, and lambda gauges were installed. The lambda gauge measures the actual air to fuel ratio in comparison to the theoretical stoichiometric ratio. When running at stoichiometric mixture, the lambda gauge reads a value of 1 with richer mixtures reading less than 1 and leaner mixtures reading greater than 1. While the addition of the lambda meter required an additional wide band oxygen sensor, the added cost was justified by the value of the information feedback. While this was useful for development, it would not be need on a production snowmobile.

TURBOCHARGER AND INTERCOOLER

The stock Polaris engine was equipped with both a turbocharger and intercooler. A turbocharger is used to increase the volumetric efficiency of an engine by increasing the intake manifold pressure through compression. This increase in pressure forces more air into the cylinder during the intake stroke of the piston. The turbocharging of the intake air increases the temperature of the air being fed to an engine. Because cold air is denser than warm air a greater mass of air is able to be introduced to the cylinder. An intercooler is used as a heat exchanger to reduce the heating effects of compression on the intake air charge temperature. Greater air mass in the cylinder requires a greater mass of fuel injected, leading to an increase in energy released.

To make better use of both the turbocharger and intercooler, the team made a couple of modifications to the intake system. The turbine shaft is equipped with an internal waste gate to allow the exhaust gases to bypass the turbine to prevent excessive turbine speeds. The blow-off valve was relocated to a position prior to the intercooler. The rubber tubing connections of the intercooler were removed and aluminum pipe was installed in its place where feasible, smoothing the air flow and reducing losses.

COLD START CHARACTERISTICS

As shown in Table 2, the heat required for vaporization for ethanol blended fuels is much higher than that of gasoline. This presents a problem with winter starting conditions as ethanol will not vaporize at temperatures below 11^{0}C. Just as gasoline and diesel pump fuel is switched to a winter blend during the colder months, E85 is also adjusted. A blend of 70% ethanol and 30% gasoline is more appropriate for proper vehicle starting and operation during the winter months. For marketing simplicity however this blend is still advertised as E85. [7]

To further aid cold starting the team programmed the ECU to adapt through fuel enrichment. A greater volume of fuel is injected into the cylinder during a cold start to allow enough gasoline into the cylinder to vaporize and initiate combustion.

CHASSIS

The focus for chassis improvements was to reduce weight and increase overall structural integrity while enhancing the ride and handling characteristics and overall aesthetic appeal of the snowmobile. The steel bumper designed for last years competition to allow suspending of the front portion of the snowmobile for technical inspection was removed and replaced with a lighter aluminum unit. The tunnel of the sled was reduced in length to match the reduced track length. The front spindles were replaced increasing the overall track width by ½" to improve handling.

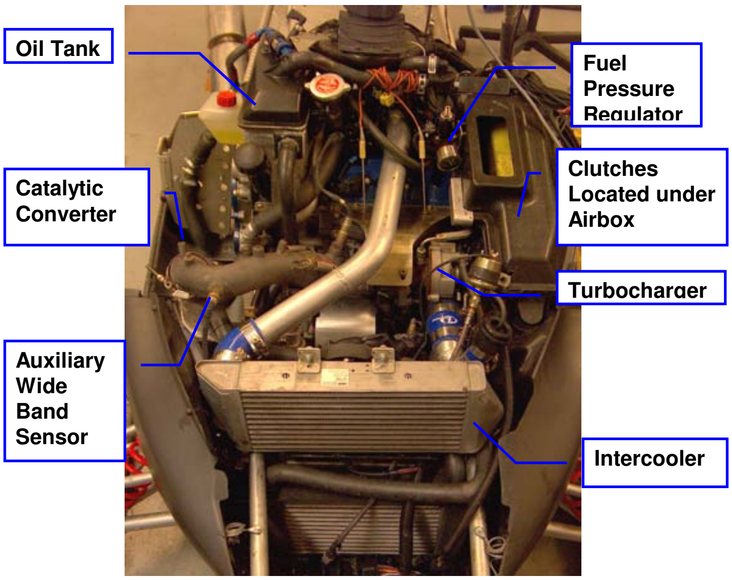

Figure 3. Engine Compartment

TRACK AND SUSPENSION

To improve handling and reduce weight the 144 inch track was replaced with a shorter 121 inch track. The reduction of the track length also meant less rotational mass and less power required to drive the track.

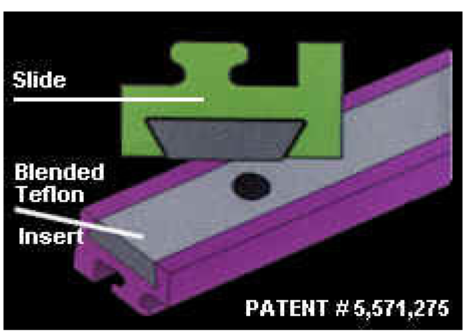

Figure 4. Composite Teflon Insert Slides [8]

To further reduce friction and increase fuel efficiency, the stock track slides were swapped out in favor of composite Teflon insert slides shown in figure 4. These slides have a melting temperature greater than 372ºC (702ºF). In comparison to the stock slides that have a melting temperature around 149-163^{0}C (300-325ºF), the Teflon inserts have better wear characteristics, especially during icy conditions where the track is not exposed to sufficient snow to cool and lubricate the slides. [8]

CONTINUOUSLY VARIABLE TRANSMISSION

Typical power transmission for snowmobiles has been the continuously variable transmission (CVT). A CVT works on the principal that it can adjust to an infinite number of transmission ratios with the high and low ratios dictated by the clutch range. The CVT has efficiency concerns however in that significant energy losses can be attributed to belt slippage and the resulting heat. Especially at low engine speed the belt squeezing force is well below the optimum belt region as show in figure 5.

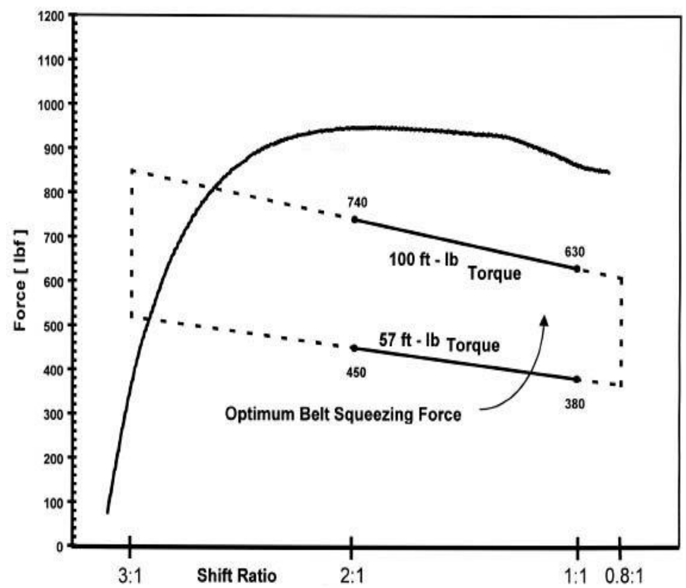

Figure 5. Belt Squeezing Force Chart of Typical Snowmobile [9]

The primary clutch uses 3 weights which convert centrifugal force to belt squeezing force and up shift forces as the engine output shaft rotates. Figure 6 shows several positions of a clutch weight as engine speed is increased.

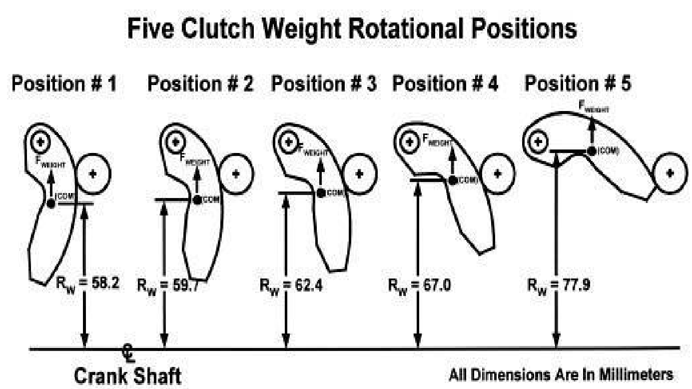

Figure 6. Clutch Weight Rotational Positions [9]

At low engine speeds the weight remains in a retracted position with the center of mass (COM) creating a force that acts mainly on the weight pivot pin. As engine speed increases the weight begins to "fly out" creating a moment about the weight pivot pin. This moment is opposed by the roller pin which causes the sheave to move. As the sheave moves in, a force is exerted on the belt. Depending on sheave angles this force is divided into belt squeezing and up shifting forces as shown in figure 7.

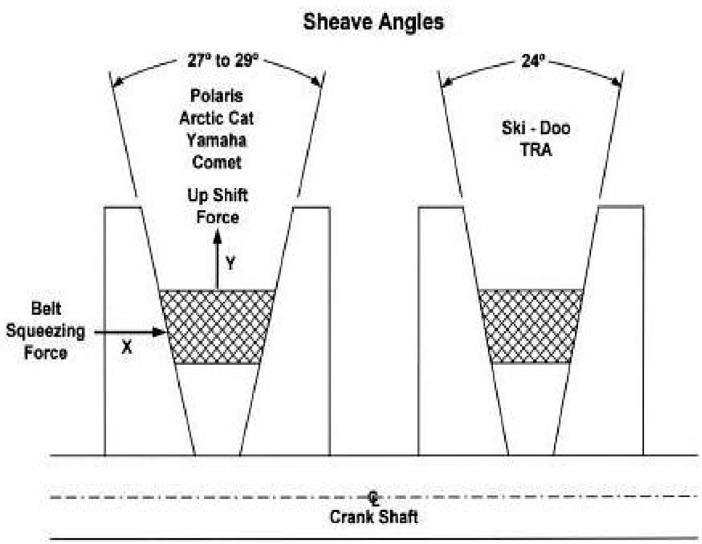

Figure 7. Belt Shifting and Squeezing Forces Based on Sheave Angles. [9]

By dividing the clutch weight into quadrants, with the pivot pin being the center of these quadrants (see figure 8) it is seen that the majority of the clutch weight's mass resides in quadrant 4. In static position the COM is very near the centerline of quadrants 3 and 4 where it is least effective in producing squeezing force.

To reduce low speed belt slip, the team chose to use Heal Clicker HC54-7 clutch weights. They add an additional mass to quadrant 1 above the position of the roller pin. There it acts as a secondary COM quickly creating a moment about the pivot pin. As a result, a greater belt squeezing force is delivered at relatively low engine speeds. The difference in belt squeezing force can be seen in figure 9. This additional belt squeezing force reduces belt slippage and improves overall efficiency of power transmission from engine to track. [9]

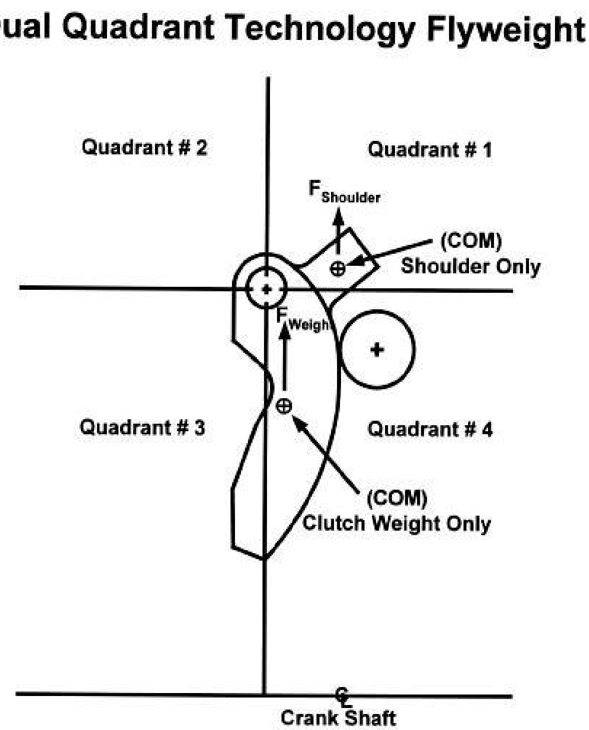

Figure 8. Clutch Weight with Added Shoulder [9]

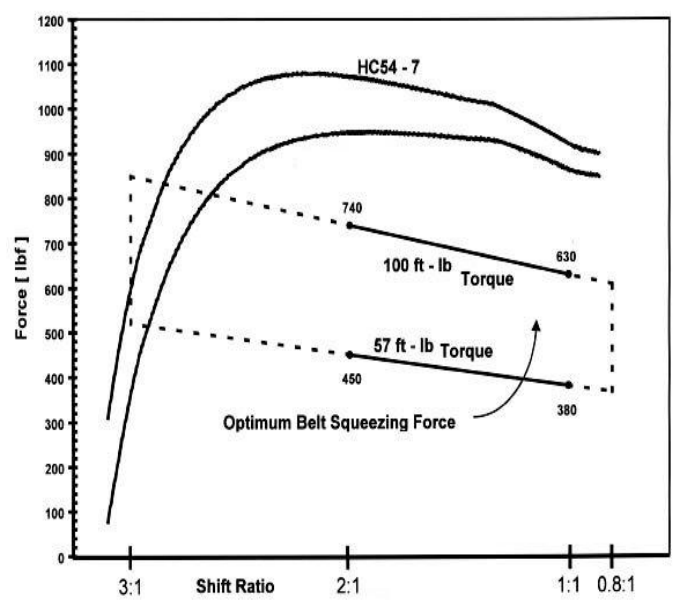

Figure 9. Belt Squeezing Force with New Clutch Weights [9]

NOISE REDUCTION

Noise from snowmobiles can be attributed from a number of different sources including the engine, intake, exhaust and track. To determine overall noise emissions of the snowmobile the team performed testing as specified by SAE standard J192.

INITIAL TESTING

The course layout for the SAE J192 standard for snowmobile noise testing is shown figure 10. Using a ½" pre-polarized condenser microphone from FEV, the team performed pass-by testing. Pass-by noise is the combination of all noise sources present when the snowmobile passes the microphone. [10]

To perform the SAE J192 test, the snowmobile must approach the measurement areas at 15 mph. At the entrance the rider must hold the throttle wide open and accelerate for 150 feet while sound levels are recorded. This is performed for three passes in each direction. The results are averaged and both directions are reported in the form of dB(A).

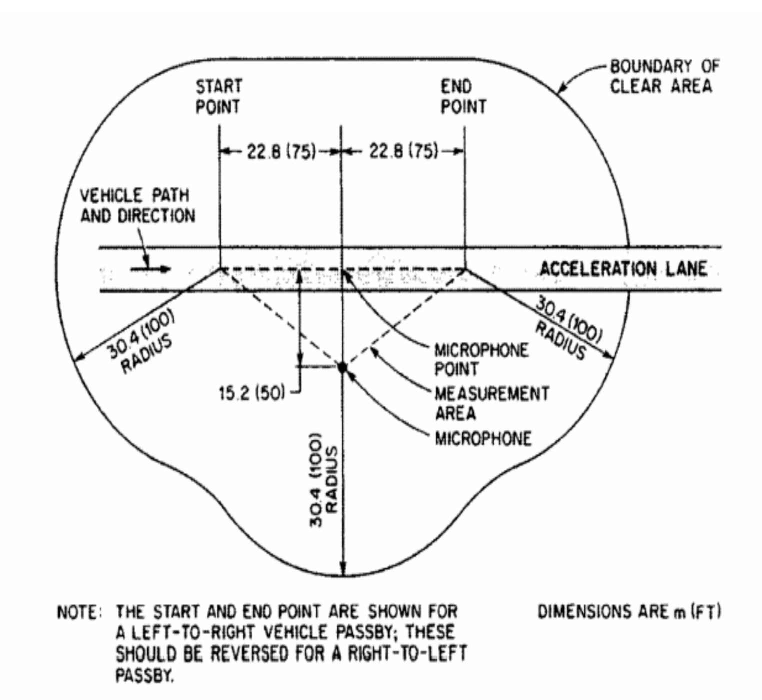

Figure 10. SAE J192 Microphone Locations [10]

MUFFLER

The muffler presented several opportunities for improvement. The stock muffler was a large and heavy unit that created a great of deal back pressure. For the 2006 competition, this unit was swapped in favor of two inline smaller and lighter mufflers. Switching to these units reduced weight and improved airflow, but increased overall noise. For the 2007 competition the team investigated several different units. The solution was to route the exhaust into the track, closing it off with side panels. This allowed free expansion of exhaust gases into an enclosed sound isolating area without inducing power robbing backpressure. Noise results from this design were not available at time this paper was written.

Muffler Design

The goal of the muffler design was to reduce noise and improve performance by reducing backpressure with better designed mufflers. The design for the 2007 competition is an exhaust system comprised of three mufflers in series, as seen in figure 11. Muffler one is a diffusion style reflective unit where an extended tube is installed on the outlet. The extended tube causes the gases to tumble around it and the sound wave to reflect off of the back wall of the muffler disturbing the gas, causing a loss of energy and a decrease in noise. Muffler two is also a reflective style but with the extended tube coming off of a spark arrester installed in outlet. Muffler three is an absorption style unit, with a perforated straight through tube wrapped in a sound deadening fiberglass material. After initial testing, a Hemzholt resonator was designed to focus on the noise in the 250-280 Hz range. Noise results with the resonator were not available at the time this paper was written. [11]

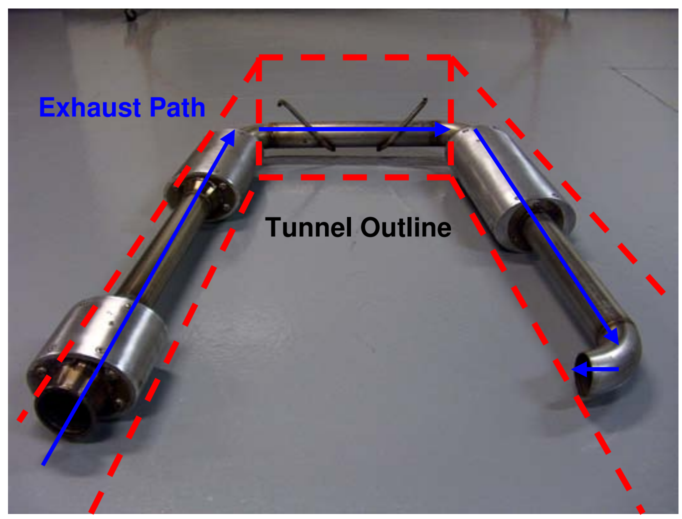

Figure 11. Preliminary Exhaust Muffler System

NOISE PLOTS

Figures 12 and 13 show the noise plot of the measured dB(A) vs. time and dB(A) vs. Hz respectively. For both plots, the red line depicts the baseline 2006 competition muffler design, the green line is the preliminary 2007 competition design, the blue line is comparison 24" glasspack muffler and the black line is the preliminary 2007 competition design with a basic auxiliary muffler (BAM).

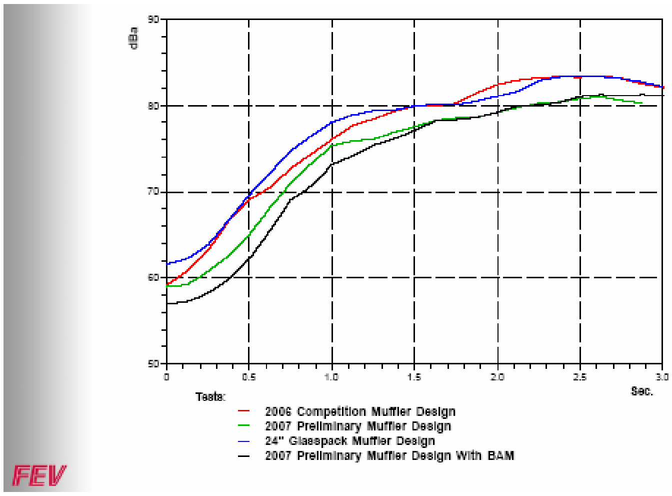

Figure 12. 2007 Noise Test Data: dB(A) vs. Time Plot of Muffler Designs

Figure 19 depicts the Hz range where noise was heard. Between 100 and 300 Hz two spikes are seen from all but the BAM configuration. These spikes are the primary and secondary combustion events. As the figure depicts the glasspack muffler was the least effective at reducing this noise region. Aside from the BAM configuration the preliminary 2007 design was most effective. Beyond 500 Hz the noise is attributable to the track and engine mechanical vibration. Extra noise seen for the BAM test in this region was attributed to mass loading of the tunnel and developing of a resonance frequency.

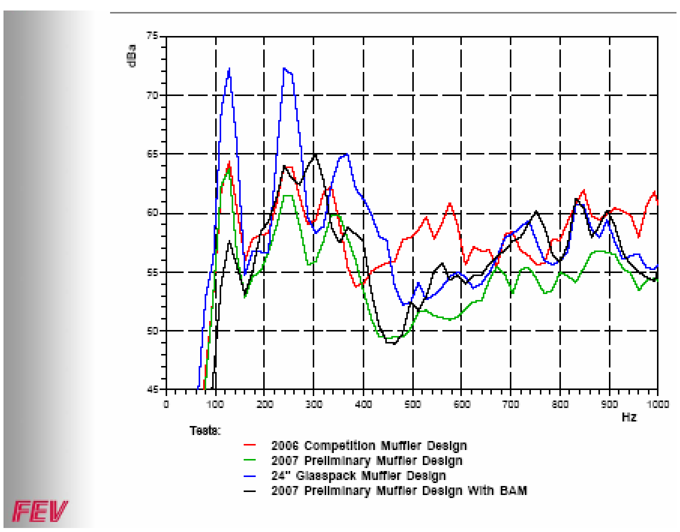

Figure 13. 2007 Noise Test Data: dB(A) vs. Hz

Figure 14 shows the data from the transmission loss cold flow test. This figure compares the 2006 competition muffler design to the preliminary 2007 design with the extended tube reflective mufflers. While this data indicates the 2007 design does not reduce transmission of noise as much as the 2006 design, it also indicates a lower overall system backpressure.

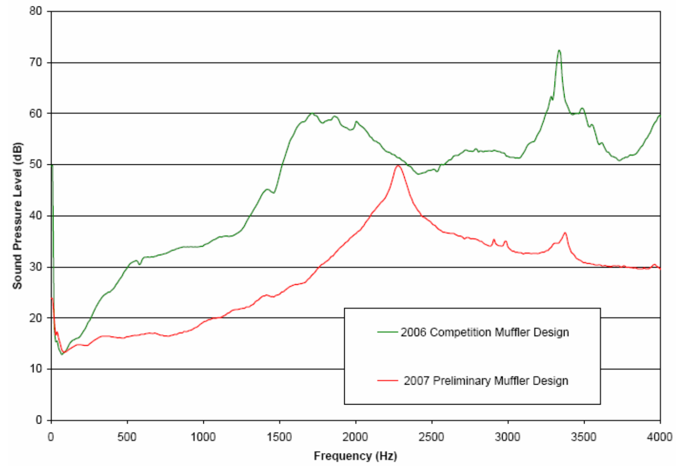

Figure 14. Transmission Loss Test

Figure 15 compares the muffler system backpressures. As the figure depicts the preliminary 2007 competition muffler design (green) had less backpressure than the baseline 2006 competition muffler (red), but more than the 24" long 5" diameter glasspack muffler (blue). This data verifies the results seen in transmission loss test. When compared to the noise plots (figures 12 and 13), the data suggests that while the preliminary mufflers produced less back pressure, they also reduced the overall noise emission, demonstrating an overall better designed exhaust system. Realistically, once final adjustments are made to the exhaust system the backpressure might exceed that of the 2006 design. However, data was not available at the time this paper was written.

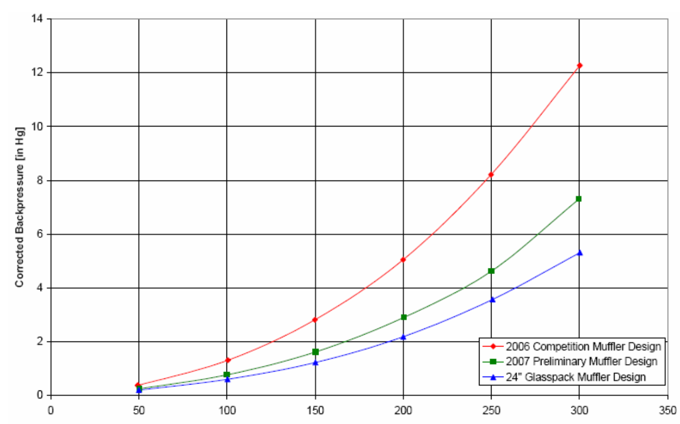

Figure 15. Cold Flow Test for Backpressure

MECHANICAL NOISE

To isolate the mechanical noise, the snowmobile was placed on a stationary warm-up stand and run at different speeds. Sound readings were taken from different points around the snowmobile. The greatest noise levels were found to be coming from the engine compartment and the track tunnel. As a countermeasure thick sound deadening paint was used on the underside of the tunnel to reduce sound wave vibrations while specially designed water and heat durable foam insulation was installed under the hood.

EMISSIONS REDUCTION

In addition to E85 conversion, the team had custom catalytic converters built to handle carbon monoxide (CO), hydrocarbon (HC) and nitrogen oxide (NOx) emissions. Figure 16 shows the “brick” catalyst.

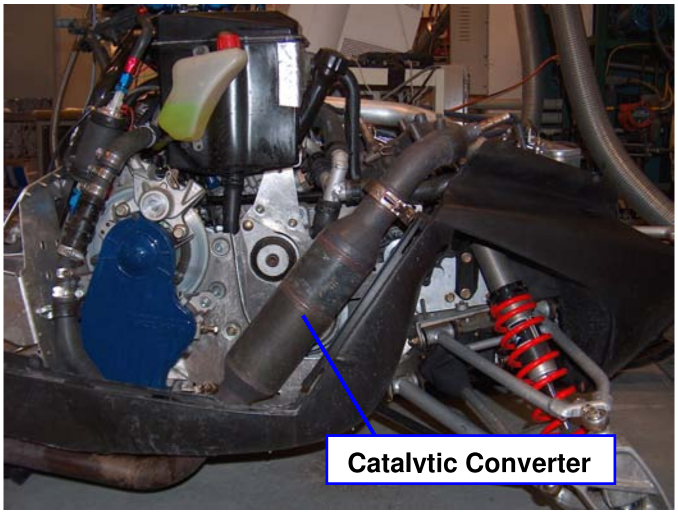

Figure 16. Side View of Engine Compartment

INITIAL TESTING

Running the snowmobile on a water brake dynamometer, the team was able to test the emissions using a Horiba Mexa 7100 Exhaust Gas Analyzer. The dynamometer test matrix followed the 5 mode test cycle detailed in the SAE Paper No. 982017. The matrix is detailed in table 3.

Table 3. Emissions Test Procedure [12]

5-Mode Emissions Test (SAE Paper No.982017)					
Mode	**1**	**2**	**3**	**4**	**5**
Speed, %	100	85	75	65	Idle
Torque, %	100	51	33	19	0
Wt. Factor, %	12	27	25	31	5

CATALYTIC CONVERTER

The catalyst “brick” is a metallic substrate with cell density of 300 cells per square inch measuring 90 mm (3.54 in.) in diameter and 75 mm (2.95 in.) long. This catalyst is mounted in the place of the stock muffler. Figure 17 shows a cross section view of the cells.

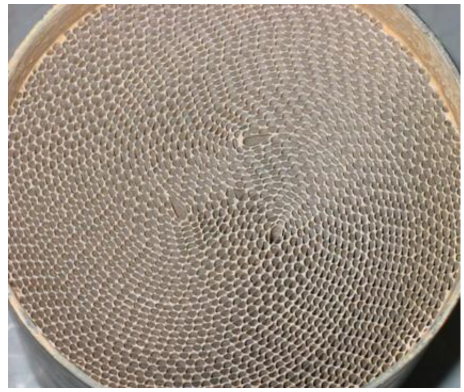

Figure 17. Catalytic Converter Cross Sectional View

Data from a snowmobile powered by a four stroke spark ignited engine modified to operate using blends up to E85 is shown in figure 18 [5].

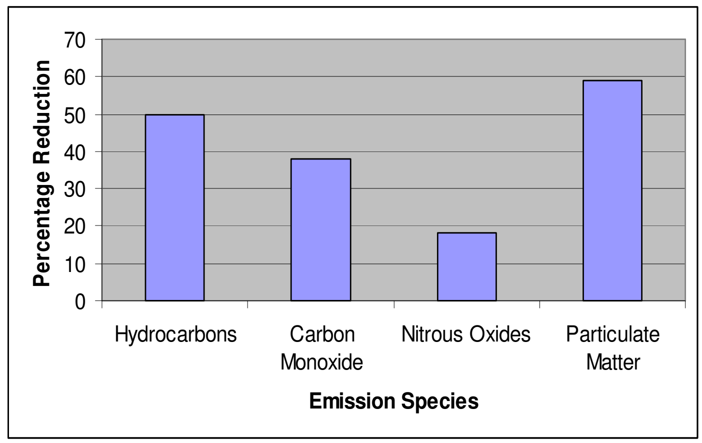

Figure 18. Reduction in emissions from a snowmobile running on E-85. [5]

As shown by the graph, snowmobiles have experienced reductions in emission species as high as 80% by switching to E-85.

The test results from an automotive engine tested by the EPA, optimized to run on E-85 are shown in figure 20.

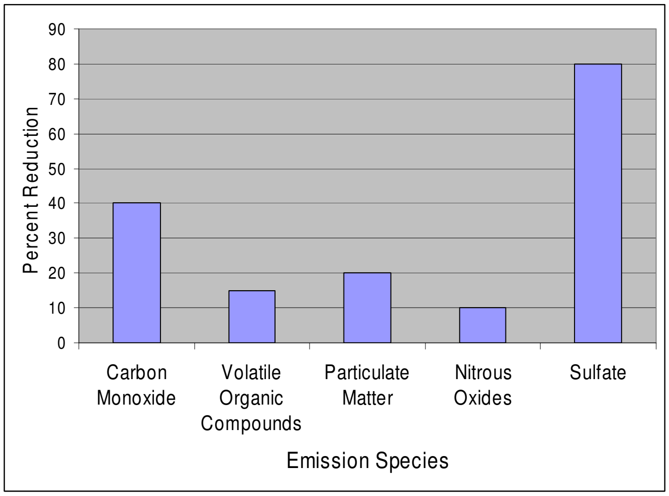

Figure 19. Reduction in emissions when using E85 compared to E10. [5]

To establish a baseline, the engine emissions were tested without the after treatment catalytic converter with the engine running on winter blend E85. Baseline emissions were recorded and are shown in figure 20. Once baseline emissions were established the catalyst was installed and the 5 mode test procedure was run once again. Further testing with 2 degrees of advancement in spark timing was also conducted. These results are shown in figure 20.

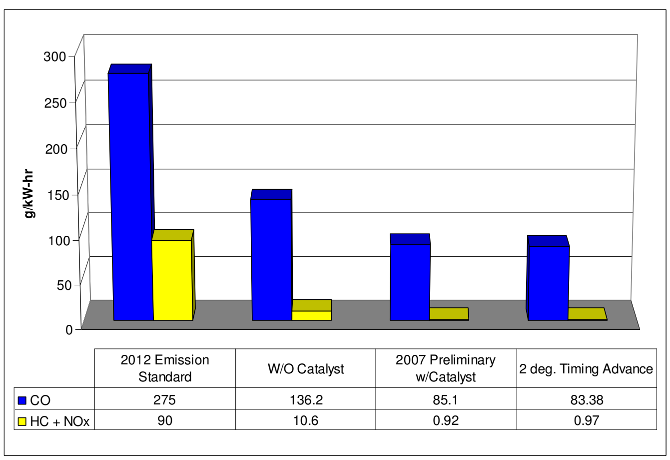

Figure 20. Emissions Testing vs. 2012 Emissions Standard

In order to receive points for competition the 2012 emission standard must be exceeded. Preliminary testing showed that baseline emissions by running E85 without a catalyst met this requirement. Further testing with the catalyst improved carbon monoxide (CO), and hydrocarbon (HC) plus nitrous oxides (NOx) emissions. By advancing spark timing by two degrees an even further reduction of CO emissions was seen with only a slight increase in HC and NOx emissions.

Further preliminary emission testing could not be completed because of a spun rod bearing. First thought was that this was contributed to the advancement in spark timing. However, as seen in figure 21 there was no detonation evidence inside the combustion chamber from either the piston or spark plug. This bearing failure can be attributed to lack of oil to the bearing. The history of the engine could not be verified because it was originally a Polaris development unit. Therefore, the team could not verify whether damage to the bearing occurred during emission testing or from previous testing. Further data from spark advancement was not available at the time this paper was published.

Figure 21. Piston and Spark Plug from Damaged Engine.

DURABILITY

To maintain integrity of the stock chassis the team focused on enhancement of the structure rather than modification. While the tunnel was shortened, the section that was removed was a riveted on piece from the factory. The front bumper, originally a plastic unit, was removed and replaced with a structural aluminum unit. By maintaining much of the stock snowmobile and adjusting certain characteristics to suit the needs of the clean snowmobile competition, the team is confident to be able to field a reliable snowmobile.

RIDER SAFETY

As with any recreational vehicle there are safety hazards to consider. Per competition rules the clutch was enclosed with a guard which was wrapped with Kevlar explosion containment belting. The battery was placed inside of a sealed aluminum box to prevent acid spills. To avoid arching across the battery terminals the aluminum was coated with a non-conductive material.

COST EFFECTIVENESS

The stock Polaris FST has a base Manufacturers Suggested Retail Price (MSRP) of $9,199. After figuring in the mass production costs of the Kettering Team's added technology, the estimated MSRP for the E85 ready Polaris FST was $10,487. However, this covers cost of items added such as the fuel pump, fuel filter, fuel injectors and the fuel pressure regulator. As the stock snowmobile was equipped with these basic items from the manufacturer, only the added component cost should be figured into the MSRP for an estimated $9,810 base price.

CONCLUSIONS

In conclusion, the design objectives of the team were met. The Kettering University Clean Snowmobile team was able to deliver a quieter, cleaner, more efficient snowmobile without compromising the cost, durability, rider safety or performance.

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