Development of the Kettering University Snowmobile for the 2008 SAE Clean Snowmobile Challenge

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ABSTRACT

Kettering University has developed a cleaner and quieter snowmobile using technologies and innovative methods which can be applied in the real world with a minimal increase in cost. Specifically, a commercially available snowmobile using a two cylinder, four-stroke engine has been modified to run on high-blend ethanol (E-85) fuel. Furthermore, a new exhaust system which features customized catalytic converters and mufflers to minimize engine noise and exhaust emissions has developed. This paper provides details of the snowmobile development and the results of these efforts on performance and emissions.

INTRODUCTION

The first snowmobile was developed in 1935 and was capable of carrying 12 people. The introduction of the snowmobile meant that emergency medical personnel could get to those in need of care even during heavy snowfall. This often meant the difference between life and death. Snowmobiling as a recreation did not gain popularity until the late-1950s. This was facilitated through the development of smaller gasoline engines. This meant that manufacturers could offer smaller and lighter one or two passenger snowmobiles. Within a decade, dozens of manufacturers began producing snowmobiles. Only four manufacturers remain today, with global industry sales of approximately 200,000 snowmobiles annually. [3]

In 1972, the snowmobile first came under scrutiny for its environmental hazards. An executive order from President Nixon stated 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 riding without harm to underlying vegetation, soil and wildlife. [5]

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

Considering 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. Additionally, cold fuel does not combust as easily leading to higher emissions. The greater amount of pollutants passed through the tailpipe into the cold, dense ambient air will not disperse as rapidly as they would in warmer conditions.[5]

In an effort to reduce emissions, the Environmental Protection Agency (EPA) mandated the following strategy for emission reduction of carbon monoxide and unburned hydrocarbons:

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

The solution for manufacturers has been a shift to four-stroke engines in place of the typical two-stroke engines. 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 stream. The four-stroke engine is also quieter, in addition to being cleaner burning.

DESIGN OBJECTIVES

The Kettering University team chose to modify a 2007 Yamaha Phazer GT for the 2008 CSC competition. The improvement efforts included:

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

SYSTEM MODIFICATIONS

The starting point for the 2008 competition is a 2007 Yamaha Phazer GT. The team focused on reducing emissions, noise, and weight while maintaining the performance, comfort, safety and durability of the sled.

ENGINE

The Yamaha Phazer GT is factory equipped with a 499cc four-stroke normally aspirated two-cylinder engine (see Table 1). Given the lightweight design of this engine and 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.

Table 1 Yamaha Phazer GT Specifications.

Displacement:	499 CC
Configuration:	Twin Cylinder
Block Material:	Aluminum
Cam system:	6 Valve-DOHC
Ignition:	Coil on plug
Valves per cylinder:	Three
Compression ratio:	12.4:1
Bore in/mm:	3.03/77
Stroke in/mm:	2.11/53.6
Aspiration:	Normal
Engine Control System:	BigStuff3 & Mitsubishi
Snowmobile Weight:	221 kg (487 lb)
Front Suspension Travel	229 mm (9 in)
Rear Suspension Travel	409 mm (13.9 in)
Track Length	3070 mm (121 in)

POWER

In stock form the Yamaha Phazer GT was rated to produce 80 hp (60 kW) at 11,000 rpm. Initial dynamometer testing revealed a power output of 70 bhp (52 kW) at 10,500 rpm. The team did not run the engine to its maximum engine speed due to concerns with the ability of the dynamometer to hold steady state at high speeds.

FUEL SELECTION

The Kettering CSC team has run E85 fuelled sleds the past few competitions; however the 2008 competition rules mandate that all internal combustion engine powered snowmobiles must run a bio-fuel; either E85 or B10 bio-diesel.

With the instability of petroleum prices in the growing global economy, the demand for alternative fuel sources to fossil fuels has significantly 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 several advantages over gasoline in terms of power output and emissions production. In comparison to pump gasoline, E85 is safer to transport since alcohol is water soluble and biodegradable. With this and the fact our starting point employed the use of a spark ignited engine in mind, the team chose to stick with the recent trend in Kettering's CSC sleds and convert the stock snowmobile engine to run on E85.

Ethanol blend fuels can be made from renewable resources such as corn or sugarcane. The alcohol derived is mixed with a hydrocarbon for denaturing, typically gasoline. In the United States, most pump gasoline contains 10% ethanol by volume. While this low percentage of ethanol content does not present compatibility issues with vehicles produced today, vehicles must be modified in order to be used with E85. Many of the standard fuel components must be upgraded to tolerate the higher concentrations of ethanol.

While E85 has a smaller lower heating value than gasoline (see Table 2), operating an engine at the proper stoichiometric value will produce an increase in power because E85 has a stoichiometric air to fuel ratio of about 10 to 1, whereas that for gasoline is 14.7 to 1. Therefore, by running E85, more fuel can be delivered to the engine. For the same amount of air as the equivalent gasoline fuelled engine, 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. [2]

FUEL SYSTEM MODIFICATIONS

Before E85 could be used in the snowmobile several of the standard fuel system components had to be upgraded because of the corrosive nature of ethanol. The conversion to run E85 also requires approximately a 26% increase in fuel flow; therefore this had to be factored into sourcing new fuel components as well.

The in-tank fuel pump was replaced with an ethanol compatible, inline external fuel pump with a larger flow rate. The stock paper fuel filter was replaced to accommodate the required increase in fuel flow. An E85 compatible adjustable fuel pressure regulator with gauge was also installed.

In the past the Kettering CSC team has sampled fuel system components and performed immersion testing in E85 in order to ensure that they were compatible with the fuel. The team recorded the initial condition of these component samples, and then placed them in a solution of E85 and sealed the containers. The samples were examined after a two week soaking period with no visual effects of deterioration observed. They were then returned to the container for a year with still no visible deterioration. Based on this past experience, the team believes that the stock fuel system parts that are retained will be durable in contact with E85.

The stock injectors were running near the upper limit of their pulse-width duty cycle, therefore increasing pulse-width was not an option. In order to enhance the fuel delivery capability to compensate for the increased fuel volume requirement, the stock injectors were replaced with larger units.

Table 2 Fuel Properties. [2]

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	$1x10^{-14}$	$1.35x10^{-9}$	$1.4x10^{-9}$

ENGINE CONTROL UNIT

The snowmobile was factory equipped by Yamaha with a Mitsubishi engine control unit (ECU), however there is no way for the team to access and reprogram it. The original plan was to use a Bosch M7.4.4 ECU; however, this was not possible due to the fact that the 499cc two cylinder Yamaha engine is not an even fire engine. The cylinders of the Yamaha fire 180° offset, then go through their exhaust and intake strokes and repeat the process, as seen in Figure 1.

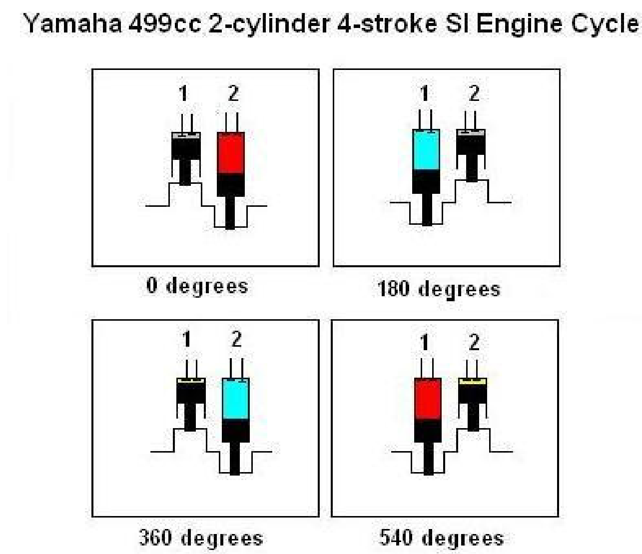

Figure 1 Yamaha Engine Cycle.

As a result of this issue, the team the team had to find an ECU that allows for uneven firing of the cylinders. The team decided on a BigStuff3 ECU with closed loop wide band oxygen sensor feedback. Closed loop engine control allows the ECU to monitor the oxygen content of the exhaust gases and adjust the air/fuel mixture accordingly. The Mitsubishi controller utilized an open loop system which can lead to overly rich air/fuel mixtures due to the fact the ECU is not constantly monitoring the air/fuel ration and actively compensating for changing conditions. The Mitsubishi ECU was retained to control spark for the engine to reduce our dependence on the new engine controller.

Through the use of the BigStuff3 calibration software, the team is able to adjust the engine map to avoid undesirable, excessively rich mixtures which increase emissions. Maintaining fuel economy based on speed and load conditions with the switch to E85 was also a goal of the new engine calibration. The new ECU also allows for tuning of the fuel delivery for each individual cylinder, which gave the team even greater capabilities in adjusting for improved emissions.

GAUGES

The Mitsubishi ECU was also retained in order to operate the factory gauge cluster. The team determined that any information that a potential rider might need to monitor was provided by it. Any other data that was necessary to monitor in calibrating the engine was done so through the calibration, emissions and dynamometer software interfaces.

COLD START CHARACTERISTICS

As shown in Table 2, the heat required for vaporization of ethanol blended fuels is much higher than that of gasoline. In cold weather starting conditions this presents a problem as ethanol will not vaporize at temperatures below 11℃.[2] Just as gasoline and diesel pump fuel is switched to a winter blend during the colder months, E85 is also adjusted to compensate for colder ambient temperatures. 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]

In addition to the use of a blend with more gasoline, the team programmed the ECU to adapt for the cold at startup using fuel enrichment. This is done by injecting a greater volume of fuel into the cylinder during a cold start in order to allow enough gasoline into the cylinder to vaporize and initiate combustion.

CHASSIS AND BODY

Chassis modifications were kept to a minimum since the Phazer was already a significantly lighter starting point than previous CSC sleds run by Kettering in the competition. A replacement side panel was fabricated (see Figure 2) from glass fiber reinforced plastic (GFRP) to clearance the Kevlar belted aluminum clutch guard and allow for the addition of sound deadening insulation. The GFRP panel also had to be fit tight enough to the components it covers to reduce risk of damage from sources such as the ski when the suspension is fully compressed or low branches hanging over into the trail.

Figure 2 Fabrication of Mold Plug for Side Panel.

In addition to the GFRP side panel, the team added neoprene rubber side skirts as seen in Figure 3 to the sides of the track tunnel in order to enclose them and contain some of the noise generated by the track.

Figure 3 Track Side Skirts.

TRACK AND SUSPENSION

The 2007 Yamaha Phazer GT came stock with a 121 inch track, which performed well enough during testing to forego modifying it with studs or replacing it with a different track.

The suspension was also left stock, as it performed satisfactorily in testing as well. The additional cost of a higher performance suspension setup was deemed unnecessary as a result.

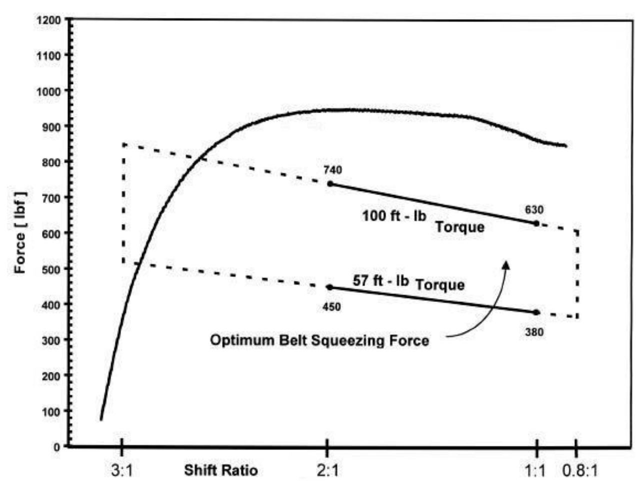

Figure 4 Belt Squeezing Force of a Typical Snowmobile. [6]

CONTINUOUSLY VARIABLE TRANSMISSION

Typical power transmission for snowmobiles has been through the use of a continuously variable transmission (CVT). A CVT works on the principle that it can adjust to an infinite number of transmission ratios with the high and low ratios dictated by the clutch range. However, the CVT has efficiency concerns. 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 4.

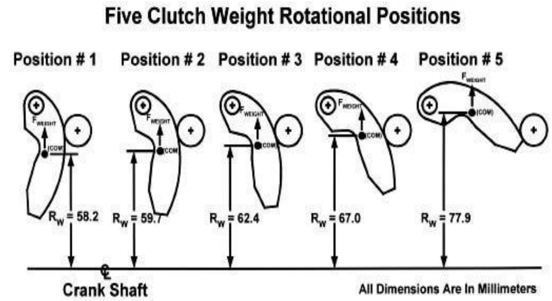

Figure 5 Clutch Weight Position. [6]

The primary clutch uses 3 weights which convert centripetal force to belt squeezing force and up shift forces as the engine output shaft rotates. Figure 5 shows several positions of a clutch weight as engine speed is increased.

At low engine speeds the weight remains in a retracted position with the center of mass 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 6. The stock Yamaha clutch operated efficiently enough for the application, therefore was left as is.

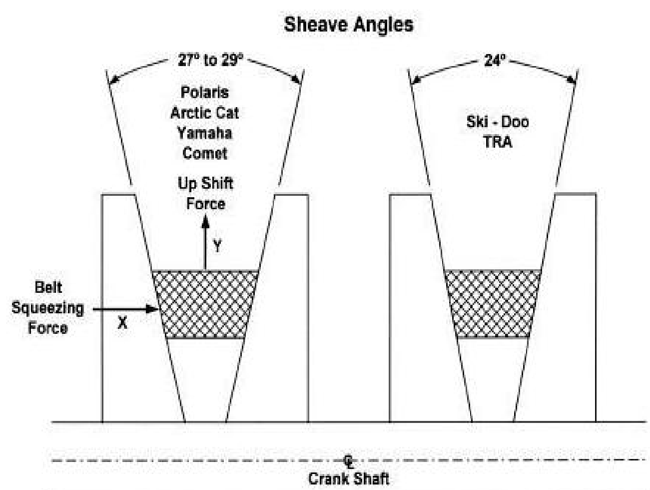

Figure 6 Forces Based on Sheave Angles. [6]

NOISE REDUCTION

Noise from snowmobiles can be attributed to a variety 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 7. 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]

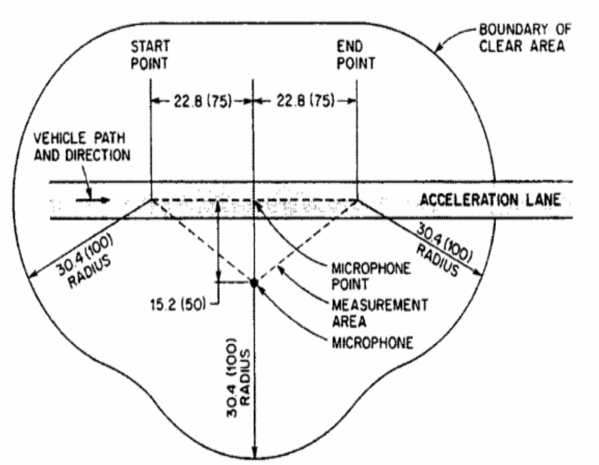

Figure 7 SAE J192 Microphone Locations. [4]

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).

MUFFLERS

The muffler setup presented several opportunities for improvement. The stock muffler did a fair job of reducing noise caused by the exhaust; however, the addition of a glass-pack muffler after the stock one helps to further reduce noise contributed by the exhaust system. The solution used on the Polaris FST which Kettering ran in the 2007 CSC competition had the exhaust outlet run into the area housing the track, which was closed off by neoprene rubber side skirts to further muffle exhaust noise by keeping it in an enclosed area. This allowed free expansion of exhaust gases post-outlet into an enclosed sound isolating area without inducing further backpressure to the system. This solution worked well, so it has been applied to the new sled on which it also contributes a reduction in detectable noise in pass-by testing. Noise results from initial testing before modifications were measured at 83 dB(A) on unpacked snow. After modifications the sound was measured at 80 dB(A) on hard packed snow.

EXHAUST ROUTING DESIGN

The goal of the muffler design was to reduce noise from exhaust picked up in pass-by testing. On the Yamaha Phazer GT the space provided by the stock exhaust routing was limited. The exhaust ports exit the back of the engine just in front of where the fuel tank is located.

The exhaust primaries in the stock configuration are separate for 21 inches before the collector routed almost straight down the middle of the sled. From the collection point there was only 18 inches before the stock muffler location. Packaging was therefore a major concern in the design with the need to add a catalytic converter in addition to the noise reducing features.

The design for the 2008 competition is an exhaust system comprised of two mufflers in series, as seen in Figure 8. Muffler one is the stock Yamaha muffler unit. The exhaust system exits the stock unit and makes approximately a 180° bend into muffler two which is placed next to the stock Yamaha unit in the tail of the snowmobile. Muffler two is a glass-pack style muffler. After the second muffler unit, the exhaust turns down and dumps into the track area which has been closed off with the side skirts. [11]

Figure 8 Exhaust System Layout.

NOISE PLOTS

The Kettering team performed preliminary pass-by noise testing to determine which systems were contributing to the total noise level. The baseline data showed a high half-order contribution. This was determined to be caused by the uneven firing of the Yamaha engine. The cylinders firing 180° offset causes this. This was an unforeseen benefit of the Yamaha engine in terms of noise emissions. The half-order contribution of the engine helps to reduce overall noise levels due to the use of an A-weighting filter. It attempts to emphasize the frequencies of sound most audible to the human ear. An even fire engine, such as the 750cc turbocharged one in the Polaris FST used in the competition last year contributes a first-order signal to noise emissions. This will contribute a greater amount of noise using A-weighting since it has a higher order frequency contribution, and therefore is not compensated for to the same degree.

A comparison of the noise emissions of each side of the sled was also done. This showed that the CVT side of the sled contributes a greater degree of sound than that of the opposite side. This was further shown by comparing a run without the side panel on the CVT side to the runs with panels as seen in Figure 9.

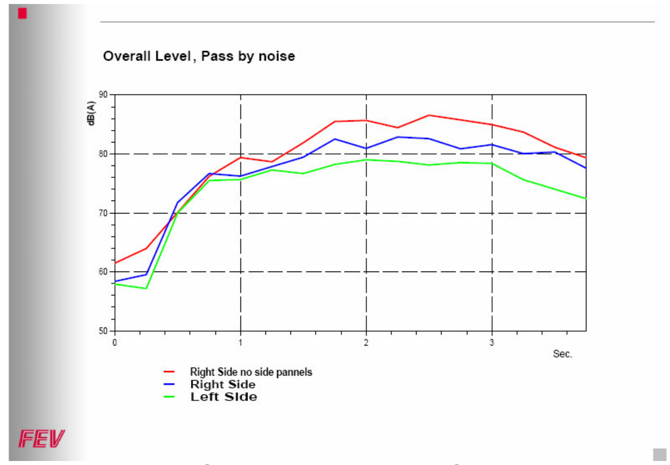

Figure 9 Side Dependent Noise Comparison

In an effort to further understand the noise contributions of the CVT, the runs with and without panels were plotted in a 3rd octave plot as seen in Figure 10. The area on the right side of the graph is the contribution of the CVT to the noise level. It comes into play as engine speed increases. The run without the panels has even more noise at these higher engine speeds. This has led to the team adding sound deadening mat to the inside of the side panels to reduce the noise emissions from this major contributing area of the snowmobile.

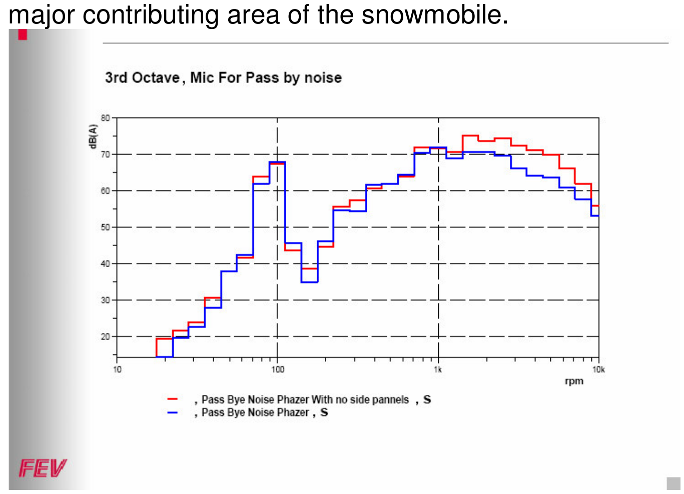

Figure 10 Phazer Panel Dependent Noise Comparison.

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 snowmobile was also tested in pass-by testing with and without the side panels on. The data was then compared to observe the noise reducing effects of the panels on engine and CVT noise. The greatest noise levels contributed by mechanical systems were found to be coming from the engine compartment and the track tunnel.

In an effort to reduce mechanical noise, specially designed water and heat resistant foam insulation was installed under the hood deadening mat was used in the engine compartment. The side panels are lined with this mat also in an effort to reduce the noise escaping through the sides of the engine compartment. The stock CVT side panel would not clearance the required clutch guard so a replacement panel was designed and fabricated that would both clear the guard and allow for the addition of sound deadening material. The clutch and CVT noise contributed a significant amount of noise, especially at partial loads. The addition of this sound deadening material has reduced this contribution to the overall noise output of the sled.

The track noise is reduced through the use of a sound deadening coating on the inside of the track tunnel, as well as the addition of the neoprene rubber track side skirts. The combination of these solutions will help to contain noise generated by the track in an enclosed area. As discussed in the section on exhaust noise, the noise reducing techniques used to reduce the contribution of the track to overall levels also help to reduce the contribution of the exhaust further. This will result in lower noise levels experienced by bystanders or in pass-by testing.

EMISSIONS REDUCTION

In addition to the conversion to E85 and altering the engine management accordingly in an effort to curb emissions, the team employed the use of a 3-way catalytic converter designed to handle carbon monoxide (CO), hydrocarbon (HC) and nitrogen oxide (NOx) emissions.

Figure 11 Catalyst Brick.

CATALYTIC CONVERTER

The catalyst "brick" is a custom unit from Umicore. It features a metallic substrate with cell density of 300 cells per square inch measuring 90 mm (3.5 in.) in diameter and 108 mm (4.25 in.) long. This catalyst is mounted just before the stock muffler. Figure 11 shows the "brick" catalyst.

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. [1]

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

Data from a snowmobile powered by a four stroke spark ignited engine modified to operate using blends up to E85 is shown in Figure 12 [5]. As shown by the graph, snowmobiles have experienced reductions in emission species as high as 80% by switching to E-85. The PM was measured using a full-scale dilution tunnel and a gravimetric analysis.

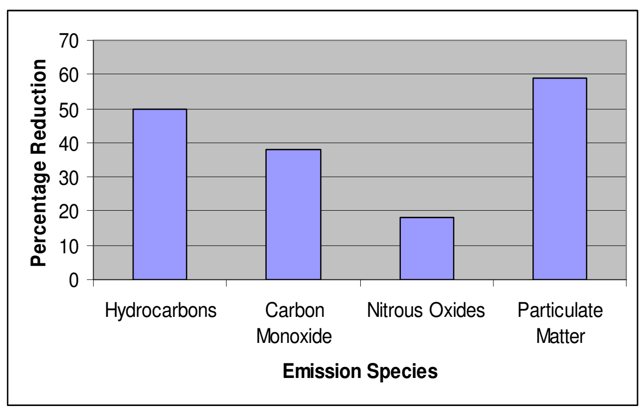

Figure 12 Reduction in Snowmobile Emissions Using E85. [2]

For comparison, the test results from an automotive engine tested by the EPA, optimized to run on E-85 are shown in Figure 13. These results also show substantial gains.

Scoring points in the emissions event requires that the 2012 emission standard be met. Preliminary testing was done to determine baseline emissions running 93 octane (RON+MON/2) without a catalyst. The team discovered that the highest CO emissions of the various modes tested were produced during Mode 1 testing. The highest CO_2 and NOx emissions were observed in Mode

2, while the highest O2 and total hydrocarbons were in Mode 5.

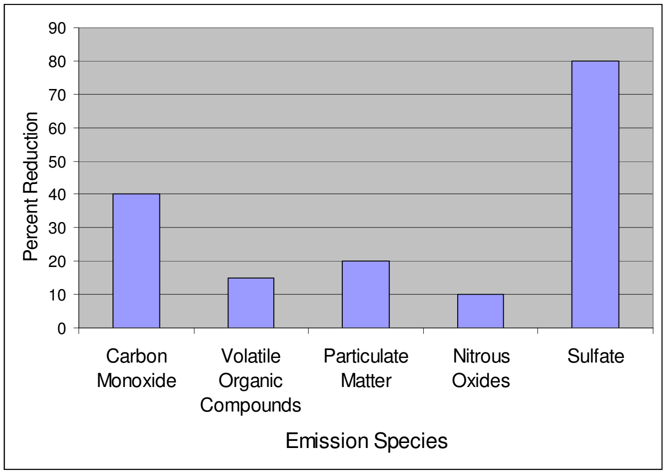

Figure 13 Reduction in Automotive Emissions Using E85 Versus E10 [2]

Emissions testing will next be done on the engine fueled by E85. This will be followed by testing with the three-way catalyst installed to analyze the effects of the addition of only a catalyst to an E85 fuelled Phazer. This will finally be followed by testing after adjusting ignition and fuel maps. The combination of all the modifications to reduce emissions should bring them well below the 2012 standard.

DURABILITY

To maintain integrity of the stock chassis the team focused on enhancement of the structure rather than modification. 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. As per competition rules, the clutch was enclosed with a guard made of aluminum wrapped with Kevlar explosion containment belting. The battery was placed inside of a sealed aluminum box to prevent acid spills. In an effort to avoid arching across the battery terminals, the aluminum was coated with a non-conductive material.

COST EFFECTIVENESS

The stock Yamaha Phazer GT has a base Manufacturers Suggested Retail Price (MSRP) of $7,599. After including the mass production costs of the Kettering Team's added technology, the estimated MSRP for the E85 ready Phazer GT was approximately $12,000. 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 $11,250 base price.

CONCLUSIONS

The members of the 2008 Kettering University Clean Snowmobile Challenge team believe that the best snowmobile has been produced utilizing the collective engineering knowledge of the team members to attain the goals set forth for the upcoming competition. The team believes it has been able to deliver a quieter, cleaner, more efficient snowmobile without compromising the cost, durability, rider safety or performance.

ACKNOWLEDGEMENTS

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Umicore
Walbro

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