Implementation of Advanced Automotive Powertrain Technologies for Powersport Application

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ABSTRACT

The Rochester Institute of Technology has constructed a technologically advanced snowmobile for the 2013 SAE Clean Snowmobile Challenge. The 2013 RIT entry was constructed with the following four design objectives. 1 - Maintain a level of performance for a potential customer, 2 - Increase fuel economy, 3 - Lower atmospheric emissions, 4 - Decrease sound output of the machine. RIT chose to accomplish these goals by meshing two different Polaris machines. The revolutionary Polaris Pro Ride chassis took the industry by storm when it was released in 2010, however, it has only been offered with two stroke engines. By installing a four stroke turbo (FST) engine from a Polaris IQ Turbo, a snowmobile could be created which would accomplish all 4 of RIT's goals. In order to increase the fuel economy of the FST, a cooled Exhaust Gas Recirculation (EGR) system was used. The EGR recycles a portion of the exhaust back into the intake to increase fuel economy and lower emissions, RIT designed a system which utilized a liquid to air cooler in order to decrease the temperature of the gas being recycled into the engine. By cooling the recycled gas, the combustion temperature is lower than compared to an uncooled EGR system, this results in lower NOx emissions. To combat CO and HC emissions, a three way catalyst was integrated into an RIT designed muffler system. To control the new systems, a Vi-Pec V88 standalone ECU was installed, along with a Haltech flex fuel sensor in order to allow for the automatic calibration for E0 to E85. By implementing advanced technology into an existing power train in a state of the art chassis, RIT has created a snowmobile which accomplishes the major objectives of the Clean Snowmobile Competition: a clean, quiet snowmobile which the average consumer will enjoy owning in a recreational setting.

INTRODUCTION

The SAE Clean Snowmobile Challenge began in the year 2000 after snowmobiles were banned from Yellowstone National Park because of excessive noise, and emissions. The Challenge was initiated in order to give collegiate design teams the objective to create a cleaner burning, more fuel efficient, and quieter snowmobile. The 2013 Clean Snowmobile Competition will be held from March 4-9th in the Keweenaw Peninsula of Michigan.

This paper will go into detail describing the machine built by RIT for the 2013 CSC. This will be the first year that RIT has had an entry into the competition. Because of this, several set backs were encountered over the course of the year, such as not having a snowmobile from the previous year to compare data too. Also, at the time of writing this report, the 2013 RIT entry has yet to have its engine started. Therefore theoretical data will be discussed based of the power train design of the snowmobile.

This paper will discuss the machine RIT has designed and built, which includes the selection of the engine and chassis, design strategy, turbo charger selection, cooled EGR implementation, selection of an electronic throttle body, flex fuel capability, muffler design, emissions control, as well as projected MSRP for the RIT designed and manufactured snowmobile as it would be in a mass production setting of 5000 units per year.

SNOWMOBILE SELECTION

Selection of an appropriate machine for this year's Clean Snowmobile Challenge was based off of several factors. In order to create a snowmobile that was economical and clean burning, two stroke engines were immediately ruled out because of their oil burning based lubrication system. Two technologically advanced, 4-stroke engines immediately stood out as possible power trains for the 2013 entry, the Skidoo 600cc ACE, and the Polaris 750cc FST. After analyzing each one of the engines, the team chose the 750 FST for its far superior power output when compared to the 600 ACE (130hp FST vs. 60hp ACE). The consideration which weighed the largest on the engine selection is the fact that the majority of snowmobiles are recreational vehicles. Appropriate power levels need to be maintained in order to ensure to the average consumer that the machine will create an enjoyable experience to ride.

However, because of the popularity of the light weight two stroke powered snowmobiles for recreational users, chassis development has surpassed that of the 4-stroke counterparts. In order to create a 4-stroke powered snowmobile with a state of the art chassis, and engine swap would be required. It was decided that the previously selected Polaris FST engine would be used in a new Polaris Rush Pro Ride chassis. This combination would provide the best of both worlds, a 130hp turbo charged 4-stroke engine in the state of the art chassis.

ENGINE INSTALLATION

The Pro Ride chassis revolutionized rear suspension design when it was first released to the public in 2010. It's linear rising rate rear suspension had taken a page out of the motocross linkage handbook, and had created a system which allows the shock shaft velocity to increase throughout the compression of the shock. As the shock velocity increases, the suspension becomes stiffer, creating a ride that is plush and supple in smaller bumps, yet becomes stiff as one plows through larger bumps on the trail.

However, the Pro Ride chassis was specifically designed for 2 stroke engines, which meant that a multitude of modifications were necessary in order for the FST to be installed. During the engine swap, RIT attempted to use as many stock FST parts as possible in order to use an already proven component, as well as save on fabrication time. Major stock FST parts which were able to be retrofitted to the Pro Ride chassis included the oil tank, oil cooler, intake runners, intake plenum, primary clutch, and intercooler.

Engine mounts replicating the style of the factory FST mounts were fabricated out of 6061 T6 aluminum plate. The steering also had to be modified in order to allow for room for the turbo charger. Fortunately, the Pro Ride chassis is designed in such a way that it is easy to mirror the stock steering system by cutting and reversing both steering posts. A custom bracket was also machined to clamp the lower steering post to the frame to prevent any welding on the aluminum over structure, which greatly affects the structural integrity.

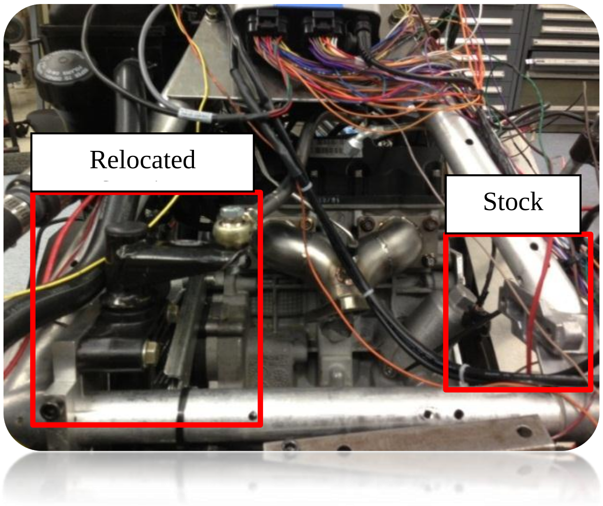


Figure 1: A Comparison of stock steering location vs. RIT modified steering location

The largest issue which presented itself during the engine installation was the FST intake system. The stock FST intake consists of a charge pipe running over the valve cover of engine to a plastic plenum, which splits the flow into two throttle bodies (One for each cylinder), and then into two tuned length intake runners. In the Pro Ride chassis, the gas tank sits in between the rear A frame structure, greatly limiting the space behind the FST engine. Several solutions were presented and considered, however in the end it was decided to put a controlled indentation into the stock Rush gas tank, and to switch from twin mechanical throttle bodies to a single electronic throttle body.

In order to accomplish this, a vacuum pump was hooked to a regulator, and then the breather hose on the gas tank. By pulling a small controlled vacuum on the gas tank and heating specific areas slowly and evenly, the team was able to heat the gas tank to its leather region. The leather region is the state when the polyethylene tank becomes soft and malleable. Once the vacuum was pulled and the tank was soft, small amounts of pressure were applied to certain areas and held while cooled in order to ensure the gas tank would hold its newly formed shape.

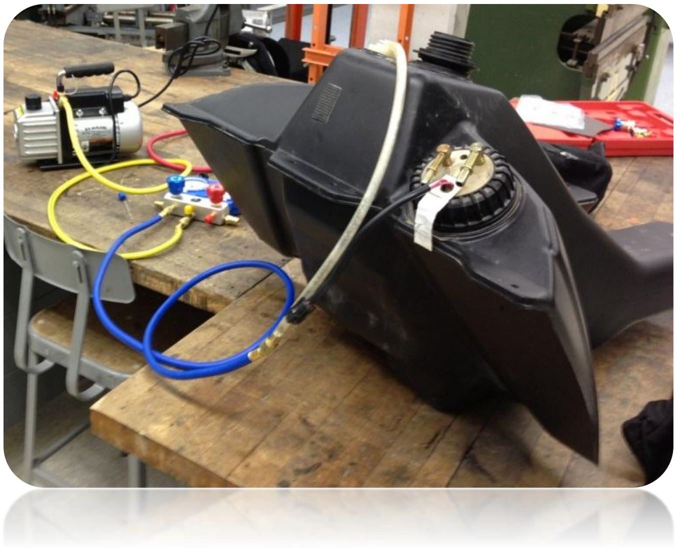


Figure 2: Vacuum thermoforming stock fuel tank.

POWERTRAIN DESIGN STRATEGY & OVERVIEW

In stock form, the 750cc FST engine from the 2006 IQ Touring FST makes approximately 130 hp. Article 4.2.1 of the 2013 SAE Clean Snowmobile Challenge Rulebook imposes a peak horsepower limit of 130 hp. To maintain an acceptable level of performance, RIT designed the powertrain with the goal of keeping power near the peak limit without exceeding it, while increasing average torque across the rpm range. This will allow for a lower operating RPM and reduce fuel requirements. The resulting near-flat torque curve helps greatly with improving performance for a trail oriented snowmobile while improving upon emissions and fuel economy.

TURBOCHARGER SELECTION

RIT first plotted baseline set points on the compressor map for the stock BorgWarner (KKK) K03 Turbocharger. This compressor was very well matched to this engine for a high-revving, sharp peaky power-band with two-stroke-like engine characteristics. Unfortunately, this turbocharger and engine combination has a high boost-threshold and its adiabatic efficiency range does not match up well for this application. Because of this, a new turbocharger that better suits RIT's needs was chosen.

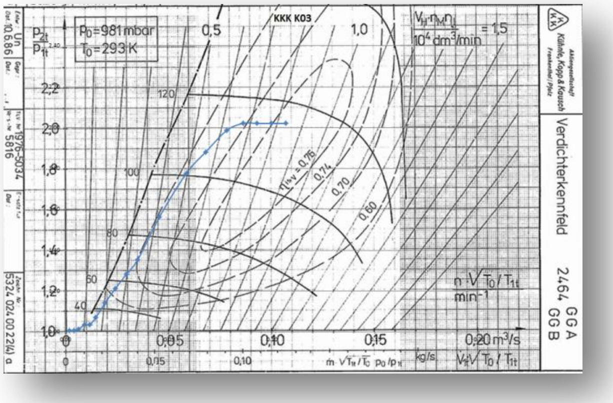
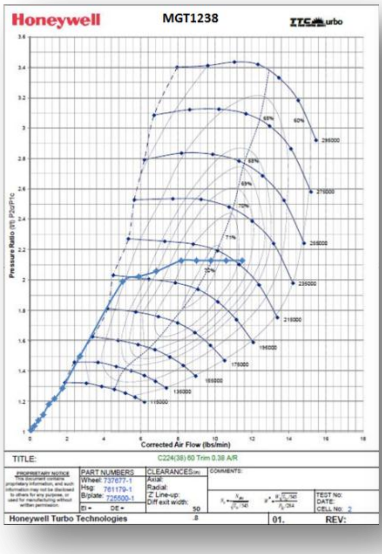
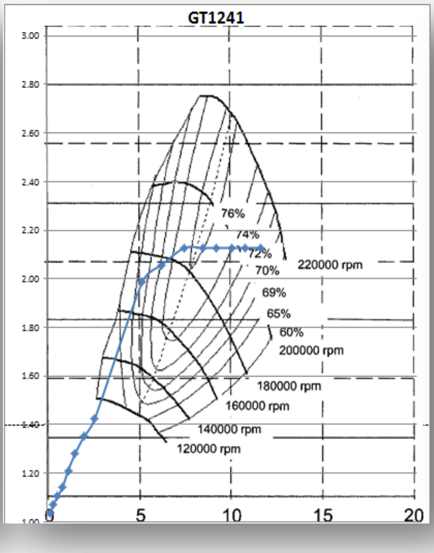
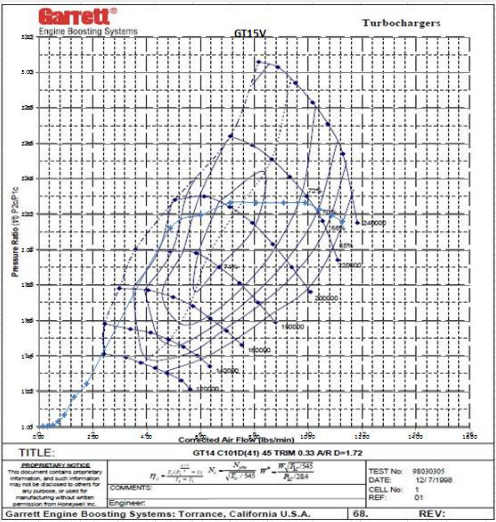


Figure 3: K03 Compressor Map

The turbochargers considered were the Honeywell GT1241, MGT1238 and the Honeywell GT1541V. All three match well for this application with mass-flow, pressure ratio, and adiabatic efficiencies within acceptable limits. The major difference between them is the way shaft speed is regulated; the MGT1238 and GT1241 use a traditional internal wastegate to bypass exhaust gas past the turbine, while the GT1541V uses more advanced variable nozzle turbine (VNT) technology to vary exhaust flow velocity through the turbine. This technology is usually reserved for diesels, but because of the lower than usual EGT's from the high ethanol content fuel it will work well on this application.







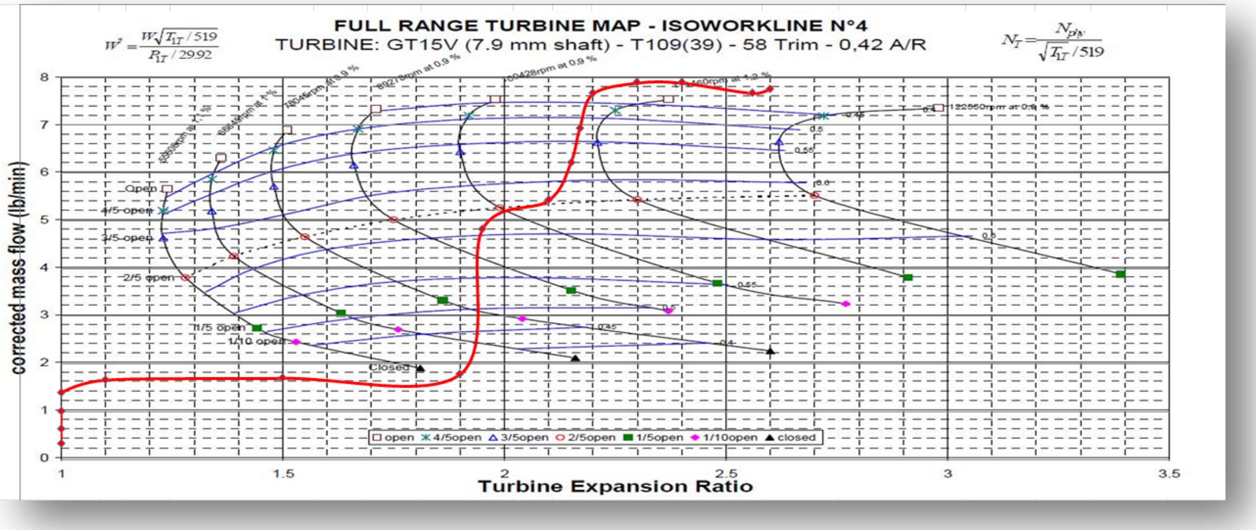
The MGT1238 was not selected because its flow characteristics are very similar to the stock K03 compressor wheel. This would be a good choice for a high-boost and high-rpm application, not for a broad, usable torque curve. The GT1241 compressor map matches much better than the MGT1238. The boost target is met at 6000 RPM and the set points pass through the highest efficiency island. However, the boost threshold is still higher than desired; this is a good "medium-high" performance choice for high-rpm operation therefore the GT1541V met the design requirements. Boost target is met at 4000 RPM, with most of the boost target set points above 72% efficiency. This compressor will allow for an extremely wide power curve without adding excess heat to the intake charge, which will increase ignition advance tolerance and lower EGT's. A corrected mass air flow, corrected wheel speed, and compressor power requirements for our set points were calculated from 500 – 8000 RPM in 500 RPM intervals using the equations:

$$W_C{}^* = \frac{W\sqrt{T_{1_C}1/545}}{P_{1_C}/13.95} \qquad Lc = \frac{W_C \times C_p \times T_{1_C} \times \left\{(\pi_C)^{\frac{\gamma-1}{\gamma}} - 1\right\}}{\eta_C} \qquad N_C = \frac{N_{phy}}{\sqrt{T_{1_C}/545}}$$

Variable nozzle turbine's (VNT) adjust wheel speed by adjusting the expansion ratio of the nozzle, effectively accelerating or decelerating the exhaust gas mass-flow as it enters the turbine. Because of the variance in stoichiometry, exhaust mass-flow at a given set point depends on ethanol content. Turbine performance was modeled for both extreme values (E40 and E85) to account for this. Corrected exhaust (air + fuel) flow, turbine power (produced at shaft) and corrected turbine speed were calculated using the equations:

$$W_T{}^* = \frac{W_T\sqrt{T_{1_T}/518.4}}{P_{1_T}/14.70} \qquad N_T = \frac{N_{phy}}{\sqrt{T_{1_T}/518.4}}$$

The required turbine expansion ratio was then determined from the corrected mass-flow chart. The expansion ratios are transferred to the turbine efficiency chart and matched to their respective shaft speeds – isentropic efficiency is then found and is used to calculate the power produced at the turbine shaft using the equation:



$$L_T = {W_T}^* \times C_p \times T_{1_T} \times \left\{1 - \left(\frac{1}{\pi_T}\right)^{\frac{\gamma-1}{\gamma}}\right\} \times \eta_T$$

Figure 5: GT1541V turbine map. Note horizontal curves denote % open VNT

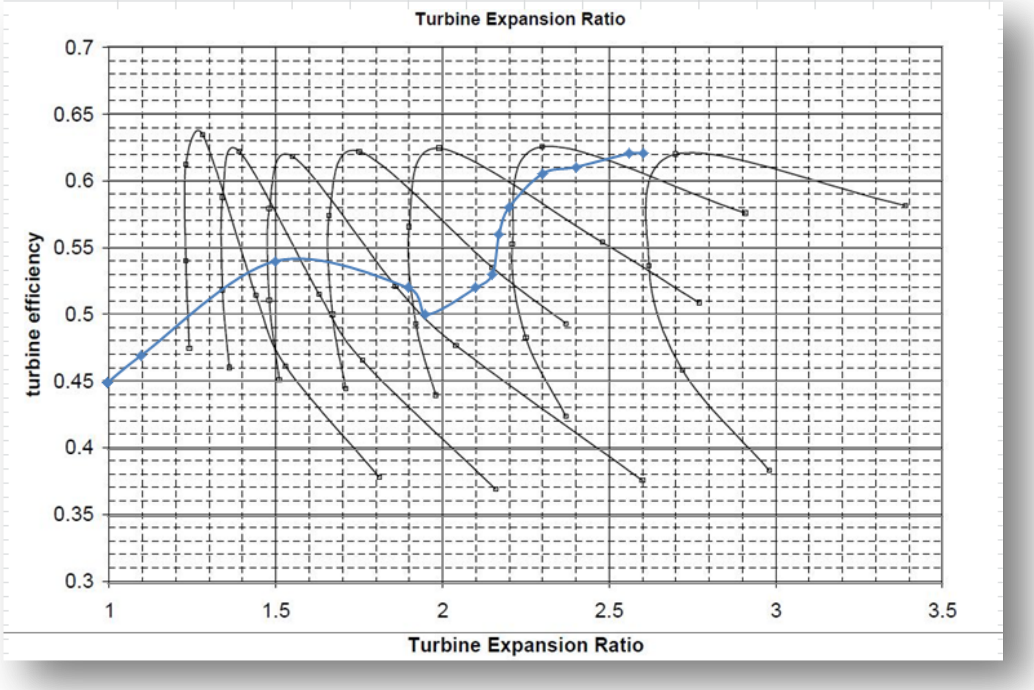


Figure 4: Isentropic Turbine Efficiency. Curves correspond to their respective corrected wheel speeds from turbine map 1

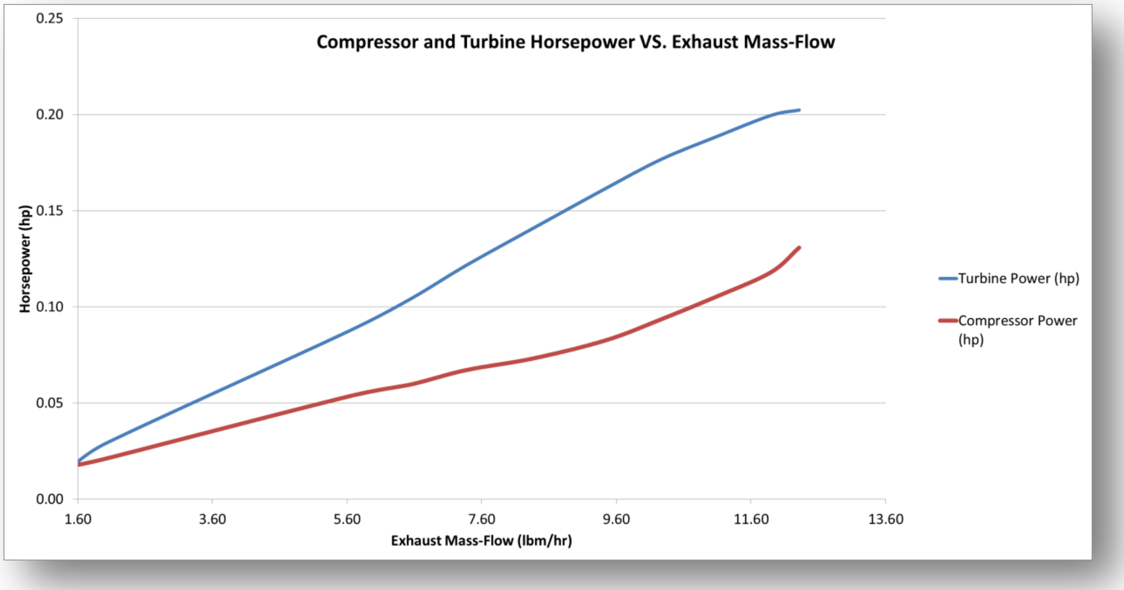


Figure 6: Power produced by turbine must be greater or equal to power consumed by compressor for set points to be realistic.

VNT CONSIDERATIONS

Most traditional turbochargers use a wastegate to control shaft speed and boost. The wastegate is a valve which diverts exhaust around the turbo. This system functions well and is simple, but because the aspect ratio is fixed (often called an A/R ratio) the engineer is forced to either choose smaller turbo for faster transient response, low boost threshold and improved drivability, or a larger turbo with higher mass-flow capability. The disadvantage to this is that the smaller turbo will choke the system at higher engine speeds, and the larger turbo will do nothing until higher operating speeds and will likely suffer from slow transient response, have a high boost threshold, and will exhibit “turbo lag”.

The wastegate is generally controlled by pneumatic linear actuator, called the wastegate actuator (WGA) which is usually supplied with a boost-pressure “signal” from the intake manifold *before* the throttle body. For electronic boost control, a boost-control solenoid is placed in-line between the wastegate actuator and pressure signal. The ECU can use pulse width modulation (PWM) to control actuator position by venting the actuator to the atmosphere, allowing full pressure to the actuator, or any pressure in-between.

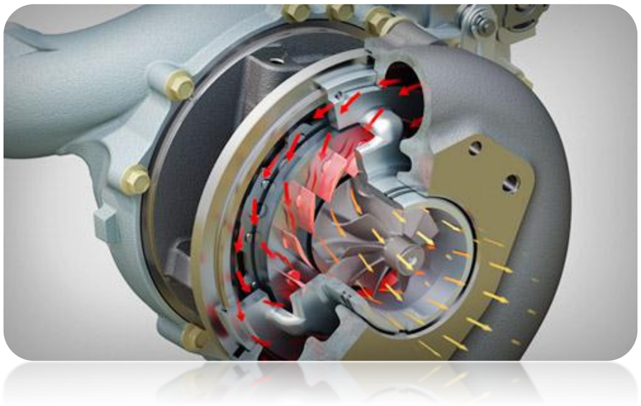


Figure 7: Honeywell VNT Internals

VNT technology is the next step in turbocharger technology. Instead of diverting and wasting exhaust gas energy, all the exhaust flows through the turbine at all times. The variable nozzle ensures that the A/R is optimized for all operating conditions on a properly matched system. This gives the calibration engineer greater flexibility in his control strategy, and can allow him to artificially decrease response times by closing the vanes during “off-throttle” transient events, reduce boost threshold by holding the vanes closed or he can even choose to reduce boost at cruise-conditions to improve fuel economy

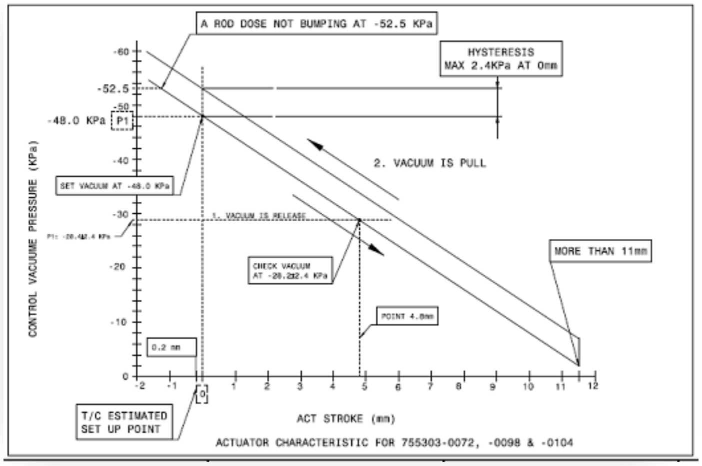


Figure 8: Control vacuum vs. Actuator displacement

The preferred method of vane control is also a spring-biased linear pneumatic actuator with a PWM control solenoid, but because of the aggressive nature of the vane’s effect on turbine speed a fail-safe is implemented so that it should always fail in the full-open position (slower shaft speed). This is difficult to accomplish because at idle with no boost the vanes will not close, and the turbo will spool slowly. To solve this design problem a *vacuum* actuator with integrated position sensor was selected. To provide a constant vacuum signal an internally regulated vacuum pump (OE on light-duty diesel Ford trucks, used for HVAC actuation) was selected. The vacuum pump was disassembled, and the internal vacuum regulator was synchronized to shut off when vane actuator reaches 100% duty at approximately 18 inHg vacuum to increase the service life of the pump, decrease mechanical noise, and reduce the charging load placed on the engine. The signal will be passed through a PWM control solenoid which is closed-loop controlled by the ECU, with mapping based on ethanol content, throttle position, and RPM.

Figure 10: Electric vacuum pump

Figure 9: Internal vacuum regulator

COOLED EXHAUST GAS RECIRCULATION

Exhaust Gas Recirculation (EGR) uses a valve to allow burned exhaust gas back into the combustion chamber. The EGR runs directly from the exhaust manifold to the intake manifold and hot exhaust gas is routed back into the engine. This has several emissions and fuel-mileage benefits, but also presents a few design challenges from a controls and drivability standpoint.

Using EGR lowers HC by burning a mass fraction of the exhaust gas twice, allowing any unburned fuel a second chance to be burned. It also reduced reduces combustions temperatures considerably, and can allow an engine to run in a lean-state without overheating or producing excess NO_X. EGR can also be used to offset throttling losses (pumping loss) at part load and improve fuel mileage. The design challenges are that EGR reduces power output; the addition of EGR at a steady state will be felt as a power reduction to the rider and can result in an annoying drivability issue. The addition of electronic throttle control offsets this, as throttle is added without the user ever realizing there was a decrease in performance. Also, too much EGR can reduce combustion stability and can actually be detrimental to emissions and efficiency if not properly implemented - careful calibration prevents this.

In RIT's EGR system an electronic linear solenoid EGR valve was sourced from a 2007 Honda Civic for computer-controlled closed-loop control of the EGR system. This was combined with a heat exchanger sourced from a Volkswagen TDI to cool the exhaust gas before re-combusting. This is referred to as the EGR Cooler.

The EGR cooler removes heat from the exhaust gas before recirculating it; further reducing combustion temperatures. This allows much more aggressive engine calibration, as spark and boost tolerance is increased, higher lambdas can be targeted, and knock tolerance is increased. Because of this, NO_X is reduced even more so than with a normal "hot" EGR and BSCF is reduced as well.

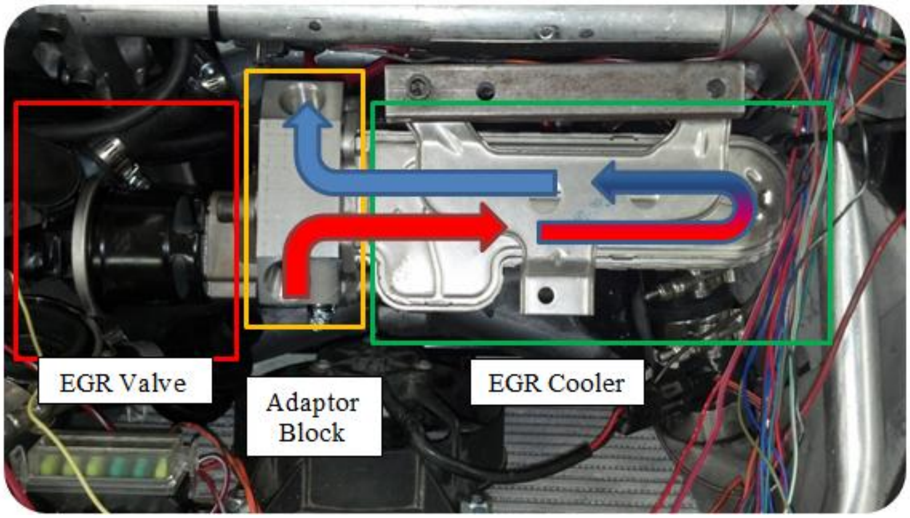


Figure 11: EGR Components and Gas Flow

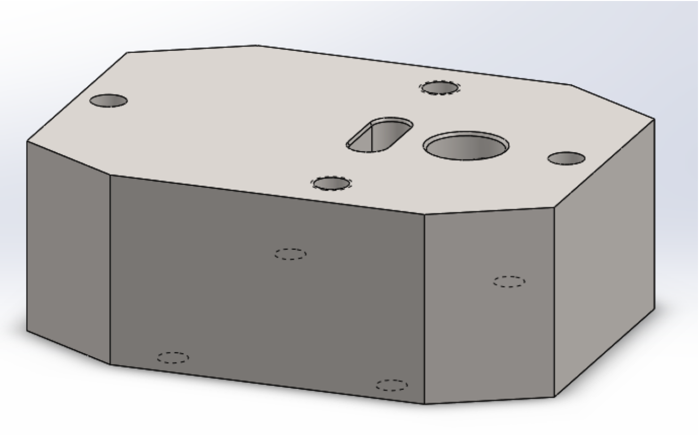


Figure 12: EGR Adapter Block

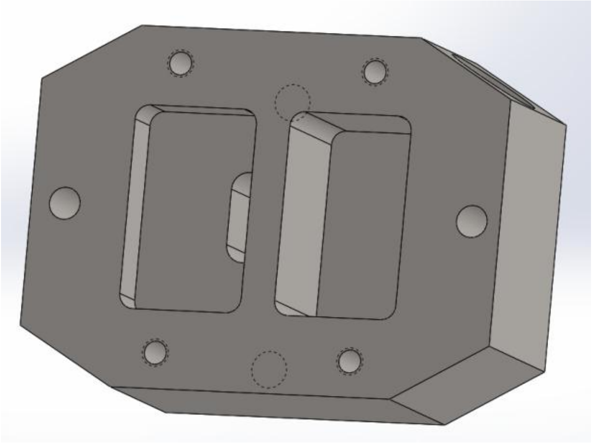


Figure 13: EGR Flow Area into Cooler

ELECTRONICALLY CONTROLLED THROTTLE

Electronically controlled throttle removes the mechanical connection between the throttle lever and the throttle blade and replaces it with a closed-loop computer-controlled servo motor. The user still uses the stock Polaris thumb-throttle lever, but the cable moves a spring loaded Foot Position Sensor (FPS) sourced from a 2007 Acura TL. Because of the severe consequences of a sensor fault, there are *two* redundant, linear 0-5V analog FPS outputs, called FPS (Main) and FPS (Sub). At zero throttle input, FPS (Main) and FPS (Sub) output 0V and 5V respectively; at 100% throttle input they read 5V and 0V respectively. The same is true for the Throttle Position Sensor (TPS) – there is a TPS (Main) and TPS (Sub), both of which are non-contact hall-effect sensors. This sensor configuration allows the ECU to continually monitor both FPS and TPS for correlation errors. If an error is found, the electronic throttle relay loses its ground, and the throttle body faults. This causes the ECU to force a “Limp Mode” and engine speed will not exceed 1800 RPM as a fail-safe.

Figure 14: Acura TL FPS. Note the cable actuation. This is a somewhat unique design

Figure 15: Delphi Gen 6 Electronic Throttle Body

The electronic throttle control gives the ECU total control over the throttle blade angle, giving the calibration engineer greater flexibility to improve drivability, reduce emissions, and reduce driveline noise; all while adding control features (cruise control, selectable ramp rate) and eliminating costly componentry. Drivability can be optimized with precise PID (proportional-integral-derivative) tuning, and with multi-axis throttle target tables. Fuel economy is increased because accidental low-load acceleration enrichment is reduced by filtering throttle input during low engine speed operation. Because the ECU commands all throttle changes, transient emissions are generally reduced. Drivability is also improved during a lean-cruise or warm-up event; when fuel input is reduced, engine performance suffers and the ECU can open the throttle accordingly without the user ever noticing the change. "Tip-in" ramping reduces driveline shock and noise, allowing for cheaper, less robust mounts, bushings, may improve drive-belt life and keeps operating noise down. Closed loop idle is also achieved without the use of costly idle stepper motors and controllers, which may require reset programming procedures upon engine shutdown.

FLEX FUEL IMPLEMENTATION

A requirement for the 2013 Clean Snowmobile Challenge is that the snowmobile must accept any fuel between 40% and 85% ethanol. E85 requires more fuel mass-flow than gasoline due to its lower stoichiometric ratio and the stock fuel system could not maintain the flow rates required during high-load situations. The consequences of an undersized fuel system can cause a lean condition at max power which will raise combustion temperatures, cause detonation, and possibly severe engine damage – to prevent this the fuel system was upgraded accordingly. It was determined that the maximum design injector duty cycle should be no more than 80% to ensure a long injector service life, and to allow for more power output if future upgrades or rule changes allow. Fuel Injector Clinic's saturated 1100 cc/min injectors met these requirements nicely. It was also determined that an auxiliary Walbro 155lph fuel pump was required to support the new fuel supply requirements.

The design intent for flex-fuel functionality was to optimize the engine calibration for varying mixtures of ethanol content with zero input. The calibration adjusts spark advance, lambda targets, cold start enrichment, and boost targets based on the output of the Haltech ethanol content sensor. This sensor outputs a square-wave signal, where frequency (Hz) equals ethanol content percentage, and pulse width (ms) equals fuel temperature. The control system is also closed loop with a Bosch LSU4.2 Universal Exhaust Gas Oxygen sensor (UEGO). This sensor allows accurate AFR measurement from .75 to 1.15 Lambda regardless of fuel type. The interface between the ethanol content sensor, UEGO and the ECU will allow for optimized power, emissions, and fuel economy no matter what ethanol mixture the fuel supply is.

Figure 16: Haltech Ethanol Content Sensor (By Continental) and Bosch LSU 4.2 UEGO Sensor

MUFFLER DESIGN

Sound output levels are weighted heavily during the Clean Snowmobile Challenge, as excessive noise is one of the primary complaints with snowmobiles. Because the majority of snowmobiles are recreational vehicles, the average consumer does not give much thought to the sound which their machine outputs, and sometimes will even add an aftermarket exhaust system to their machine in order to gain more performance, which almost always adds to the noise output of the engine. Muffler design is difficult, as it is very give and take when it comes to the relationship between power and sound. Mufflers need to be free flowing in order to minimize backpressure and maximize horsepower, however by doing this, the louder a muffler will be. Quiet mufflers tend to interrupt the flow of exhaust, increasing backpressure, and decreasing power output of the engine.

To combat this problem, RIT designed and fabricated a custom four chamber muffler with an integrated cartridge catalyst. The design was originally 3D modeled in SolidWorks in order to test multiple designs. After the best design was chosen based off of design simplicity, performance, and ease of manufacture, the design went through several different possible flow situations, shown in Figure 18. Parameters used for the flow analysis were created based off of the theoretical mass flow rate of the GT15V turbo charger.

RIT's muffler design features a "Cup and Ball" socket for attachment to the down pipe, which is identical to the joint found on the stock FST muffler. Once the exhaust gas flows into the socket, it immediately enters the catalyst, then into the first chamber. After entering the first chamber, the gas is guided into a downward tube which features a velocity stack in order to promote laminar flow into the tube. The top half of the first down tube is solid core piping to prevent the gas from entering the wrong chamber. Once the gas passes through the length of solid pipe, it flows through a perforated core to damp the high frequency sound waves. The second chamber features nine holes on the roof which the exhaust gas must flow through. This second chamber is highlighted by a low velocity vortex in in the exhaust flow. This vortex helps to restrict the flow of exhaust by damping sound waves; this however will result in a reduction in overall power which was not considered an issue based off the stock power output of the Weber engine.

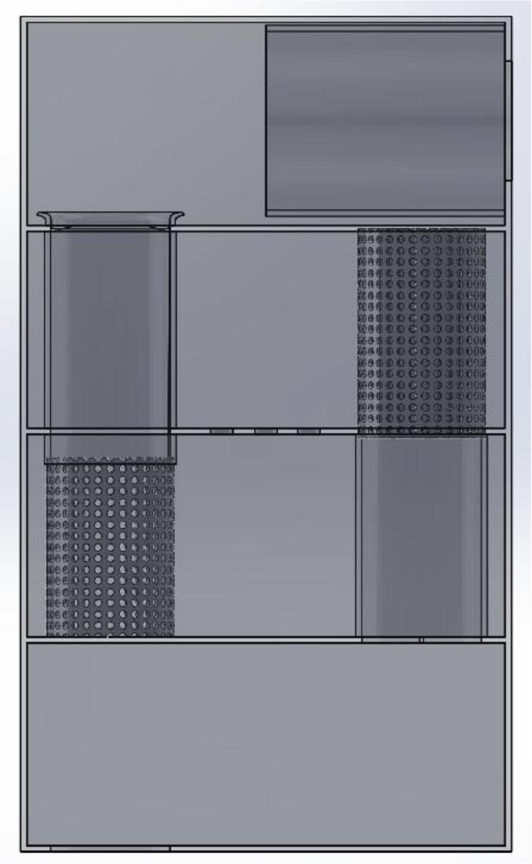


Figure 17: CAD Model of RIT Muffler

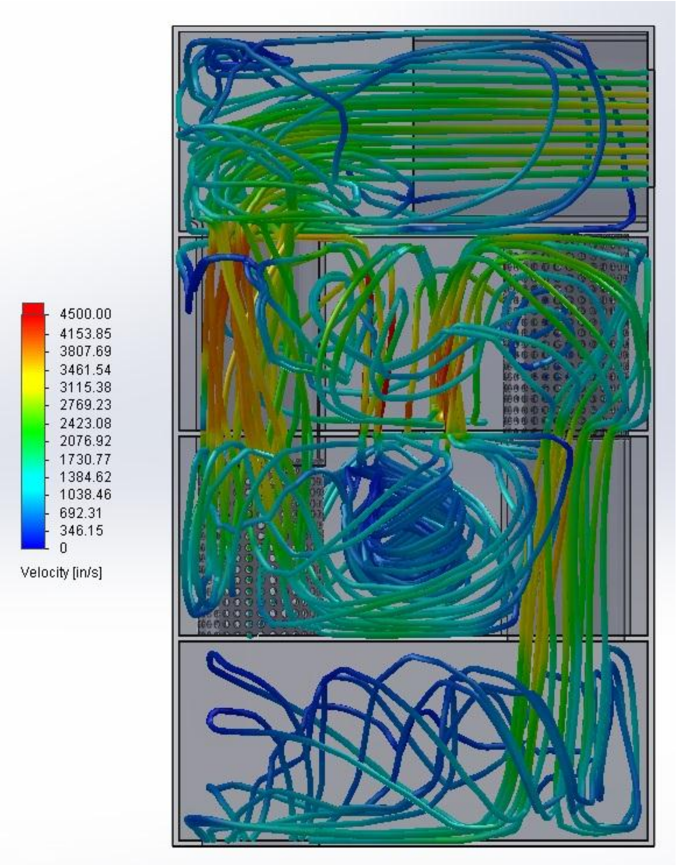


Figure 18: CAD Model of RIT Muffler

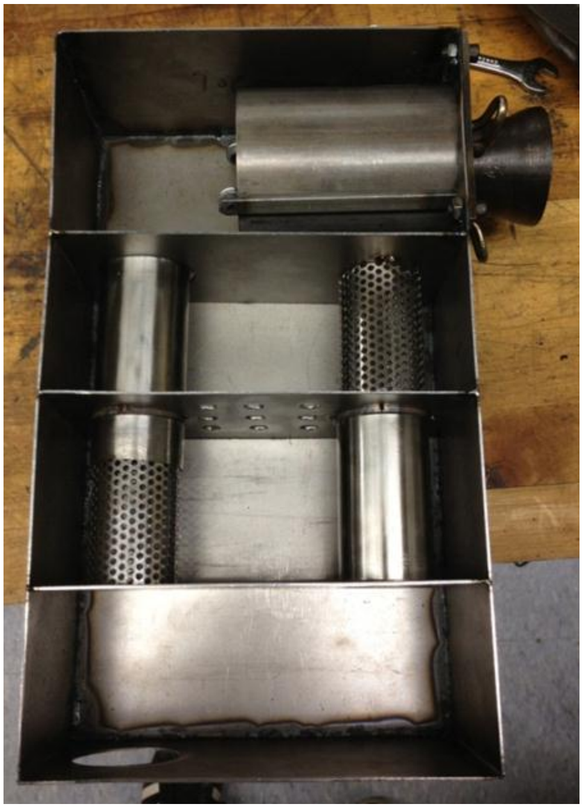


Figure 19: Completed Muffler

EMISSIONS CONTROL

In order to meet the stringent emission standards which are placed on the snowmobiles at the Clean Snowmobile Competition, a catalyst is all but mandatory as they do an excellent job of decreasing the amount of harmful chemicals exiting the exhaust system. The rate at which a catalyst works is directly affected by the temperature which the catalyst reaches, because of this; catalysts are generally placed close to the engine to maximize the amount of heat which they receive. Because of size constraints, as well as maintenance requirements, RIT chose to design a new system to integrate the catalyst into the muffler. This was accomplished by designing a clamp system which allows for the catalyst to be clamped into a fixture that includes the “Cup and Ball” connector. This cartridge can then be bolted into the muffler from the outside.

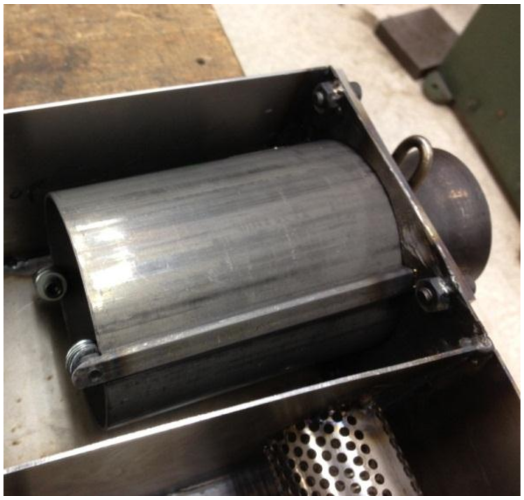


Figure 20: Cartridge Catalyst

SUMMARY/CONCLUSIONS

By implementing new technology including a variable geometry turbocharger, cooled exhaust gas recirculation system, flex fuel capability and RIT designed muffler onto the already proven Polaris FST engine, the RIT Clean Snowmobile team was able to create a power train which will not only increase fuel economy and lower emissions, it will also be incredibly fun to ride for a potential consumer. By installing this power train into Polaris' state of the art Pro Ride chassis which features the first ever fully progressive rising rate rear suspension on a snowmobile, the RIT Clean Snowmobile team is confident that if put into production and offered to the public, this machine would be popular with the snowmobile industry for years to come.

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ACKNOWLEDGMENTS

The RIT Clean Snowmobile Team would not have been possible without the incredible support of RIT Student Government, President Bill Destler, our advisor Dr. James Lee, Dr. Alan Raisanen, Dr. Mary Beth Cooper, Nathan Theiss, Steve Kosciol, Carol Giuliano and the RIT Club Office, The College of Applied Science and Technology (CAST), and the Center for Integrated Manufacturing Studies (CIMS).

The team would also like to thank each and every one of our sponsors who made the idea for this team into a reality. Polaris, Honeywell, Curve Industries, Innovative Tuning, Aristo, WNY Energy, NYS Snowmobile Association, SolidWorks, Castle X, Fuel Injector Clinic, MAPerfomance, NGK, Weber Power, Myles Tool, Eazy Move Sled Carts, Synapse Engineering, Advanced Automotive, DynoTech Research, SlyDog, and Factory Pipe.

DEFINITIONS/ABBREVIATIONS

EXX	An ethanol content rating. E100 = pure ethanol. E85 = 85% ethanol.
EGT	Exhaust Gas Temperature
EGR	Exhaust Gas Recirculation
VGT	Variable Geometry Turbo charger
FST	Four Stroke Turbo
SAE	Society of Automotive Engineers