Improving a Snowmobile to be Quiet, Fuel Efficient, and High Performance Using Flex Fuel in a 4-Stroke Turbocharged Engine

Eric Oswald, Spenser Lionetti, Ron Stawniczy, Carl Twynman, John Unterhalter, Jeffery Phelps
Rochester Institute of Technology Clean Snowmobile Team

Abstract

The 2017 Society of Automotive Engineers (SAE) Clean Snowmobile Challenge (CSC), demanded innovation and ingenuity from the teams. The Rochester Institute of Technology Clean Snowmobile Team (RIT CST) took on the task of designing, validating, and refining a snowmobile. The RIT CST has designed and manufactured a low emission, muffled, and efficient snowmobile. The best chassis platform for this year's competition was determined to be the 2016 Polaris 800 Rush Pro-S Axys Chassis. The chassis was chosen to reduce the all-around weight and improve handling on the trails. The engine that has been selected, to obtain the best all-around engine performance, was the Weber 750 CC. The engine has been turbocharged to increase speed and acceleration by including a Garret MGT1238. The engine has been modified to enhance performance by adding a liquid cooled exhaust gas recirculation system, which was added to further reduce emissions. To increase engine performance, the calibration allows the engine to have the capability to run a range of various ethanol contents. Through the power of simulation the snowmobile was designed and validated before physical testing. The engine was modeled in GT Power and performance simulations were run to identify areas of improvement and changes needed to the design. After the design was refined for the first time and the snowmobile was manufactured, dyno testing was carried out to build the best calibration for the most efficient engine.

Introduction

The Clean Snowmobile Challenge (CSC) was created in response to the ongoing discussion surrounding the use of snowmobiles in Yellowstone National Park. Environmental concerns eventually led to a freeze on snowmobiling in the park. Environmentalists continue to disagree with the use of snowmobiles due to their pollution whether it is the emissions or noise pollution that disturbs the wildlife in the park. Also park goers claimed that they could not breathe at times and that the noise also interrupted the peace. The snowmobile industry has responded to this by designing and manufacturing cleaner and quieter snowmobiles that can conform to emission standards and park regulations so the sport may continue on for years to come. The CSC competition tasks the schools for this collegiate event to design and manufacture a snowmobile that will help promote the future of the sport while helping maintain low emissions. The

CSC challenge is a weeklong competition in which the teams' snowmobiles are put under a microscope to evaluate the performance of the snowmobile. Snowmobiles are tested and analyzed for emissions, noise pollution level, acceleration, and handling, to name a few. The CSC demands innovation from the teams to come up with cutting edge ideas and new technology. Teams are also challenged with working around classes and finding time to put hours into designing a product from start to finish. There is a steep learning curve when transferring knowledge as students graduate every year and good team management must also be a large part of the team to be able to continue to compete from year to year. The RIT CST has done just that to answer the demand for a cutting edge snowmobile. The process was to start with our chassis selection and to design an engine to fit within the given chassis. The work continues after chassis selection through the choice of an engine and optimization of the engine to meet the design constraints of the competition. The final steps are to validate and test through dyno time and riding time.

Chassis Selection

For the 2017 season, RIT CST has chosen to use a 2016 Polaris Rush Pro-S as the base chassis due to its general capability as an all-purpose machine, riding well on and off trail. The largest difference between this year's snowmobile and the snowmobile that was used at the 2016 competition (Polaris Pro RMK) is the bulkhead, being shorter front to back and shorter vertically. This caused a need to fully redesign the packaging and location of the components. The choice to use the Rush series was made in part because they offer a bulkhead of comparable size to our 2016 Pro RMK. Another deciding factor was the more trail oriented design that offers better handling than the mountain/deep-powder orientation of the Pro RMK. The S series was used rather than the X series due to a stiffer front end offering improved handling. The front end on the Rush Pro-S sits lower than most other models including the Rush Pro-X, this effectively lowers the center of gravity slightly helping offset the fact that our engine is heavier and sits higher than the stock one.

Figure 1 This is an image of the 2016 Polaris 800 Rush Pro- S Axys chassis that was selected for this year's competition.

Rear Suspension

A redesign of the rear suspension was used in order to reduce overall friction within the track. Belt friction can be calculated using the following equation: $T_2 = T_1 e^{\mu\beta}$

Where:

T_2 = Tension of pulling Side

T_1 = Belt Tension

μ_s = Static Friction

β = angle

Using the above equation Belt Tension, friction, and *e* are all constants. Our design used the advantage of the angle produces with the rear bogie wheels changing with size. A relationship was developed that shows the larger rear bogie wheel will decrease the angle produced. Lowering the angle will lower the exponent in the equation and lower the Tension of pulling side. Reducing the tension of the pulling side reduced the amount of torque that is lost within the track system and more torque can be transferred to the ground to propel the snowmobile forward.

FEA (Finite Element Analysis) was done on the new design in order to gain a perspective on how the new design will perform structurally. Calculations were done in order to obtain a force that was used during the FEA. Below is the calculations used to find the force, using max engine torque and the gear reduction though the drive gears.

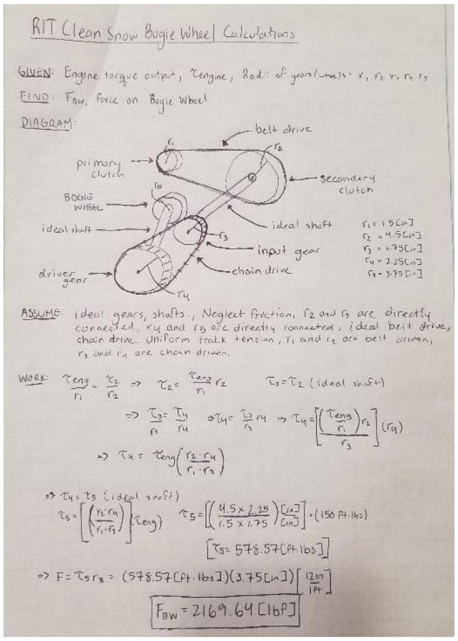

Figure 2 Calculation used to find the force on the Bogie Wheel to be used for FEA.

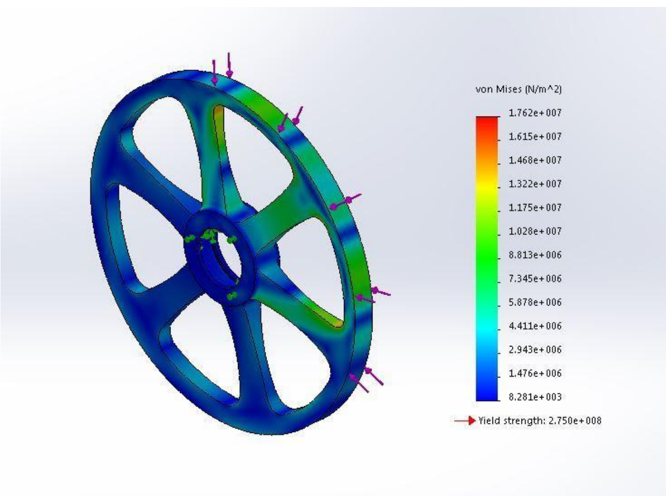

Figure 3 FEA model from SolidWorks to find the factor of safety.

Engine Selection

The RIT Clean Snowmobile team has chosen to use the Weber 750 MPE for the 2017 Clean Snowmobile Challenge. The stock engine, used in a 2008 Polaris IQ Touring FST snowmobiles, meets the minimum CSC brake specific emissions, but also is very powerful for the weight of the engine at an impressive 1.54 kW/kg. This engine will provide a low emissions power plant for the snowmobile while still maintaining the power and performance an environmentally friendly snowmobile. The table below, Table 1, shows the power and emissions rating for the top engines used in the CSC.

Base Engine Comparison					
Engine	Power (kW)	HC	NOx	CO	E-Score
Weber 750	99	4.72	*	122.69	176
600 Cleanfire	84	3.84	*	156.9	129
Ace 600	43	63.2	*	61.69	192
*Note - EPA does not certify snowmobile NOx emissions No NOx data available for E-Score calculation					

Table 1 Shows the comparison of engines to determine the proper engine to select for the 2017 Clean Snowmobile Challenge

The engine features different technologies built in to reduce parasitic losses which makes it ideal for this application. A dry sump lubrication system ensures the crankshaft and valve train are supplied with adequate lubrication and reduced windage. Another design feature that Weber integrated into their design to reduce losses, are roller bearings throughout the camshaft and gear drive system.

Due to the stock engine exceeding the power limit stated in Rule 8.2.1, modification to the engine is necessary. The RIT CST has decided to use the same high-dilution strategy demonstrated by Southwest Research Institute's HEDGE-II (High-Efficiency Dilute Gasoline Engine, Stage II) research consortium with different strategies to obtain the improved BSCF and lower combustion temperatures. Heavy modification to the systems controls is used to achieve this approach.

Engine Simulation

There were many different engine technologies that were brainstormed for the RIT CST's engine build. The software provided through Gamma Technologies, GT-Power, was used to insure educated design decisions. The software uses 1D simulation technique to create an accurate model representation with outstanding correlation results. Heavy use of the model was used in the RIT CST 2016 build and would be used at the same frequency for the RIT CST 2017 build. Over the past months the RIT CST has made the 2016 model more robust, faster, more accurate and added more features, which turned into the 2017 model. The

2017 model features more parameters to increase different types of scenarios that can be ran to acquire data. Running a high quantity of tests allows for the designs to be optimized before production of the components. The engine models used for the 2017 CSC included predictive combustion, knock retard system, predictive wall temperatures, turbocharger control system, and integrated calibration controls. The figure below shows the model and its features.

In order to make the model accurate to dyno a data process of calibration was used to make the model correct. Dyno data was used from the 2016 CSC engine platform in order to calibrate the 2016 engine model. This includes temperatures, pressures, and emissions data. The use of an in-cylinder pressure transducer was not implemented in order to calibrate the pressure in the cylinder. In the next few years the team is looking to acquire a pressure transducer in order to get even more accurate results.

With the model fully calibrated to known engine dyno data, it was ready to be used. The model was used to make design changes to the airbox, intercooler, turbocharger matching, intake manifold, exhaust manifold, muffler, and calibration. More information about how the model was used can be seen in the respective section.

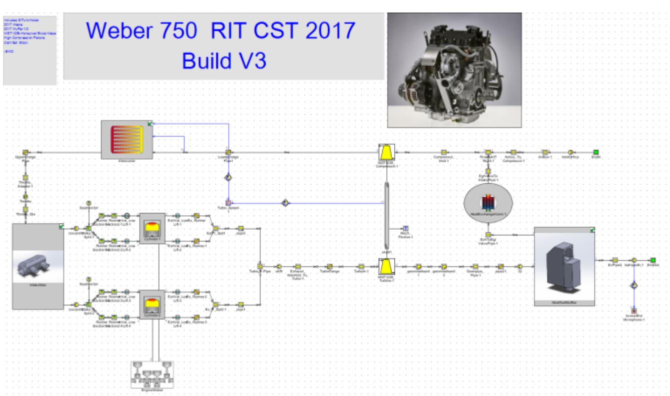

Figure 4 Selected engine Weber 750 CC GT Power engine model map.

Another program that the RIT CST integrated in the 2017 design is chemical CFD provided by ANSYS. Due to the high run time, large data files, and complex set up compared to GT-Power, the program was not utilized as much as the GT-Power, but the chemical reaction simulation was used to finalize engine designs such as piston selection. The RIT CST is looking to integrate more simulation power for the 2018 CSC through the use of ANSYS, and GT-Power. RIT CST believes that through the power of simulation there can better designs optimized for the specific engine package for future competitions.

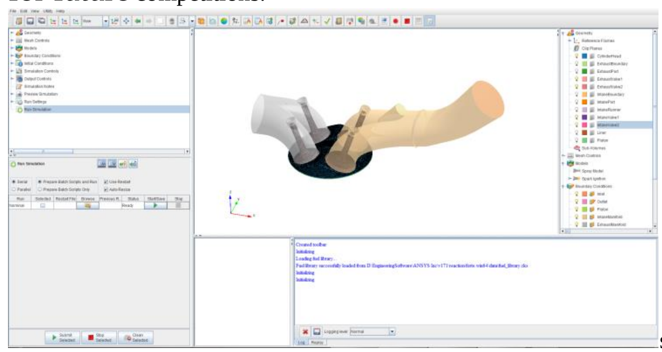

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Figure 5 Piston Selection for the engine was determined through CFD (Computational Fluid Dynamics) in ANSYS.

Turbocharger Selection

With the engine reduced in power a turbocharger was added to the system in order to make the snowmobile perform better. The RIT CST team is using a MGT1238Z that is out of a Dodge Dart. This is an appropriate turbo for our engine because the turbocharger matches the engine at the points where the engine will operate. Below are pictures of the compressor and turbine maps.

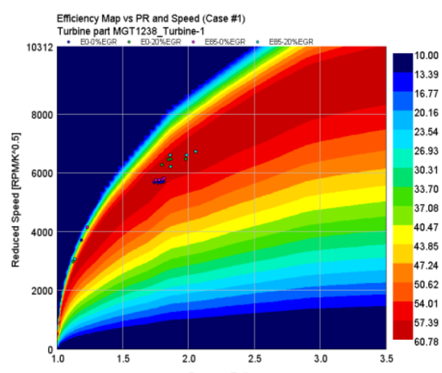

Figure 6 Turbine Map

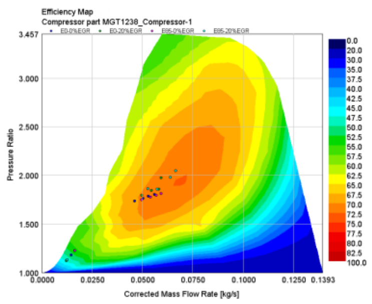

Figure 7 Compressor Map

These maps were imported into the GT-Power simulation in order to match the turbocharger correctly. In the process of finding the correct turbocharger, different models were considered including the GT06, MGT1238, and GT17V. The MGT1238Z had the best match for the engine with the easier control due to it being a waste gated turbocharger.

During the matching process, the MGT1238 was entering surge which caused catastrophic malfunction. This was observed in the 2016 CSC but not in the 2016 CSC preparation. After the challenge the RIT CST started to diagnose the root cause of the failures. The 3 main hypotheses that were formed were lack of oil pressure, the turbocharger entering surge, and the turbocharger over speeding. Another problem with constant boost building, even at idle, was also observed.

A pressure gauge was placed on the oil supply in order to gain the correct pressure, and a clear tube was installed to observe discharge flow rate. With the engine on the dynamometer it was run at a variety of loads and speeds. Both of these variables were considered in working condition so that lack of oil pressure was ruled out. This left over speeding and surge as an issue that could have caused failure.

A speed sensor was placed on the MGT1238Z in order to observe the shaft speed of the turbocharger. The engine was placed at the point of operation where the turbocharger shaft speed would be the greatest and the shaft speed was recorded. After the test was completed this showed that over speeding was not an issue because the shaft speed would remain well below the threshold.

With the other two problems diagnosed to not contributing to the failure surge was the last hypothesis to be tested. In GT-Power a plot was set up in order to watch the real time turbocharger operation. The simulation showed that the turbocharger was entering surge across a normal operation point in the engine. A plot of the operation is pictured below.

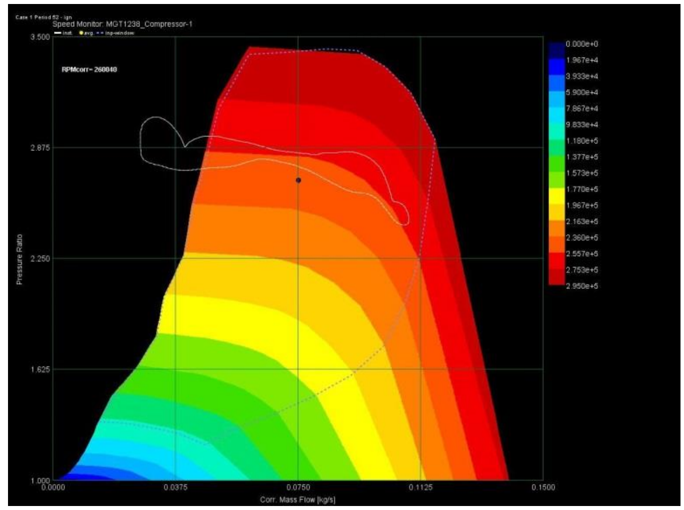

Figure 8 Plot showing where the turbocharger was entering surge.

The white line shows operation of the turbocharger over a cycle of the engine. It is clearly crossing the surge line which is the root of the problem.

The solution to the problem lies within the wastegate. When the wastegate opens enough the turbocharger would not enter surge. Due to the wastegate actuator not having enough displacement, it was preset to automatically be open. In the 2016 CSC the turbocharger wastegate effective diameter range was from 0mm to 10mm, in the 2017 CSC the effective wastegate diameter will be around 10mm to 20mm. This change would prevent the turbocharger from entering surge.

Piston Selection

The Weber 750 offers two different piston geometries that can be used, a low compression piston features on Weber's turbocharger set-up, or a high compression piston used on the natural aspirated engine. Advanced simulation was used in order to determine if the high compression piston would offer better emissions and power rating. The higher compression in a cylinder would offer reduced brake specific emissions in NOx and CO emission compared to the naturally aspirated pistons. Below is a figure that shows the % reduction in the emissions generated by our simulation software GT-Power.

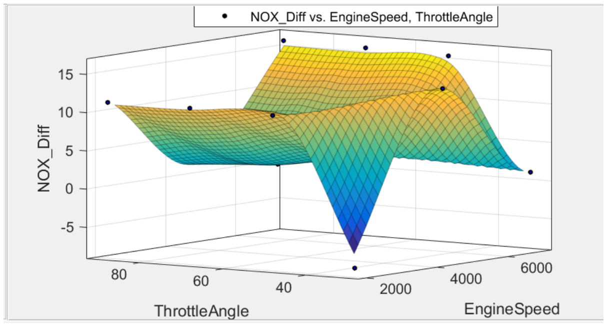

Figure 9 Shows the percent reduction in NOx

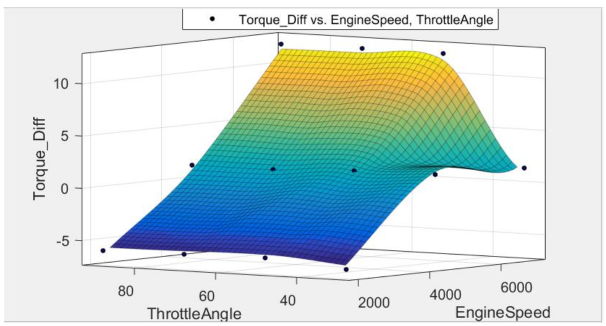

Figure 10 Shows the percent increase in torque

Intake Manifold Design

A new intake manifold design is needed for the new 2016 AXYS chassis. This is due to new engine placement and underhood packaging. The intake manifold used in the 2016 CSC was tested for fit but it intersected the chassis near the fuel tank. CFD Flow simulation along with GT-Power was used to confirm that there was no scavenging between cylinders under normal operation. Below is a figure that shows the CFD simulation with vector arrows.

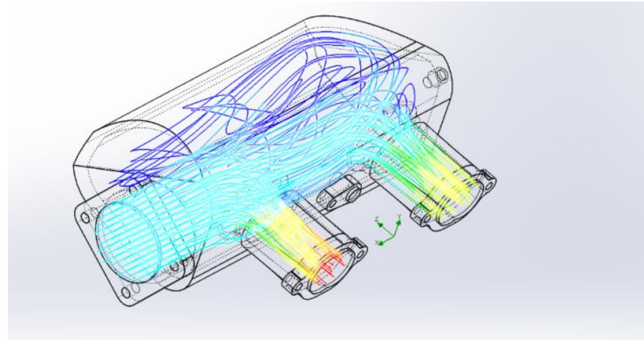

Figure 11 Intake manifold CFD results for final design.

Once the design was finalized, HARBEC Inc. has the ability to make the manifold through 3D printing process. This process was chosen due to the complex internal geometry of the manifold, and the excellent thermal properties of the material. The thermal properties that are in interest to the CST is the heat transfer. The intake manifold is bolted to the cylinder head, which exhausts a lot of heat. In order to keep intake temperatures down, a low heat transfer coefficient is used for the intake manifold. Plastic generally has a very low coefficient heat transfer.

Electronic Throttle Body

An Electronic Throttle Body was integrated into the engine control system of the snowmobile for a variety of reasons, the deciding factor being in order to increase control over the engine for smoother engine control. As a butterfly valve opens the mass flow rate allows to flow per angle decreases as the angle reaches 90°. The ECM can take this reading into consideration through the PPS and allow for a linear control surface. Due to the PPS and ETC the rider's thumb displacement has a linear relationship with engine power.

Another reason an ECT system was integrated was due to ease of starting. The injected fuel is correlated to the PPS and changes based on location. This allows for a "Flood Clear" mode to be activated while cranking. The rider can squeeze the pedal to full opening and crank the engine over to cut fuel being injected into the cylinders. This can be used if the rider believes the engine will not start due to having too much fuel in the cylinders.

The ECT system uses an electronic throttle body off of a Kia Soul. This diameter and flow characteristics were considered the best for the Weber 750 at full load, due to the flow rate and lack of pressure drop across the throttle body. The diameter and pressure drop were checked using GT-Power in order to confirm that the throttle body would work for the application.

The PPS that is used to control the ECT is a throttle off of a Ski – Doo Ace 600. This PPS was chosen because it is the only electronic throttle position that offers a thumb throttle used on snowmobiles. It uses two Hall Effect signals to determine the position of the throttle. The sensor outputs two signals to the ECM, which correlates the signals to make sure that they are reading the same position. This increases safety because if the two signals do not correlate together then the ECM will output a DTC code and the engine will not be operational until the problem is fixed. This will prevent the possible failure of over speeding or having a runaway engine.

Liquid Cooled Exhaust Gas Recirculation (EGR)

The low pressure EGR System on the 2016 CSC sled was improved for the 2017 CSC. Upon designing the original system it was seen that the cooler was big and bulky. It offered good cooling throughout the system but the connections were not easy to get to and made routing difficult. A smaller cooler out of a Kia Sportage, with better port placement, still maintained the cooling aspect of the original cooler. The EGR valve is out of a VW Jetta. It is the same one that was used in the 2016 CSC so there was no need to research data on the valve.

The EGR system is a critical component in the engine strategy for the High-Efficiency Dilute Gasoline theory. This would allow for cooler exhaust temperatures and lower NOx emissions and HC. The NOx is reduced by reducing oxygen within the engine cylinder and decreases HC by giving the unburnt fuel a chance to burn again which being recirculated into the engine cylinder.

The system is setup to pull exhaust gas from the muffler, go through the cooler and then through the EGR valve. The valve is placed in between the air filter and the turbocharger compressor inlet, so that the vacuum created from the turbocharger will pull the exhaust gas into the intake system, rather than post compressor. The poppet valve is controlled by the ECM to allow a flow mixture into the intake system based on engine operation conditions. The flow simulation that was carried out for the 2015 CSC was reused for values, but due to the cooler being changed the GT-Power simulations were redone to accommodate for the change in geometry. The simulation was used to see if the cooler was sized property, and what the lowest temperature of the exhaust gas could be. It was determined that the lowest temperature the exhaust gas can be is 45° C, so there was no concern with condensation. If condensation is formed, corrosion of the components would be a concern because exhaust gas forms Nitric Acid.

Muffler Design

For the 2017 CSC the RIT CST has used a new muffler design. This is because of the issues that were present in the 2016 CSC muffler design. The problem with the 2016 muffler was the back pressure created under engine operation. In 2016 the muffler created a 0.8 bar pressure differential, while in 2017 the muffler was designed to have a 0.5 bar drop. This number was chosen in order to retain a noise level within the muffler. Obtaining the proper pressure drop was done by strategic planning on the baffle location, hole size, and flow path. GT-Power was used check the muffler design for both exhaust gas flow, and noise level.

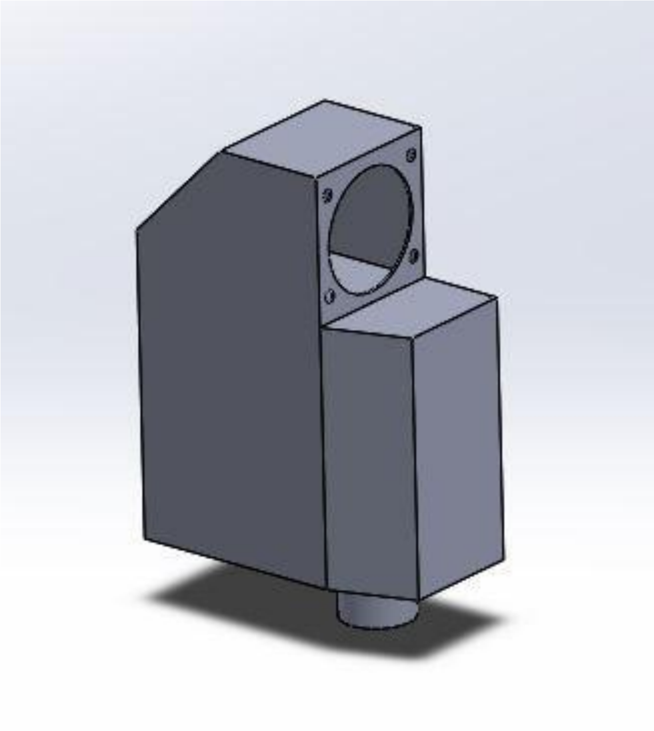

Figure 12 SolidWorks model for 2017 RIT CST custom muffler

AfterTreatment

In order to reduce emissions more an oxidation reduction catalyst was integrated into the muffler design. This is due to the little amount of space that is offered under the hood of the snowmobile. Through the use of precious metals a chemical process of reduction of HC, CO, and NOx emission. Catalysts perform reduction of NOx into O2 and N2, Oxidation of CO to O2 and CO and another oxidation of HC and H2O to CO2 and H2O. With the combustion chamber creating a high amount of NOx during the operation of the engine. The reduction of NOx is the soul reasoning behind a 3 way catalysts as opposed to 2 way catalyst that wouldn't deal with NOx as well.

Flex Fuel

In the design rules there is a need to have the engine burn a range of fuels. This range is defined by Ethanol content 0% to an Ethanol content of 85%, otherwise known as "Flex Fuel." In order to solve this problem the Oxygen sensor in the snowmobile is able to monitor the real time fuel ratio. The ECM reads the fuel ratio and makes adjustments to the injected mass to maintain the fuel ratio. This is a closed loop system that keeps the fuel ratio even with changing ethanol content by changing the fuel injector pulse width.

The ECM is also smart enough to learn from the previous fuel measurements in order to gain a better fuel control strategy and return the fuel ratio to the correct value quickly. The ECM will be able to know what fuel is entered under a few strokes for the oxygen sensor to read the exhaust gas fuel ratio.

Another concern with changing fuel is the density of ethanol is not the same as fuel. It takes roughly twice amount of ethanol in order to maintain the same fuel ratio that gasoline would maintain. The fuel injectors were considered with this modification. The injectors needed to be sized larger to accommodate for the larger amount of fuel that needs to be injected. GT-Power was used to find the correct flow rate of a full E85 mixture of the engine at full load and speed. The conclusion that can be drawn from the simulation is that the injectors are sized correctly for the E85 mixture.

Engine Control Module (ECM)

In order to control the engine a Delphi MT88 was used. The MT88 has all the inputs and outputs that are needed to control all the hardware, ECT, turbocharger and EGR system, and offers closed loop control for a various different parameters. The ECM is communicated through the calibration software TechniCAL in order to update the engine calibration, but is not open source. Therefore there is no changing the source code which is the biggest disadvantage. The RIT CST is working on getting a open-source ECM for the future competitions. Due to time constraints the RIT CST will not be using the open-sources ECM but is working on getting it up and running as quickly as possible.

Validation

After the building process of the snowmobile was complete, it was tested for the functionality aspect. The best way for testing the snowmobile is under normal operation on a trail system. Due to the restriction of New York State on our snowmobile and lack of snow, the RIT CST improvised and attached wheels in place of skis on the snowmobile. A figure below illustrates the design that was used in order to accommodate the wheels.

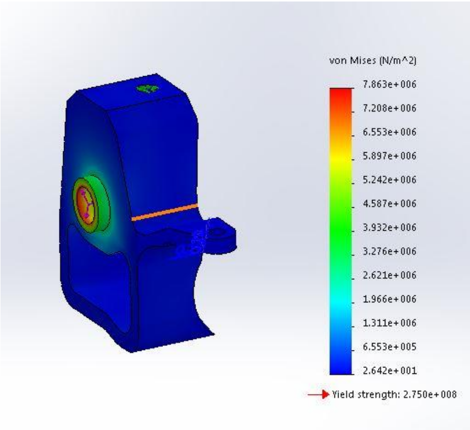

Figure 13 Spindle made to integrate wheel skis for testing, as seen FEA to check factor of safety.

In order to simulate a 100 mile endurance ride the snowmobile was taken to RIT's campus loop. The snowmobile will experience similar drive cycle as it would be on public trails. Changes to the calibration were made in order to make the snowmobile more controllable and enjoyable to ride. A picture below shows the route of which the snowmobile would follow.

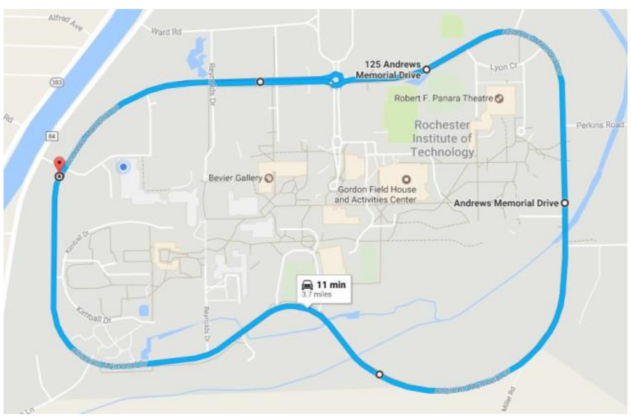

Figure 14 RIT campus loop used for sled testing, pulled from google maps.

Summary/Conclusions

For the 2017 CSC the RIT CSC took a stock 2016 Pro 800 from Polaris and made it more environmentally friendly in regards to noise and fuel efficiency. The stock 800 2 stroke engine was swapped out for a Weber 750 which featured turbocharging, custom calibration with wiring harness, Liquid-cooled EGR, and a 3-way catalyst. In order to accommodate for the new systems a custom intake & exhaust system was needed. To reduce emission further the RIT CST took it further and added a rear suspension that would reduce friction with in the track. The team plans to integrate an open-source ECM and a dual coil spark system. The RIT CST will continue to innovate and lead the way in the future to reduce emissions and continue the tradition of snowmobiling for all ages young and old for many years to come.

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Acknowledgments

The 2017 Rochester Institute of Technology SAE Clean Snowmobile Team would like to acknowledge the sponsors and supporters for the 2017 season, especially RIT President Destler for his generous donation. We are thankful to have support from Polaris, Curve Industries, Cummins, and Honeywell. The team also appreciates the continued support from Gamma Technologies, Dassult System, ANSYS, CD- Adapco, New York State Snowmobile Association, Fly Racing, Triple 9 Optics, and Camso. Some other companies and organizations we would like to thank are Aristo, Western New York Energy, Monster Energy Drinks, Skinz Protective Gear, RSI Racing, Harbec, SMC Metal, Delphi, and the Rochester Institute of Technology College of Applied Science and Technology.

Without the generosity and great support from all these great groups and companies the RIT CST would not be where we are today.

The team would also like to extend are gratitude and thanks to Dr. James Lee our advisor and Jeffery Lonneville; their guidance, support, knowledge, and use of facilities were essential in completing this year's snowmobile.

Definitions/Abbreviations

BSFC	Brake Specific Fuel Consumption
CFD	Computational fluid dynamics
CO	Carbon Monoxide
CSC	Clean Snowmobile Challenge
CST	Clean Snowmobile Team
DTC	Diagnostic Trouble Codes
ECM	Engine Control Module
ECT	Electronic Throttle Control
EGR	Exhaust Gas Recirculation
GT	Gamma Technologies
NOx	Nitrogen Oxides
PPS	Pedal Position Sensor
RIT	Rochester Institute of Technology
SAE	Society of Automotive Engineers