Michigan Technological University's Lean Combustion Calibration Strategy for a Greener Tomorrow

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ABSTRACT

The Michigan Technological University (MTU) Clean Snowmobile Team is entering the 2015 SAE International Clean Snowmobile Challenge with an improved Yamaha Phazer 500. The snowmobile has been redesigned and improved to operate with reduced noise, reduced emissions, and with greater fuel efficiency, while also maintaining competitive performance characteristics for the trail snowmobile market. There were many aspects that the Michigan Technological Snowmobile team targeted as goals in the designing and calibration phases of the 2015 competition build. The major aspects of the vehicle that were showed improvements when compared to the initial chassis was a rolling resistance. The rolling resistance was seen to increase 58% over the stock configuration. The engine calibration strategy was designed around lean combustion. The target lambda values were increased from stock of 0.85 to 1.1 for the entire operating range of the engine with the exception of mode one which targets 0.95 lambda. The last aspect that showed improvement was the exhaust system. The stock exhaust system provided a decibel level of 97 dB and with the MTU custom designed dual muffler and added expansion chamber was seen to produce a decibel level of 86.5 dB. The competition vehicle also was calculated to have a low MSRP value of $9428.40 over the initial sled cost of 8599.00 and the added value of $829.40 was seen beneficial due to the implementations and additions that were added.

INTRODUCTION

To address concerns and the banning of snowmobiles due to environmental impact of snowmobiles in Yellowstone National Park, The Society of Automotive Engineers (SAE) developed the Clean Snowmobile Challenge (CSC) in 2000. The Clean Snowmobile was introduced in the winter of 2000 in Jackson Hole, Wyoming. The goal was to invite university students to design and produce a clean and quiet touring snowmobile to be ridden primarily on groomed snowmobile trails throughout the park. Competitors of the Clean Snowmobile Challenge used OEM designed vehicles that were implemented various types flex fuel applications and calibration strategies with the expectations of demonstrating a reduction in unburned hydrocarbons, carbon monoxide, nitrous oxide, and noise emissions while still maintaining the consumer acceptable level in performance. For teams competing in the snowmobile challenge to be deemed successful, the vehicle must demonstrate reliability, increases in efficiencies, and cost effectiveness of the improvements. In 2003, the competition was moved to the Upper Peninsula of Michigan and was hosted by the Keweenaw Research Center (KRC), just north of Michigan Technological University's campus.

The Clean Snowmobile Challenge is sponsored by SAE International as part of the collegiate design series. The snowmobiles are evaluated in several static and dynamic events, including manufacturer's suggested retail price (MSRP), technical presentations, emissions, noise, and fuel economy. For 2015, the competition remains at the KRC and runs from March 2nd to the 7th. The competition has evolved to include both internal combustion snowmobiles and zero emissions electric snowmobiles.

For the 2015 Clean Snowmobile Challenge, the Michigan Tech Clean Snowmobile refocused on the important aspects of the Clean Snowmobile Challenge. The different aspects in which the team addressed was on was being fundamentally sound, with the goal of completing every event entered. This was possible by switching from the previous year's Polaris Indy chassis with the RZR Ranger Engine to a 2014 stock Yamaha Phazer. The following paper discusses how the Michigan Tech Clean Snowmobile team has made improvements to the Yamaha Phazer chassis as well as the engine to optimize all aspects of both with the common goal of achieving the maximum efficiencies as well as preserve the stock ride and performance characteristics. The first section addresses the engine and chassis choices and which one was selected. The second section of this paper describes the implementation of the flex fuel sensor and the necessary calibration strategy used to implement the bio-isobutonal capabilities for the stock Phazer. The third section focuses on the emissions improvements from Environmental Protection Agency (EPA) results from the stock engine calibration to the new calibration for the range of 16-32% bio-isobutonal. The next section focuses on the designing and implementation of the exhaust system that was designed to reduce noise and vibration. Finally, the paper describes all the engineering changes that were implemented to enhance technologies previously mentioned in this section of this paper.

Michigan Tech's 2015 Clean Snowmobile Team is composed of 25 members from various educational disciplines, including Mechanical Engineering, Mechanical Engineering Technology, Chemical Engineering, Environmental Engineering, and Civil Engineering. The team is divided into three sub-teams: Engine, Chassis, and Business. The chassis and engine teams are focused primarily on the design, fabrication, and calibration of the snowmobile, while the business team is dedicated to public, sponsor, and inter-team relations.

INNOVATIONS FOR A GREENER TOMORROW

This section discusses the overall goals that we are going to complete with the additions and modifications as well as the descriptions of the general breakdown for the 2015 MTU Clean Snowmobile Challenge.

Table 1: Primary component breakdown of the 2015 MTU Clean Snowmobile

Component	Description
Chassis	2014 Yamaha Phazer
Engine	499 CC stock Genesis 80
Fuel System	Standalone P.E. engine management with OEM Yamaha Phazer injectors and fuel pump
Intake System	OEM throttle body with and air intake
Exhaust System	**Catalyst:** BASF 3-way catalyst canned by V-converter
	Muffler: MTU designed and fabricated dual-muffler system
Drive Train	**Primary Drive:** OEM YXRC-Yamaha
	Secondary Drive: OEM YXRC-Yamaha
Suspension	**Front Suspension:** Stock Yamaha A-Arms and shocks
	Rear Suspension: Yamaha Viper 137" equipped OEM shocks and 10" big wheel kit
Track	144"x1.0"x14" Camoplast Hacksaw

ENGINE AND CHASSIS SELECTION

Given that the Clean Snowmobile Team was starting over for the 2015 Clean Snowmobile Challenge, a decision was made on a new engine. The most important aspects that were put into this decision were engine performance, engine durability, power to weight ratio, emissions, and overall sound output. These aspects were given the highest overall ratings when determining engine choice. The overall highest qualities that would tie into the consumer demand as well as the CSC objectives are the power to weight ratio and the engine durability. The engine choices the Michigan Tech CSC Team considered are as follows:

- Four-stroke Polaris Prostar 900
- Four- stroke Skidoo 900 ACE
- Four-stroke Skidoo 600 ACE
- Four-stroke Yamaha 1049 Viper
- Four-stroke Yamaha 1049 Nytro
- Four-stroke Yamaha 499 Phazer

Each engine considered for selection are all port fuel injection engines. Selection of a four stroke type engine was the overall best choice due to the overall team's calibration strategy when compared to the competitor two stroke type engine. The MTU CSC Team developed a decision matrix in order to pick the best overall engine chassis combo that would best suit the MTU CSC's needs and goals. The overall criterion for each sled was weighted on the basis of how important each individual criterion was to the team's overall goal. This decision matrix can be reviewed in Appendix B. Based on the totals that were found once each item was scored, the clear winner was the 2014 Yamaha Phazer with the highest normalized score of 7.24. The 600 ACE had the second highest score with a normalized score of 5.15. Due to the amount of teams running the Skidoo 600 Ace at competition and the price of the 600 ACE, it was wise to choose the Yamaha Phazer engine chassis combination. The new engine and chassis metrics are listed below in Table 2.

Table 2: Yamaha Phazer Engine Metrics

Engine	Yamaha Genesis 80
Engine Type	Four-Stroke
Cooling	Liquid
Cylinders	2
Displacement	499 cc
Bore and Stroke (mm)	77 x 53.6
Ignition	Digital T.C.I with T.P.S
Exhaust	2 into 1
Fueling	PFI
Compression Ratio	12.4:1

For the 2015 competition, the MTU Clean Snowmobile Team determined the stock Yamaha Phazer 499cc Dual Overhead Cam (DOHC) four-stroke five valve engine would be the overall best motor choice due to the lean style of combustion calibration that the team was after. This engine proved to be very reliable and tolerant to the wide range of ethanol and bio-isobutanol blends tested during the research and development for the 2014-2015 competition season. Equipped with a Performance Electronics ECU, and new dual exhaust muffler system; the team was able to implement a lean combustion calibration strategy for the Phazer engine to achieve an overall better reduction in emissions during competition.

PERFORMANCE ELECTRONICS

The 2015 competition snowmobile utilizes a PE3-8400A Engine Control Unit (ECU) from Performance Electronics Ltd (PE). The compact size and light weight of the stand-alone control unit allowed for easy mounting into the Phazer chassis. Due to the ECU being manufactured by Mitsubishi for both the performance electronics ECU as well as the stock Yamaha ECU it was able to utilize the stock ECU placement and location. To adapt the PE ECU to the stock wiring, a piggy back harness was made. The piggy back harness bridged the gap between both the stock and the team standalone ECU in a way that the piggy back could be removed and the stock ECU could be plugged back in. This is useful if there were any questions or concerns about the sled and engine integrity. The PE engine control unit manipulates fuel and ignition needs for the engine, based on different operating conditions. Using the controller, modifications can be made to the fuel injection open times, ignition timing of the engine and numerous other engine parameters to optimize performance and fuel efficiency. In addition, the control unit allows for real-time tuning of the engine with on-board data logging of engine parameters and external inputs. Performance Electronics also supports wireless tuning, which allowed for the MTU Clean Snowmobile Team to operate the snowmobile at a wide range of in-service testing modes while adjusting the timing and injection parameters remotely to the desired air/fuel ratios. This feature allowed for precise transient calibration of the ramp modal five mode emissions testing. For the transients there were controls of the acceleration and deceleration to ensure that the engine was receiving the necessary fuel or cutting it on deceleration to conserve fuel. Utilizing the calibration capabilities of the ECU, the team was able to optimize the engine's designed lean combustion to calibrate to the approximate 1.1 lambda running conditions on bio-isobutonal for the Phazer engine.

CALIBRATION TECHNIQUES

The Michigan Tech CSC Team's overall calibration strategy was to first design a data acquisition system that would be able to record the OEM ECU for the starting point of the calibration. This was done by designing y-cables and bridging the gap between the ECU and the extension wires that hung from the wire rack in our dyno cell. Once these y-cables were completed, the signals that were gathered were as follows: Injector MAG, Injector PTO, Coil PTO, TPS, Cam Position, and Crank Position. These y-cables were attached to BNC connectors that would run back to a National Instruments 9234 DAQ module where the data was recorded in LabVIEW. Data recording started at 4000 RPM and was recorded up to 11250 RPM in 250 RPM increments. This data was then processed to determine the Injector open times relative to TDC as well as the duration of injection for each cylinder. Injector compensation was also determined depending on the speed and load case the engine was running at as well as other running parameters such as cold start and initial engine warmup, acceleration enrichment, and deceleration control for throttle chop cases. This data is shown in Figure 1. Linear interpolation was needed to determine the correct data points. Once these points were calculated, it was then tested to see if they match the other recorded data for the rest of the fuel and ignition tables.

To find the fuel injector open times, a zoomed-in plot that shows the opening and closing of the injectors, such as Figure 1, is referenced. The difference between time values of the data points at the boundaries of the open and closed sections show these open and closed times. Averages of these time differences were used to normalize the data. The cam sensor data is overlaid in Figure 1 to show the top dead center position in relation to injector one and injector two open times. The fuel injector open times for all of the modes except idle can be found in Table 3. The target injector duty cycle for calibration strategy was based on both engine speed and load.

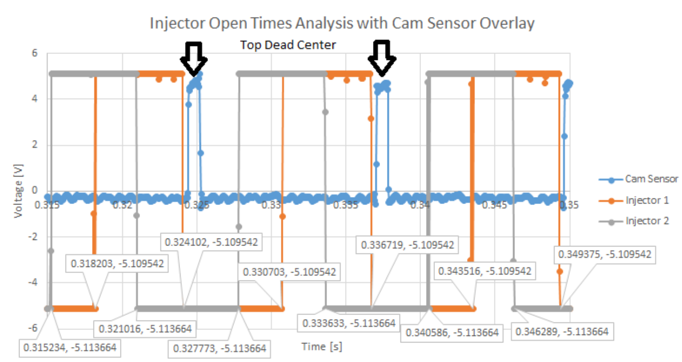

Figure 1: *Figure one shows the injector open time relative to TDC*

Table 3: *Fuel Injection Duration at Modes 1, 2, 3, and 4*

	7300 RPM	8450 RPM	9550 RPM	11250 RPM
Injector 1	0.004933 s	0.005496 s	0.005925 s	0.006118 s
Injector 2	0.004987 s	0.005304 s	0.005782 s	0.005983 s

Once the data was all processed, a 3D fuel and ignition map was populated to see the overall shape of the fuel and ignition maps for the entire operating range of the engine. Emissions were recorded for the each of the different test points and averaged to see if the results would match that of the data for the EPA testing that was done for this engine family. All of the data was recorded on our engine dyno shown below in Figure 2 and recorded with the Land and Sea Dynomite software.

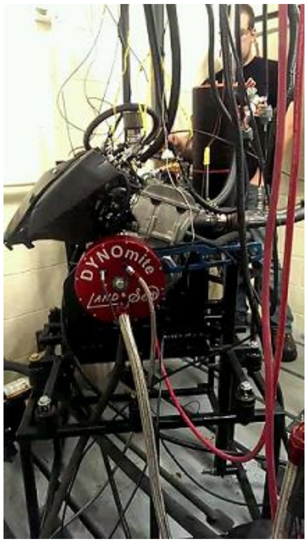

Figure 2: *Figure 2 shows the MTU CSC team's engine dyno and configuration for engine calibration.*

From this data the MTU CSC Team was able to develop the total open time for the stock injector duty cycle and the degrees of advance and retard timing for the stock ignition tables with respect to the maximum break torque curve. These were then plotted in a 3D graphical representation and can be seen in figures 3 and 4 below. The 3D plotted tables were used to visually see the physical representation of both the fuel and ignition tables. These tables were used to trim out areas as well as add to areas that seemed that they did not match the contours of the rest of the tables. The modifications that we made were used to smooth out the contours to eliminate any large dips or spikes.

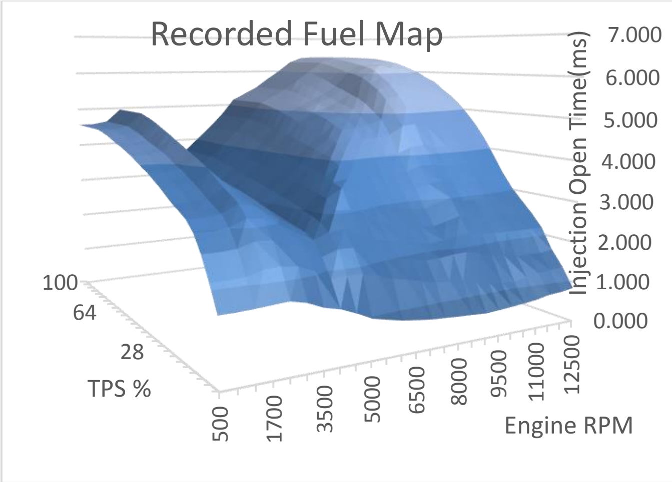

Figure 3: *Figure 3 shows the 3D plots of the recorded stock fuel tables.*

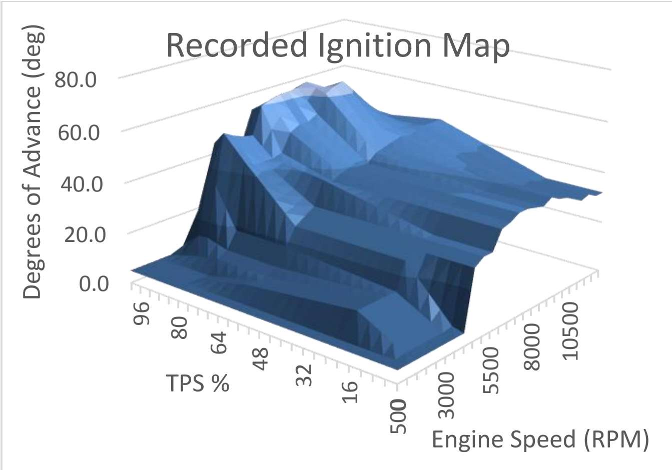

Figure 4: *Figure 4 shows the 3D plots of the recorded stock ignition tables.*

In order to develop the specific MTU CSC specific engine calibration based on the baseline measured maps of fuel and ignition from the factory ECU configuration were used as the baseline starting point. Since there was no way for the team to know what Yamaha used for fuel and spark compensation values, the data collected was considered for base calibration only. The team later calibrated the cold start, acceleration, battery offset, and knock offset values through vigorous testing and dynamometer data analysis.

Verification of the tables proved that the system worked and the data was accurate to develop the base calibration table for lambda 1.1. Through research and talking to Arctic Cat and Yamaha calibration engineers it was determined that the design of the Phazer Engine was capable of running with a lambda value of 1.2 before the engine would be close to failure zones. The engine failure zones are the areas of the fuel and ignition table where engine would start to knock because of the increase of combustion temperatures as a result of lean combustion. The two issues stated above would cause the spark plug to start the combustion process where pre-ignition occurs. The effect of this pre-ignition causes engine knock as well as exhaust gas temperatures reach over the determined limit of 800 degrees Celsius, the coolant temperature would be seen over the limit of 85 degrees Celsius, and the oil temperature reaching temperature limits of 200 degrees Celsius. If the lean combustion limit is reached it will cause the engine to misfire due to not enough fuel molecules between spark plug electrode causing the pre-ignition. Once this phenomenon takes place within the engine it will cause emission failure due to raw fuel exiting though the exhaust. Once this happens it will cause the catalyst substrate ignite the unburnt fuel resulting in overheating and holes to be burnt inside of the catalyst.

Once verification of the tables were at a repeatable level the engine was then tuned to the desired lambda value of 1.1-0.95 on a 91 octane pump gas. This was for verification that all engine temperatures would be considered in the safe zone for a lean combustion state. Once this was verified calibration for the same lambda values began for bio-isobutanol. In order for this to be completed there was increase of injector open times of approximately 17% due to the oxygen content that was contained in the competition fuel. The MTU CSC Team started at a value of 32% isobutanol because this would be the most fuel and ignition that would be added to the entire combustion cycle. Once this was determined the base fuel table was refined in a closed loop type calibration to accurately determine the requirements that were needed to produce the range of lambda values as well as the MBT values that the team strived for. When the initial calibration was completed the new tables for ignition and fuel were created in the same 3D style fashion that the base tables were plotted.

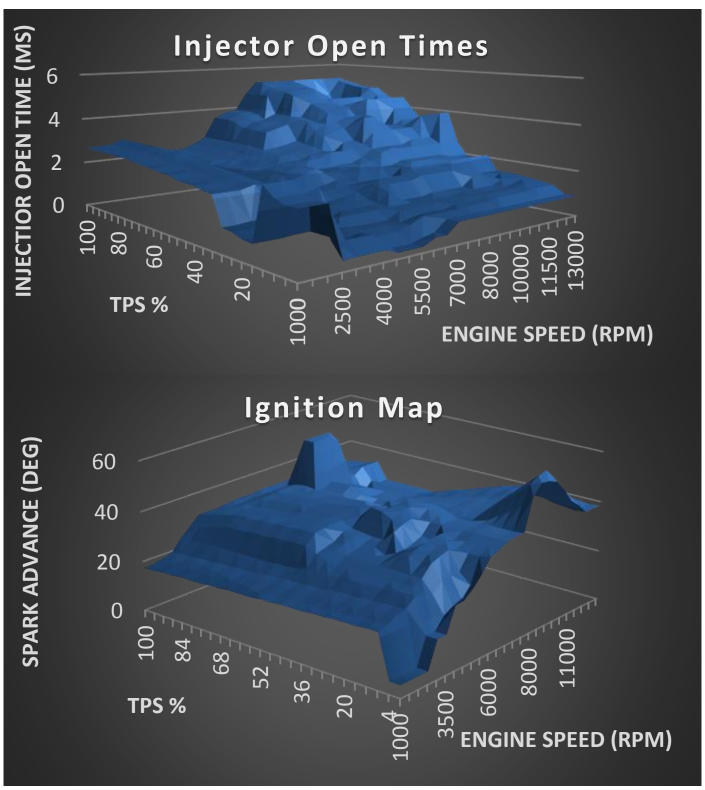

Figure 5 and 6: *The plots 5 and 6 show the isobutanol calibration tables for ignition and fuel.*

The MTU CSC Team divided the base fuel and ignition tables into zones as a means for applying criteria to different engine operating conditions [3]. **Zone 1** correlated to the idle region of the engines base tables. The commanded fuel was determined while targeting lambda of 1.1. This was created for both emissions output and fuel consumption. Great care was taken to ensure proper engine operation within this zone. Due to a lack of idle control, the idle speed was maintained by the force balance between the friction of the engine and the torque output created by combustion.

Zone 2 contains the tip-in portion of engine operation. The tip-in portion, in this case, was the event when the primary clutch engaged the drive belt. The delivered fuel was still a function of the target lambda value of 1.10. The ignition advance was set to maximum brake torque (MBT) timing to account for the clutch engagement. **Zone 3** can be described as the cruise region of the base tables. This region contains the speed-load points that the competition vehicle would experience during the Endurance Run. In contrast to an automobile, snowmobiles experience greater engine loads during cruising due to the added drag forces created by the skis and rotating track. MBT timing was used to extract the maximum amount of energy from each combustion event. This allowed for an increase in mechanical efficiency during this relatively light-load engine operation. For **Zone 3** the target lambda zone ranged from 1.1-1.0. At the low end, the desired lambda value was set to 1.1 to maximize fuel efficiency as well as a target to reduce emissions. As RPM increased the lambda value was set to lambda 1.0 to ensure engine stability and engine safety to compete in all events of the competition as well as create a good customer experience.

Zone 4 contains the area of the tables that are related to a slight acceleration event. The throttle blade in this case would not be completely open, but moderately open. The lambda value of 1.1-1.0 was still targeted due to **Zone 4** not being a wide open throttle (WOT) condition. MBT timing was still utilized to extract as much energy from the air-fuel mixture as possible. **Zone 5** is the region of high engine speeds and relatively low engine loads. The engine does not spend much time in this region, but will pass through **Zone 5** after a throttle-chop. Delivered fuel still pursued the lambda value of 1.00 and ignition values the team set high enough, in order to protect exhaust components. Ignition advance values of 35 degrees Before Top Dead Center (BTDC) and 50 degrees BTDC were commonly used on **Zone 5** [3]. These ignition advance values released the heat of combustion into the cylinder walls instead of the exhaust valves and catalyst.

Zone 6 was treated as the WOT portion of the base tables. The intent when operating an engine within **Zone 6** is maximum power production. Some fueling enrichment was used to better guarantee the reaction of the oxygen molecules within the intake charge resulting in a more complete burn. The target lambda value for **Zone 6** is 0.95 lambda, to keep the engine operating at safe temperature values for the duration of mode one testing. The ignition advance values were kept a significant distance away from the knock limit as well as the other defined aspects in aforementioned section of this paper. This was done by using cooler burning spark plugs as well as retarding the ignition map so that there was no pre-ignition that would cause engine knock that would be both detrimental to the engine as well as the emissions being measured. **Zone 7** contains low manifold pressures typically associated with engine braking. The continuously-variable transmission (CVT) on a snowmobile does not let the engine experience extreme engine braking conditions. This provides for a rather small region that the engine passes through very briefly. The light-load allows for a target lambda value of 1.1-1.0 to be pursued as well as moderate ignition advance values to ensure complete combustion. The ignition advance values in this zone are very similar of those occurring in **Zone 3**.

Power and Torque Curves

The stock power curve that this engine makes a rated 80 horsepower at 11250 RPM and a rated torque value of 55.91 foot pounds at 9250 RPM. The observed power and torque that was seen when the changes to the exhaust as well as the calibration for a lean combustion of lambda ranges of 1.1-0.95 the power numbers that were recorded were 72 horsepower at 11250 RPM and approximately 46 foot pounds of torque at 9250 RPM when the correction factors were applied to the power sweeps that were made on our dyno setup. The corrected power have a correction factor according to the dyno software which applied the SAE standard power and torque correction filters J607. The figure shown below shows the data taken for the power and torque curves that were ran on the MTU dynamometer.

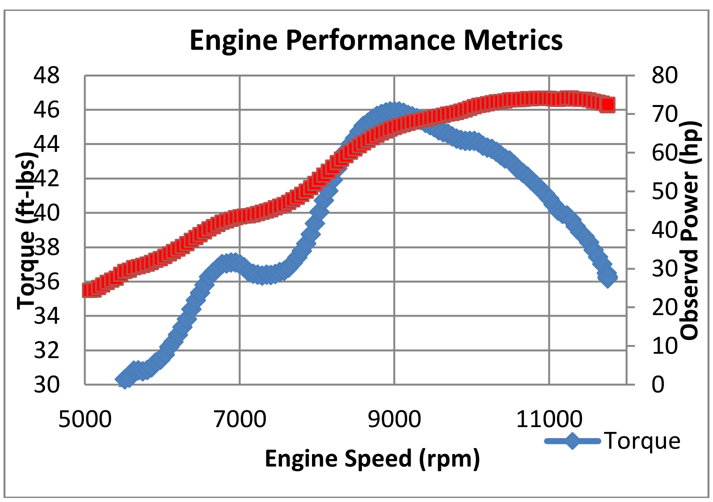

Figure 7: *Figure 7 shows the power sweep that was recorded on during calibration period of the Phazer engine*

The increase of the torque that is seen in the power sweep is the cause of effectively tuning the engine to its optimal max brake torque for the ignition table throughout the entire map until the engine ignition timing was retarded to maintain engine safety at high speed and high load. Due to the retard of ignition timing the power increase is in direct relation to making the max power numbers shown in the Figure 7 above.

FLEX-FUEL IMPLEMENTATION

As per the 2015 Clean Snowmobile Challenge rules, each competition vehicle must have the capacity to operate on corn-based bio-isobutanol fuel. The flex fuel range for the 2015 competition is 16% to 32% isobutanol content. The Michigan Technological University Clean Snowmobile Team performed calculations to determine the stoichiometric air-fuel ratio (AFR) of each isobutanol blended fuel.

To do this the team used the latent heating value (LHV)$\left(\frac{MJ}{kg}\right)$, stoichiometric values, and fuel densities $\left(\frac{kg}{m^3}\right)$. The values obtained allowed the team to calculate the mass of oxygen and the measured isobutanol content for this year's competition and equate them to the equivalent percentage of ethanol on an oxygen mass basis. The team also formed calculations that would allow the team to compute what the stoichiometric values were for different percentages of isobutanol. The calculations for the isobutanol, gasoline, and isobutanol blended fuels can be reviewed in Appendix A.

By using a Flex Fuel sensor in the fuel system, the isobutanol content in the fuel can be measured, which will range from 16% to 32%. Installed between the fuel tank and the fuel pressure regulator, the sensor monitors the amount of oxygen in the fuel real time of the fuel supply. This information is then sent to the ECU in the form of a voltage that is linearly interoperated from zero to five volts. The linear voltage increase is dependent on the oxygen content measured in the fuel. As the oxygen content of the fuel increases the voltage output from the flex fuel sensor is also increased. This signal is then sent to the ECU with a calibration offset which commands fuel injector pulse-width to include a positive or negative adder that accounts for the required increase or decrease in fueling due to the measured alcohol content which is determined by the amount of oxygen mass measured by the sensor.

The high cost associated with isobutanol fuel pushed the team to use ethanol blended equivalent during engine calibration development. It was determined that a 16% isobutanol blend corresponded to a 10% ethanol blend base and a 32% isobutanol blend was equivalent to a 21% ethanol blend, both of these calculated values are based on the mass of oxygen in both E10 and E21. The base fuel table was created for engine operation on gasoline with an octane rating of 91. The alcohol content for competition fuel was accounted for through the means of an alcohol content analyzer. This was then used in a user defined trim table to show that allows for change in the oxygen content in the fuel. Due to relatively small range of fuel that is going to be used a trim table was used to add or subtract fuel and was found to be only a very small percentage to compensate for the range of fuel.

EXHAUST

For the 2015 Clean Snowmobile Challenge the MTU CSC Team will designing and implementing a dual Walker Quiet Flow SS mufflers coupled with a MTU designed silencer chamber and isobutanol specific substrate for the engine Catalyst. The overall goal for the exhaust system for the competition snowmobile is to reduce the noise that is emitted from the stock exhaust system. The MTU CSC Team verified the changes that are discussed below will reduce the noise emissions when compared to stock the noise level of the Phazer exhaust.

Catalyst

For the 2015 MTU Clean Snowmobile exhaust system, a BASF three way catalyst canned by a V-Converter was used. This catalyst will improve the oxidation and conversion of hydrocarbons (HC), carbon monoxide (CO) and nitrous oxide (NO_x). Made up of the precious metals: Platinum, Palladium and Rhodium, this catalyst will increase conversions of harmful emissions and optimize the use of the precious metals. To further reduce emissions, the team focused on selecting a substrate for the catalyst. For the following reasons, a metallic substrate was chosen over ceramic. Metallic substrates have a thin metal foil and this reduces the pressure drop across the catalyst. A metallic substrate also has a lower heat capacity, which will allow it to reach operating temperature faster after a cold start. Another advantage is that the thermal conductivity is higher, meaning that high temperatures will be maintained throughout the substrate, preventing hot spots. The substrate will also be less likely to suffer from damage that could be produced from vibrations (3). Before selection, research was completed to find a substrate that was able to withstand high temperatures and absorb emissions such as carbon monoxide, hydrocarbons and nitrous oxides. The substrate also had to be compatible with the oxygenated fuel, bio-isobutanol. The bio-isobutanol blended fuel contained 16-32% isobutanol content. The substrate that met this criterion was FeCrAl alloy. FeCrAl alloys are designed to operate at high temperatures such as 1400° C but can be operated at lower temperatures for the use in the catalyst (1). Having this substrate in the catalyst, the simple alcohols with be converted into olefins, in this case butanol will be converted into butene and CO, HC and NOx emissions will be absorbed (2). Butene is combustion reaction of the butanol causing long chain hydrocarbons absorbed by the catalyst. Shown in figure 8 is the MTU CSC's metallic catalyst that will be utilized for the 2015 competition season.

Figure 8: *Three way catalyst that will be used in the MTU exhaust that will reduce the levels of unburned hydrocarbons, NOx CO, and* CO_2

Dual Muffler System

The dual muffler system that was chosen to improve the overall noise from the Yamaha Phazer exhaust were dual Walker Quiet Flow SS mufflers. The muffler was chosen due to the triple baffle design that cancels out both high and low flow firing frequencies. The interior of the exhaust is shown below in figure 9, the design is a triple chambered with a triple bypass that forces the exhaust to disperse throughout the entire volume of both mufflers.

Figure 9: *Figure 9 shows a cut away picture of the Walker Quite Flow SS muffler.*

Overall muffler volume is critical to reduce the overall noise output from an engine. When the two mufflers are combined it gives the overall volume of 43.4 cubic inches. When these are paired with the additional pieces of our exhaust system the amount of noise reduction was significant when compared to stock exhaust. The stock data that was taken from the SAE J192 sound test an average value of 97 dB was recorded.

When the design of the exhaust was implemented to our dyno without the catalyst or the exhaust silencer and produced a decibel sound level was found to be 86.5 dB. This is reduction in noise is significant but due the fact it was not performed as the standard J192 test procedure the data the actual level of measured sound is still subject to change.

Shown below in Figure 10 is the flow analysis that was estimated for the flow characteristics the competed would undergo with the assembled y-pipes, silencer, and catalyst.

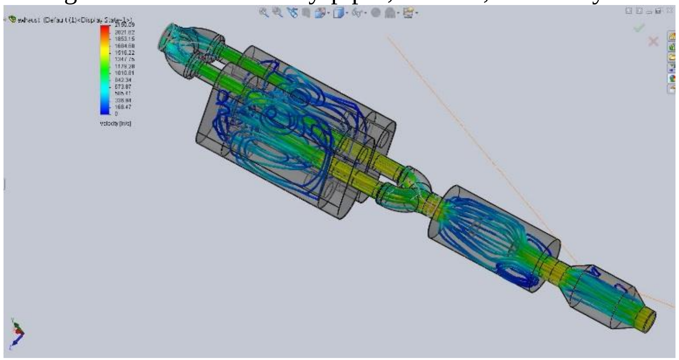

Figure 10: *Figure10 shows the flow analysis for the competition exhaust.*

The flow analysis that is shown above was constructed at WOT to show the maximum velocities the exhaust that the engine would operate at. The reason for the choosing this velocity is due to the aspect of the J192 test that starts at a cruising speed and is throttled to wide open throttle. During this test the range of RPM that the vehicle would traverse has the ability to expose both high and low frequencies that are not in resonance and would cause a large change in the sound waves. The results from the flow test the exhaust silencer as well as both dual mufflers shows the aspects of the exhaust flow and how each section dampens out the frequencies by keeping the exhaust gases in the expansion chambers for a longer period of time.

CHASSIS

For the 2015 Clean Snowmobile Competition the MTU Clean Snow Team elected to fit the 2014 Yamaha Phazer with a 2014 Yamaha Viper 137" viper skid. This change was made in order to have the capability of equipping the chassis with a big wheel kit. This would allow for an increased wrap angle that would reduce the overall rolling resistance of the snowmobile track and skid. Initially, the team determined that there was not going to be enough wrap angle to gain the overall efficiencies we were looking for. In order to keep the desired wrap angle we custom machined billet idler wheels that have a seven and a half in diameter, which increased the wrap angle and reduced the rolling resistance at a greater magnitude than expected.

Driveline Improvements

To improve the fuel mileage of our IC competition sled, there were several modifications made to the drive train in order to minimize energy loss in the system. These modifications include the implementation of larger drive cogs, larger rear and top idler wheels, and gear change in the chain case to maintain stock gear ratio. The stock drive train on a 2014 Yamaha Phazer includes a stock gear ratio of a 19 tooth top gear and a 42 tooth bottom gear, 7 tooth 2.52" pitch drivers with an outer diameter of 5.62" and 6.25" diameter rear idler wheels. The stock dimensions of the drivers and rear idler wheels results in a relatively small track wrap angle which causes the track to bend more during rotation around these areas; this bending results in efficiency losses. To increase the wrap angle of the track around the drive cogs and rear idler wheels it was decided to run a 10 tooth, 8.021" driver and a 10", "big wheel" rear idler kit, this diameter was determined by several limiting factors such as front tunnel cooler and track clearance, as well as implementing 7.5" upper idler wheels to ensure the rear suspension geometry remained functional and held the desired track wrap angle. Stock drive ratio integrity was maintained by adjusting the chain case gear ratio back to the OEM equipped gear ratio which was achieved by going to a seventeen tooth top sprocket and forty-six tooth bottom sprocket to compensate for the increased driver size.

Before installing the new drivers and idler wheels, base line testing was done to record the rolling resistance for the stock drive train. The control data collection, asphalt skis were used to pull the snowmobile across an asphalt parking lot. However, during the final data collection the snow skis were on the snowmobile and the snowmobile test was done on snow. The test done on asphalt was normalized by using asphalt skis that use wheels to replicate the resistance of the regular skis on snow. Since the track is rolling, the kinetic friction between the track and the components of the snowmobile are less than the static friction between the track and ground surface in both tests. Since the kinetic friction will cause resistance during test pulls, the difference in frictional coefficients of the two surfaces is negligible. After multiple tests were completed and recorded in table 4, it was found that the rolling resistance for the stock system was on average 53.12 lbs. with a 205 lbs. rider and 84.28 lbs. of resistance with two riders, totaling 425 lbs., on the snowmobile. After the modifications to the drive train listed in the previous section were made, multiple rolling resistance tests were completed again and recorded in Table 5. For a 220 lb. rider weight the average rolling resistance recorded was 22.84 lbs. With two riders on the snowmobile for a total weight of 430 lbs. an average rolling resistance of 34.5 lbs. was recorded. Based on the recorded data, an average of 58% reduction in rolling resistance was achieved.

Table 4: *Shows the stock rolling resistance with the stock Phazer skid.*

Stock Data		
Test	1 Rider= 205 lbs	2 Riders= 425lbs
1	55.2	86.6
2	51.7	77
3	56.3	80.1
4	50.9	90.6
5	51.6	89.9
6	51.3	84.3
7	50.1	79.7

8	57.2	81.7
9	52.4	79.5
10	54.5	93.4
avg:	53.12	84.28

Table 5: *Shows the rolling resistance data with the current modifications made to the Yamaha Phazer chassis*

Final Data		
Test	1 Rider= 205 lbs	2 Riders= 425lbs
1	23	35
2	24	28.5
3	22	38
4	23	36.6
5	22.2	34.4
avg:	22.84	34.5

SKID SELECTION

When looking at a stock 2014 Phazer XTX, the clean snow team identified the skid and track combination as a point that could be significantly improved. The team decided to run a 137” Viper skid rather than the stock 144” skid. The Viper skid has a larger length between the front and rear mounting points than the Phazer skid. Fabricating mounting brackets was required for mounting the Viper skid in the Phazer chassis. Running the Viper skid will yield roughly a 10 lb. weight reduction when compared with the stock Phazer skid. The Viper skid will also allow for bigger drivers and a big wheel kit to be implemented while using a 144” track (as these are used for other designs to increase driveline efficiency). The Viper skid rails also have a smaller approach angle, meaning that the tips of the rails don’t go as far into the tunnel providing more clearance for larger drivers.

In order to complete the testing, an initial force had to be determined to run the FEA simulator through SolidWorks. This force was determined through a worst case scenario of a direct vertical impact off of a 4 ft. drop. When solving Equation 1, the snowmobile was depicted as acting as a rigid object generating all forces directly to the area where the force would be placed on the brackets. This was done disregarding all damping that would take place from the suspension which would significantly reduce the amount of force generated to the brackets. The dynamic force (E) was determined with the force due to gravity (F_W), i.e. weight, and the height fallen from (h). The weight used for this equation was a combination of a 260 lb. rider and a wet snowmobile weight of 560 lbs. to produce a total weight of 820 lbs. falling from a height of 4 ft.

$$E = F_w * h \tag{1}$$

The steel used for the brackets was chosen to be AISI 4130 annealed at 865℃; this material has a yield strength of $4.6\ \boldsymbol{x}\ \mathbf{10^8}\ \frac{\boldsymbol{N}}{\boldsymbol{m^2}}$and a tensile strength of 5.6 $\boldsymbol{x}\ \mathbf{10^8}\ \frac{\boldsymbol{N}}{\boldsymbol{m^2}}$. This material’s properties are desirable as they will withstand the maximum forces that could take place on this machine without the possibility of failure due to the high strength. The design used to test the resulting force of 3280 lbf. from Equation 1 can be seen in Figure 10 where it is experiencing the applied load and displaying the stresses experience throughout the part. The angle of the placement of this square is based upon the angle at which the force will most likely be generated to the bracket when in operation; the size of this square is the same size as that of the circle that should be in its place to allow for as accurate of data as possible.) The maximum stress experienced by each bracket caused by the applied load shows to be $\mathbf{3.90168}\ \boldsymbol{x}\ \mathbf{10^8}\ \frac{\boldsymbol{N}}{\boldsymbol{m^2}}$; this maximum stress takes place where the force is being applied. Otherwise, as seen in Figure 10 the brackets show to have low stress concentrations throughout the final design indicating that the bracket will sustain strength and integrity under substantial impact forces.

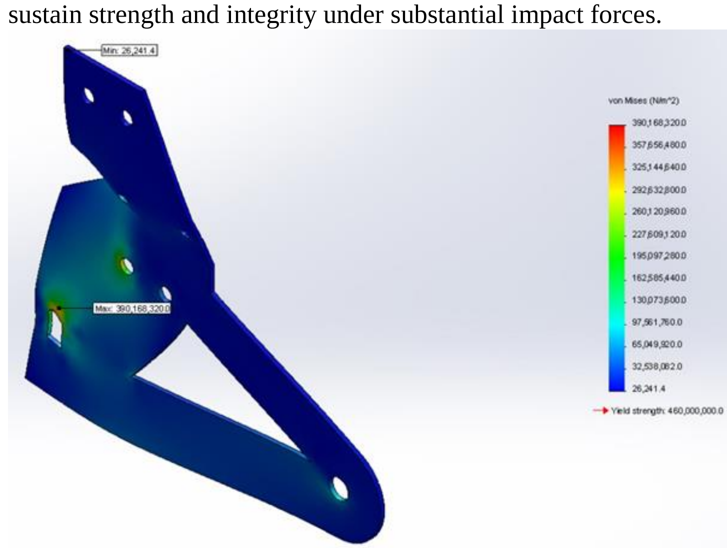

Figure 10: *FEA Von Mises Stress Analysis (minimum stress-blue, maximum stress-red).*

When completing the analysis, the maximum deflection was also determined for the brackets. This was determined to be a small value which indicates that the brackets will be able to withstand the forces received without resulting in any noticeable deflection when the snowmobile is in operation. The initial weight was discussed earlier to be 3.92 lbs. and throughout the FEA testing, this weight was reduced to 2.12 lbs. per bracket in the final design. The initial bracket can be seen on the right in Figure 11 which correlates to the red section in table 6. The final bracket design which can been seen on the left in Figure 11 correlates to the green section in Table 6.

Table 6: *All property values associated with respective changes (red line depicts initial design, green line depicts final design).*

Design Change #	Weight (lbs)	Safety Factor	Maximum Stress $(x\ 10^8)\ \frac{N}{m^2}$	Maximum Deflection (mm)
Initial	3.92	4.838	0.95091	0.0599
1	3.38	4.454	1.03276	0.0591
2	2.69	1.27	3.62288	0.2699
3	2.94	1.436	3.20418	0.2342
4	3.03	1.956	2.35077	0.1557
5	3.06	2.036	2.25892	0.1422
6	2.76	1.981	2.32167	0.1199
7	2.77	2.05	2.24372	0.1404
8	2.67	2.133	2.15588	0.0583
9	2.55	1.426	3.22571	0.117
10	2.44	1.362	3.3759	0.1273
11	2.4	1.525	3.01465	0.1058
12	2.396	1.541	2.98367	0.1085
13	2.35	1.605	2.86486	0.1011
14	2.3	1.679	2.73872	0.0998
15	2.26	2.07	2.22153	0.0652
16	2.29	1.496	3.07364	0.1371
17	2.103	0.97	4.74027	0.1503
18	2.101	1.17	3.91684	0.0828
19	2.127	1.16	3.96362	0.0833
20	2.047	1.13	4.03554	0.0835
21 (Final)	2.12	1.178	3.90168	0.0834

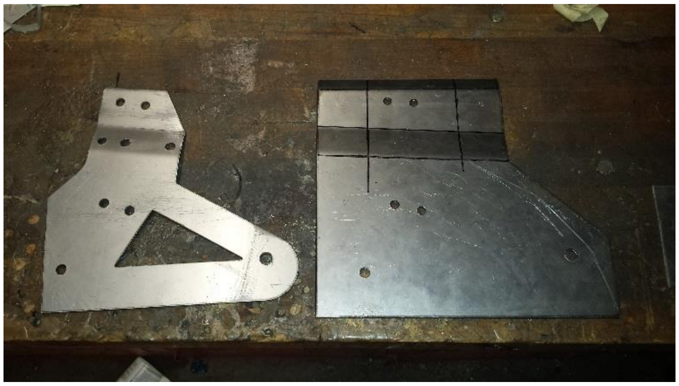

Figure 11: *Final bracket after testing (left) compared to initial bracket (right).*

Through computer aided design, the skid brackets were designed to handle any vertical load experienced during operation while at the same time reducing the weight of the brackets.

The skid brackets are designed to handle the vertical forces experienced during operation but were thought to be susceptible to yielding in the lateral direction. Figure 12 displays the lateral support brackets that were created to add support in the lateral direction. Aluminum was chosen as the lateral support bracket material to minimize the weight added to the sled while providing substantial lateral support to the skid brackets.

Figure 12: *Support bracket created to provide lateral support to the skid brackets*

ANTI-LOCK BRAKING SYSTEM

The 2015 MTU CSC Team implemented the Hayes TrailTrac braking system. The TrailTrac system is an anti-lock braking system that consists of both a hydraulic control unit (HCU) and a Hayes electronic control unit (HECU). This system, in combination with the Camoplast Hacksaw Track, will allow the machine to slow with greater control by pulsing the brake pressure based on the vehicle reference speed that is calculated off of a tone ring attached to the drive axel of the snowmobile. The calibration for the ABS uses a slip/mu curve to define the brake modulation to prevent long term locking of the track based on the reference speed as well as the vehicle yaw.

Brake lines run from the master cylinder on the handlebars to the HCU, and then from the HCU to the brake caliper on the snowmobile. The HECU is mounted on the air box to keep it away from heat that is produced by the engine and exhaust components. The HCU is located near the HECU and mounted in between the intake plenum and gas tank, also keeping it away from heat that is produced by the exhaust system. The orientation of the HCU is known to cause issues when bleeding the system, therefore, the MTU Clean Snowmobile Team mounted the unit horizontal to the direction of motion and with the fittings upright to ease bleeding the system as shown in Figure 13.

***Figure 13**: Hayes HCU and HECU mounting locations.*

COST

In an effort to keep manufacturing costs as low as possible, every component added to the 2015 MTU IC entry was carefully analyzed.

Implementation of new components as well as different hard configuration the final MSRP value of the 2015 MTU IC entry was calculated to be $9,428.40. Since the 2015 MTU IC entry includes advancements in chassis, flex fuel technology, fuel management, and produces significantly less emissions, the MTU Clean Snowmobile Team feels the additional $829.40 is well justified.

SUMMARY/CONCLUSIONS

The 2015 MTU IC entry uses a state of the art chassis and suspension technology, this reduces weight, increases drive efficiency, and improves rider ergonomics. Comprehensive data collection and analysis of exhaust systems for emissions after treatment, as well as for noise reduction have been utilized in the selection of an exhaust system. The data sound data improved from 97 dB to 86.5 dB. The overall calibration was also maximized for lean combustion through the zones one through seven targeting specific lambda values of 1.1-0.95 to produce overall cleaner emissions. The chassis of the competition vehicle was also maximized in the rolling resistance with an increase to the overall drivetrain of 58%. Through utilization of standalone engine management, stock performance has been preserved while reducing noise and emissions. The 2015 MTU IC entry melds proven four-stroke emissions and noise characteristics with modern lightweight chassis technology and reliable advanced engine technology.

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- HMK
- Industrial Graphics
- General Motors
- Woody's
- Arcelor Mittal USA
- Cummins
- Ford Motor Company Fund
- John Deere Foundation
- Vconverter
- SPI-Straighline Performance Inc
- PCB Piezotronics Inc

DEFINITIONS/ ABREVIATIONS

ABS Anti-lock Braking System
AFR Air Fuel Ratio
ATDC After Top Dead Center
BSFC Brake Specific Fuel Consumption
BTDC Before Top Dead Center
CAT Catalytic Converter
CNC Computer Numerical Control
CO Carbon Monoxide
CVT Continuously Variable Transmission
ECU Electronic Control Unit
EMS Engine Management System
EPA Environmental Protection Agency
FEA Finite Element Analysis
HC Hydrocarbon
HCU Hydraulic Control Unit
HECU Hayes Electronic Control Unit
IC Internal Combustion
KRC Keweenaw Research Center
LHV Latent Heating Value
MBT Maximum Brake Torque
MFB Mass Faction Burn
MSRP Manufacturer Suggested Retail Price
MTU Michigan Technological University
NOx Nitrogen Oxide
OEM Original Equipment Manufacturer
PE Performance Electronics
PTO Power Take Off
ROHR Rate of Heat Release
TDC Top Dead Center
WOT Wide Open Throttle

APPENDIX A: *Calculations for Butanol Percentages*

Balanced Stoichiometric Combustion Equations(Ideal)

Butanol- $C_4H_9OH + 6(O_2 + 3.773N_2) = 4CO_2 + 5H_2O$ (1)

Gasoline- $CH_{1.87} + (1 + \frac{1.87}{4})(O_2 + 3.773N_2) = CO_2 + \frac{1.87}{2}(2H_2O) + 3.773((1 + \frac{1.87}{4})N_2$ (2)

Stoichiometric AFR Calculations-Base Fuels

Butanol- $AFR_{stoich} = \frac{M_{air}}{M_{fuel}} = \frac{(MW_{air} * n_{air})}{MW_{fuel} * n_{fuel}} = \frac{(28.97\frac{kg}{mol})(6\ kmol)(4.773\ kmol)}{(4\ kmol)(12.011\frac{kg}{kmol}) + (10\ kmol)(1.008\frac{kg}{kmol}) + (1\ kmol)(16\frac{kg}{kmol})} = 11.19$ (3)

Gasoline:-$AFR_{stoich} = \frac{(28.97\frac{kg}{kmol})(1+\frac{1.87}{4}\ kmol)(4.773\ kmol)}{(1\ kmol)(12.011\frac{kg}{Kmol}) + (1.87\ kmol)(1.008\frac{kg}{kmol})} = 14.60$ (4)

Stoichiometric AFR Calculations-Blended Fuels

Assumed Densities		
Gasoline	719.7	kg/m^3
Butanol	810.0	kg/m^3

AFR's are on a mass basis, so densities were chosen.

$$0.84 * \rho_{gasoline} = 0.84(719.7\frac{kg}{m^3}) = 604.548\frac{kg}{m^3} \quad (5)$$

$$0.16 * \rho_{butanol} = 0.16(810.0\frac{kg}{m^3}) = 129.6\frac{kg}{m^3} \quad (6)$$

$$\rho_{16\%butanol} = (604.548 + 129.6)\frac{kg}{m^3} = 734.148\frac{kg}{m^3} \quad (7)$$

$$\%\text{mass gasoline} = \frac{604.548\frac{kg}{m^3}}{(743.148\frac{kg}{m^3})} = 0.8235 \approx 82.35\% \quad (8)$$

$$\%\text{mass butanol} = \frac{129.6\frac{kg}{m^3}}{(743.148\frac{kg}{m^3})} = 0.1765 \approx 17.65\% \quad (9)$$

$$AFR_s = 0.8235(14.60) + 0.1765(11.19) = 13.9981 \approx 14.00 \quad (10)$$

32% Butanol

$$0.68 * \rho_{gasoline} = 0.68(719.7\,\frac{kg}{m^3}) = 489.396\ \frac{kg}{m^3} \qquad (11)$$

$$\rho_{32\%butanol} = (489.396 + 259.2)\frac{kg}{m^3} = 748.596\frac{kg}{m^3} \qquad (12)$$

$$\%mass\ gasoline = \frac{489.396\frac{kg}{m^3}}{748.596\frac{kg}{m^3}} = 0.6538 \approx 65.38\% \qquad (13)$$

$$\%mass\ butanol = \frac{259.23\frac{kg}{m^3}}{(748.596\frac{kg}{m^3})} = 0.3462 \approx 34.62\% \qquad (14)$$

$$AFR_s = 0.6538(14.60) + 0.3462(11.19) = 13.4195 \approx 13.42$$

APPENDIX B- Decision Matrix

10=Good 0=Bad	EPA emission score	Engine Weight	Availability	Engine Displacement	Engine Reliability	Chassis	Rider Feel	Cost	Total	Total/Weight
Weight	10	10	9	8	8	7	5	2	59	
Polaris Prostar 900	4	1	9	3	4	3	2	10	238	4.03
Skidoo 900 ACE	8	2	1	3	5	3	6	1	226	3.83
Skidoo 600 ACE	8	6	1	6	5	5	6	1	304	5.15
Yamaha 1049 Viper	7	2	4	2	6	5	7	1	262	4.44
Yamaha 1056 Nytro	7	3	6	2	6	5	7	1	290	4.92
Yamaha 499 Phazer	9	8	6	7	7	7	8	1	427	7.24

The decision matrix was determined by online reviews, as well as other aspects that were determined in previous years as well as from forums about each criterion choice. The weighting factor was determined on the basis of the MTU CSC Team's overall needs and goals.