2007 UMD Clean Snowmobile Challenge Design Paper

Derek Zimney, Patrick Shaver, Chris Callender, Tony Wells, Brad Aho, Derek Pederson

ABSTRACT

The University of Minnesota-Duluth (UMD) Clean Snowmobile Challenge team has engineered a clean, quiet, and efficient snowmobile to enter in the 2007 Society of Automotive Engineers' Clean Snowmobile Challenge. The main focus for this project was to convert a 2006 Polaris FST Classic to run on E85, a blend of gasoline and ethanol. We chose E85 as a fuel because of its cleaner burning nature and its ability to be produced within the United States. The 750 cc four-stroke, twin cylinder Weber motor has had a fuel system overhaul to enable it to burn the E85 efficiently. The student team also made improvements to the exhaust system to reduce exhaust and noise emissions.

INTRODUCTION

In 1935 the first snowmobile was built for large scale transportation. Carrying 12 people, this snowmobile was well suited as a taxi when snow travel often was necessary. In the late 1950's an improvement in lightweight chassis design and smaller gasoline engines enabled the snowmobile to become a favorite winter pastime [1].

Snowmobiles today are becoming much more popular and far more technically advanced. The snowmobiles of today are capable of fuel mileage from 17 to 22 mpg, as opposed to the 7 to 8 mpg of earlier models. The typical new snowmobile cost ranges from $4,000 to $12,000 [8].

A study conducted by The Milwaukee Journal Sentinel found that the typical snowmobile buyer is 42 years old, married, and has on average an annual household income of $70,000 [8].

Today it is estimated by the International Snowmobile Manufacturers Association (ISMA) that the snowmobile industry contributes upwards of $27 billion dollars to the U.S. economy each year, with $1.2 billion coming from new snowmobile sales alone. The industry also employs an estimated 95,000 full-time jobs [2].

The positive economic impact hasn't shielded the snowmobile industry from scrutiny from the environmentalists. Research conducted in Yellowstone National Park by the Southwest Research Institute (SRI), based in Texas, found that on average at 25 mph cruising speeds a snowmobile will emit 348 gallons/mile of carbon monoxide. A typical car at 25 mph will emit roughly 45 gallons/mile, nearly an 87 % reduction over the snowmobile. This means that the 720 snowmobiles that were allowed to enter the park daily had a carbon monoxide output equal to that of 5000 cars [9].

PERFORMANCE

A demographics survey conducted by SnoWest, a western snowmobiling magazine, discovered that the number one thing that their subscribers looked for in a new machine was the engine size, followed by weight and climbing ability. Price was the fifth most popular consideration in a new snowmobile purchase for 2006 [3]. This indicates that the snowmobile market is generally performance driven, with cost being a major consideration in the purchase.

The team set out to design their snowmobile with these factors under major consideration. The team decided on a performance driven approach to maintain the appeal of the snowmobile, while keeping the modification costs down. Heavy consideration was put on reducing exhaust and noise emissions without compromising the performance of the stock snowmobile.

E85 BACKGROUND

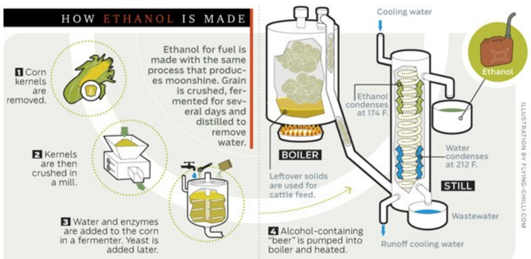

Figure 1: E85 production process

The process required to make E85 is similar to that of producing moonshine. A grain substance, in this case corn, is ground up and water-enzyme mixture is added. Then yeast is introduced to the mixture and is allowed to ferment creating ethyl alcohol. This substance is then boiled so the water evaporates and is sent through a condenser at a specific temperature and the ethanol is collected [7]. This is only a crude description of how E85 is produced. Although it is an expensive process to make ethanol there are many advantages for its use over conventional fossil fuels.

One is that E85 can be produced from corn which can be grown here in the United States, which doesn't involve mining fossil fuels in other countries, from which the majority of our fuel supply comes. If we in the United States were able to produce ethanol in higher volumes and increase the production efficiency we could ultimately reduce our dependency on foreign oil.

A couple of the other advantages of E85 involve the combustion of the fuel itself. When E85 is burned it produces much less CO and CO_2 resulting in improved air quality. Moreover, the corn absorbed CO_2 during growth, making its greenhouse gas contribution neutral.

The E85 has an energy content of about 80,000 BTU per gallon, while gasoline energy content is around 124,800 BTU per gallon. This can be misleading because E85 actually has a higher thermal efficiency than its gasoline counterpart, so the actual energy separation between the two fuels isn't as simple as comparing the energy content [7].

Starting an engine on E85 during a cold day is much more difficult because E85 is much less volatile than gasoline. This is why there is a winter blend of E85 (actually E70). The additional gasoline allows the engine to be started more easily, but the relatively large amount of ethanol in the fuel still noticeably cuts down on emissions. As an example, drag racers' with engines burning pure ethanol must start their engine on some form of gasoline before they can start burning the ethanol, even during the summer when temperatures can reach 100 ºF. Higher intake temperatures can help to vaporize the E85 more readily, thereby increasing cold starting efficiency. This is particularly well-suited to our application, as it allows us to remove the intercooler with relatively no performance loss.

Another benefit of E85 is its relatively high octane rating of 100~105 versus the 91~92 of premium gas. This allows higher compression ratios, thereby increasing the thermal efficiency [7]. This makes E85 well-suited to turbocharged engines because the turbocharger produces a boost in intake pressure, which in turn raises the effective compression ratio inside of the engine, thereby increasing thermal efficiency.

FUEL SYSTEM

The first modification that the snowmobile underwent was a fuel system upgrade to obtain compatibility with the ethyl alcohol in the E85. The high ethanol content in the E85 poses two significant problems. The first is that the ethanol has the ability to delaminate and decompose many synthetic materials including rubber, fiberglass, and many plastics. The second is the hygroscopic property of the ethanol. Contrary to popular belief, the ethanol itself is not corrosive, but rather the substances that the ethanol picks up are what give the appearance of corrosiveness. The hygroscopic quality allows the ethanol to absorb large amounts of water, which in turn can dissolve corrosive salts from anything it comes in contact with [4]. This makes quality fuel transportation a necessity to reduce fuel contamination.

Fuel Pump

The fuel system upgrade consisted of a fuel pump upgrade from the current in-tank Walbro fuel pump configuration to an Accel 75702 inline high-pressure fuel pump (as shown in figure 2 on the following page). This fuel pump has been implemented on numerous ethanol racing applications and was backed as being E85 compatible by Accel. The fuel pump is electrically driven, but the internal components have been isolated from the ethanol to reduce the risk of a fire hazard due to the high conductivity of the ethanol. The internal seals were also tolerant of ethanol in high concentrations, although Accel would not release the seal material specifications to us.

The fuel pump produces a fuel pressure of 65 psi (4.48 bar), which is just slightly higher than our target pressure of 58 psi (4.00 bar, figure 3). The stock Polaris FST had a fuel rail pressure of 44 psi (3.03 bar), so our new fuel system was providing an additional 31.8 % of fuel pressure [5]. Raising our fuel pressure increased the volume flow rate and allowed us to retain our stock fuel injectors while running the E85. The stock Bosch fuel injectors are priced at $400 per pair, so by simply increasing the fuel pressure we were able to obtain the volume flow while minimizing the implementation costs.

The new fuel pump also provided a volume flow rate of 69.7 gph (264 lph) which is more than our snowmobile requires for this application. This fuel pump supplies enough volume to fuel a 400 hp engine on E10 or a 250 hp engine on E85, and with our production engine only reaching 135 hp on E10 we were well under the maximum fuel consumption.

Figure 2: E85 Compatible Fuel Pump

Fuel Pressure Regulator

In order to raise the pressure at the fuel rail we had to replace the stock fuel pressure regulator with a new high-pressure regulator. The stock fuel pressure was regulated at 44 psi, and was replaced with a 58 psi regulator.

This pressure regulator has a reference to intake manifold pressure, so as the turbocharger spools up and starts producing boost, the fuel pressure will also be boosted to accommodate the pressurized intake air. This actually allows the fuel pressure to increase past the regulator's 58 psi rating.

Figure 3: 4.00 bar Fuel Pressure Regulator

Fuel Lines

The plastic fuel lines were a source of major concern for the team because the high levels of ethanol will erode away the plastic lines and the connectors that were used to connect the fuel lines to the fuel rail. The lines also had to be capable of running the higher fuel pressures that the fuel system was outputting.

Most of the flex fuel vehicles on the market today utilize steel fuel lines with an internal teflon coating to reduce the corrosion caused by the contaminants dissolved in the ethanol. The team considered using steel fuel line, however it was decided against after some research into chassis flex.

The possibility of continued, cycling chassis flex posed the risk of straining the steel fuel lines to the point of rupture. Chassis flex is proving to be more of a problem with today's big displacement, high horsepower machines. Extensive research has gone into testing the torsional characteristics of a chassis since a relationship between chassis flex and suspension effectiveness has been uncovered. Ski-Doo has developed the REV Pyramidal Chassis, Yamaha has the Delta Box, Polaris has an improved IQ chassis, and Arctic Cat has the new Twin Spar Chassis to help deal with these torsional problems [6]. Ride characteristics have been improved because of the improved rigidity of the next generation of chassis'.

Due to the increased concentration on chassis construction the team instead decided to implement high-pressure ethanol resistant synthetic rubber fuel lines featuring a woven fabric sheath. The continuous use rating of 85 psi was more than sufficient for our application.

Fuel Injectors

The stock fuel injectors, (figure 4), were used in conjunction with the high-pressure fuel regulator to give us our desired fuel flow. The o-rings of the stock injectors were tested with E85 to determine if they were safe to use. The o-rings were submerged for two weeks in E85 and then checked for degradation. After the submersion the o-rings had no visible signs of degradation so they were utilized in the final design.

Figure 4: Fuel Injector on Pressure Regulator on Fuel Rail

Fuel Connectors

The stock fuel connectors were a major concern because they were made of plastic and there isn't an ethanol compatible direct replacement. Testing was done in which a sample connector was submerged in E85 for two weeks and then reviewed. There were no noticeable changes in the condition of the connector, so we chose to continue using them.

Fuel Tank

The stock fuel tank is constructed out of plastic, and was tested in the same manner as the fuel connectors. A representative sample of the fuel tank was submerged in E85 for two weeks, and no decomposition was witnessed.

EMISSIONS

Exhaust Gas Emissions

Aside from the fuel use of E85, the next step to reducing emissions was to design an exhaust system capable of converting the CO, HC, and NOx into less dangerous substances such as CO_2, H_2O, N_2, and O_2. Careful consideration was given to a catalytic converter to break down the exhaust gas mixture. A major problem with E85 is that it burns much cooler than gasoline, so it takes a longer amount of time to warm up the catalytic converter and start the emission reduction process. This necessitates installing the converter as close to the engine as possible to aid in heat absorption.

After some initial emissions testing using the same exhaust setup as the 2006 Clean Snowmobile Challenge entry, the team concluded that the secondary air injection pump needed to be supplying the catalytic converter with hotter air.

The air being injected into the converter was coming from the bottom of the bellypan and was too cool to actually help the converter work more efficiently. This cooling effect was compounded by the cooler burning characteristics of the E85. These combined problems actually reduced the efficiency of the converter to the point that it actually functioned better without the air injection.

The team clearly had to come up with a new approach to improve upon the air injection system. The exhaust system would be much improved if the air injection system could inject hot air into the converter, or more heat could be transferred from the engine to the catalyst.

A problem that the team had to deal with at the 2006 competition was high underhood temperatures from the use of the turbocharger. The design strategy then changed from improving the air injection system to also removing the excessive underhood heat. The air injection system was then configured to remove some of this heat generated by the turbo and supply it to the converter to provide additional oxygen for the catalyst to break down the exhaust gases while reducing the cooling effect of the air injection system. A heat exchanger system was utilized to capture the heat produced by the turbo and move it into the converter. The forced air injection pump can be seen below.

Figure 5: Forced air injection pump

The exhaust system was arranged in the same fashion as the 2006 competition snowmobile. The team explored numerous options to mount the catalytic converter closer to the engine to achieve light-off temperature sooner but the underhood space limitations prevented the converter from being mounted any closer. The catalytic converter made use of the stock intercooler bracket for mounting to help simplify the project. The converter is mounted 68.6 cm (27 in) downstream of the exhaust outlet on the turbocharger. The current exhaust configuration can be seen in figure 6 below.

Figure 6: Exhaust system configuration with catalytic converter

An emissions test was conducted using a DYNOmite Model 5001 Exhaust Gas Analyzer. We tested three different configurations against the initial stock snowmobile. The configurations were as follows: 1) the stock exhaust system with the engine converted to run on E85, 2) a fabricated exhaust system which included a catalytic converter, 3) and the fabricated exhaust system with catalytic converter and a secondary hot air injection system. Three tests were run of each configuration at the indicated engine speed for two minutes so that the exhaust readings had stabilized. A sample was then taken and the process was repeated until three readings had been obtained. The three readings were then averaged and the data is displayed below.

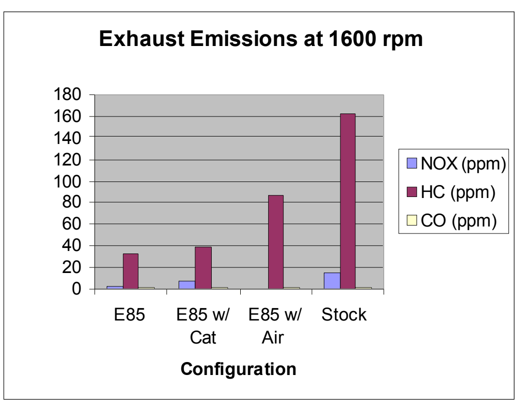

Figure 7: Exhaust emissions at 1600 rpm (engine speed during idle)

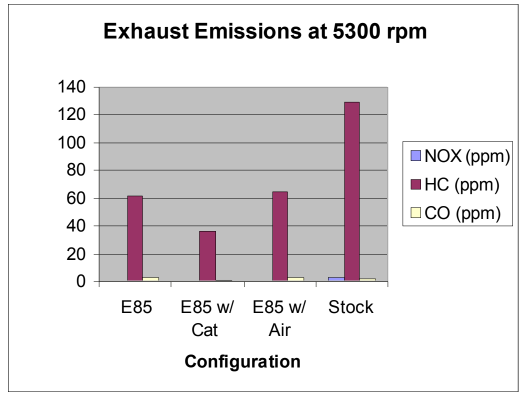

Figure 8: Exhaust emissions at 5300 rpm (engine speed during trail cruising)

It is easy to see that just the conversion to E85 alone cut the hydrocarbons emissions by 50 %. There was also a significant drop in nitrous oxide emissions. At idle the best configuration is just to use E85 without any exhaust system modifications. At 5300 rpm our best results came from using the E85 in combination with a catalytic converter to cut down hydrocarbon emissions by 72%.

1600 rpm	**NOx (ppm)**	**HC (ppm)**	**CO (ppm)**	**Total**
E85	2.47	33	1.24	36.71
E85 w/ Cat	6.3	39.3	0.65	46.25
E85 w/ Air	0.233	86.3	1.12	87.653
Stock	15.11	162	1.8	178.91

5300 rpm	**NOx (ppm)**	**HC (ppm)**	**CO (ppm)**	**Total**
E85	0.233	62	3.27	65.503
E85 w/ Cat	0.133	36.3	1.19	37.623
E85 w/ Air	0.1	65	2.58	67.68
Stock	3	129.6	1.635	134.24

Figure 9: Emissions data

Some of the more notable points in this data include a 96.7 % drop in NOx when utilizing E85 with an air injected converter at 5300 rpm. We also witnessed a 49.8 % drop in unburned hydrocarbons when using the air injected converter at 5300 rpm. The total parts per million (ppm) of emissions is quite similar for the engine running E85 and running E85 with a converter using air injection. At 5300 rpm the lowest total ppm in the exhaust came from the use of E85 and utilizing a catalytic converter without air injection.

The fabricated exhaust system also featured a wideband O_2 sensor to aid the ECU in determining the proper air/fuel ratio (AFR). The stoichiometric AFR is 14.7:1 for gasoline, while E85 requires much less air at an AFR of 9.73-9.8:1. The E85 requires roughly 34 % less air due to the lower energy content of the fuel [11].

The best emissions are achieved when the engine AFR is stoichiometric, meaning that there is just enough oxygen in the mixture to completely burn all of the fuel. The burning of the fuel converts the hydrocarbons into carbon dioxide and water, which we want to maximize by feeding the engine a stoichiometric mixture. The oxygen sensor will read the oxygen content of the exhaust gases and calculate an air/fuel ratio. The graphs below indicate rich, lean, and stoichiometric conditions with and without a catalytic converter.

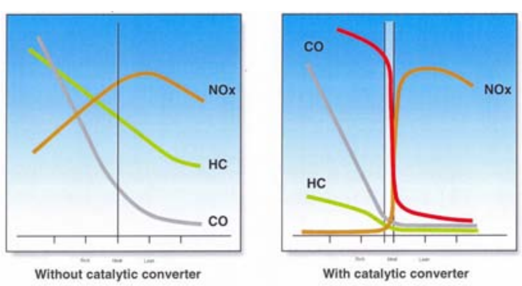

Figure 10: Emissions changes based on air/fuel ratio [12]

From the catalytic converter graph we can see that the fuel mixture must be stoichiometric or slightly lean in order to achieve the best possible emissions. This however is not a practical approach because a stoichiometric mixture tends to burn very hot and has the ability to cause severe engine damage by inducing knock. Knocking occurs shortly after maximum cylinder pressure is achieved under a high engine load. For this reason stoichiometric fuel ratios are best used during light load conditions and slightly rich fuel ratios are used when the engine is under a larger load [13].

Our engine control unit (ECU) is mapped to run slightly rich while under load to keep combustion temperatures down and maximize the longevity of the engine, while the catalytic converter is implemented to help reduce the number of unburned hydrocarbons in the exhaust gas due to this slightly rich condition.

Fuel Mileage

The team estimated fuel mileage to be roughly 11.1 mpg based on additional fuel consumption requirements due to the reduced energy per unit volume of E85. After conducting some testing, fuel mileage was estimated to be 11.8 mpg, giving the snowmobiles 9.2 gal capacity fuel tank an effective range of 108.6 miles. Testing was conducted on fresh snowfall, so the team feels that the stock fuel capacity will be sufficient to complete the endurance run.

Noise Emissions

A large portion of the noticeable noise from the snowmobile comes from the track and chassis. The tunnel will resonate at particular frequencies for a given track speed, thereby increasing the noise. The UMD team implemented a rubber skirt to help eliminate chassis and track noise by containing it within the tunnel and using the snow as an effective muffle. The rubber skirt was well-suited to eliminating high frequencies, giving the snowmobile a more pleasant sound.

Figure 11: Rubber track and chassis noise dampening skirt.

OTHER MODIFICATIONS

Lexan Hood

A lexan hood has been added to reduce the overall weight of the machine while retaining the stock appearance. The lexan is also much more flexible so in the event of a rollover the hood can collapse and pop back into shape without causing any permanent damage. Fog lights were also utilized with this hood to improve over the stock lighting by increasing the width of the light projection and reduce the overall weight. The fog lights are an ultra-white design, improving nighttime visibility.

Steering Post Support

The stock steering post support featured Polaris' Rider Select to allow for adjustable angles of the steering post, thereby allowing the handlebars to be raised or lowered. The team found that the stock steering post mount allowed some flex in the steering system, thereby creating more resistance to actually turn the skis. The team decided to modify the stock mount to accommodate a rigid mount, eliminating the Rider Select. This new steering post position encourages rider forward seating, while providing a much more rigid steering system. The new steering post support also provided a place to mount the inline electric fuel pump that we selected.

Figure 12: Modified steering post support which encourages rider forward seating.

Clutching Improvement

The stock clutching was recalibrated to allow the secondary clutch to over shift slightly at trail speeds. This has the same effect that overdrive has on an automobile, forcing the snowmobile to run at a lower engine speed at trail speeds to conserve fuel and reduce emissions.

Suspension Refinement

The stock suspension was set up to provide a large amount of ski pressure to aid in trail cornering. This resulted in a very "heavy" feeling snowmobile, which the team wanted to correct. The limiter straps on the rear suspension were loosened to allow the front track shock to carry more of the snowmobile's weight. This reduces the ski pressure and allows the sled to corner with significantly less user input.

MSRP COST ESTIMATE

2006 Polaris FST Classic

M.S.R.P	$9,199.00
Catalytic Converter	$150.00
96 Studs and Backers	$159.99
Accel Fuel Pump	$139.99
Fuel Regulator	$29.99
Air Pump	$136.00
Snow Skirt	$50.00
1'' Pipe Wrap	$50.00
Intake Modifications	$50.00
Total	**$9964.97**

CONCLUSION

The 2007 UMD Clean Snowmobile Challenge team utilized a clean burning four-stroke turbocharged engine and improved upon the already 2012 EPA compliant 2006 Polaris FST Classic. The team focused on maintaining performance while reducing exhaust and noise emissions. The first step taken towards this goal was to adapt the engine to run on E85. Test results showed that just the fuel switch to E85 greatly reduced exhaust emissions, which were further improved on with the utilization of a catalytic converter with forced air injection. Several other modifications took place to improve the overall ride quality and fuel mileage. The clutching changes allowed fuel mileage to be increased by 0.7 mpg over the initial calculations. The turbocharger's boost also raised the effective compression ratio increasing the thermal efficiency, and in turn the fuel mileage. Suspension modifications improved ride quality while a modified steering post support increased rigidity and reduced steering effort. The UMD Clean Snowmobile Challenge team has engineered a clean, quiet snowmobile that has the performance enthusiast in mind. The snowmobile minimizes its environmental impact so that snowmobile travel will be able to be enjoyed for years to come.

ACKNOWLEDGEMENTS

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The team would also like to extend a huge thank you to their advisor, Dr. Stan Burns, whose commitment of time and knowledge has allowed the team to continue to be successful.

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