Applying Lean Six-Sigma DMADV Methodology to the Design Cycle of a High-Efficiency, Low Emissions Snowmobile

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Abstract

For the 2016 SAE Clean Snowmobile Challenge, the Rochester Institute of Technology Clean Snowmobile Team (RIT CST) has designed and fabricated a quiet, low-emissions and highly efficient snowmobile using the Lean Six-Sigma process known as the DMADV. The design which resulted from this process was a Polaris Pro RMK chassis with a turbocharged Weber 750 engine. The engine was modified to include a Honeywell MGT1238Z turbocharger, cooled low pressure EGR, and capable of running with varying ethanol content.

Introduction

After years of controversy between environmentalists and snowmobile enthusiasts, the Federal Park Services at Yellowstone National Park banned the use of snowmobiles in the park due to concerns over noise and environmental pollution [1]. Due to this injunction, the Society of Automotive Engineers (SAE) created the Clean Snowmobile Competition (CSC), which allows colligate teams to develop more environmentally friendly snowmobiles, which are marketed for environmentally sensitive areas, such as those found in National Parks and other protected areas. These experimental designs are used to test the implementation of cutting-edge technology into snowmobiles, which could eventually be implemented into production snowmobiles.

The CSC is a week-long competition that consists of both static and dynamic events, which address the emissions, noise, and efficiency concerns of the snowmobile industry by developing innovative, robust, and economical design solutions. The colligate design teams are not only challenged by these events, but also by the short design cycle time, financial and resource constraints, and the turnover of students due to graduation. Due to these challenges, a system that allows for simpler and shorter design periods, as well as a well-documented decision making process is important to implement. For these reasons, the RIT CST has implemented the Lean Six-Sigma 'DMADV' process at the systems and subsystem level.

Lean Six-Sigma DMADV Process

Recently, there has been a push in industry to create manufacturing and design processes that reduce the amount of time and resources that are needed in order to create a reliable, well-designed, and desirable product. To assist these new ideals, the Lean Six-Sigma methodology was created. Lean Six-Sigma is a combination of two models, Lean and Six-Sigma. Lean is a practice that stresses the elimination of waste from a process, while Six-Sigma is a set of tools that promotes product quality improvement. When these processes are combined, they form two acronym-driven processes, the DMAIC (Define, Measure, Analyze, Improve, Control) process and the DMADV (Design, Measure, Analyze, Design, Verify) process.

DMAIC is used to improve an existing process, while DMADV is used to design a process or product correctly the first time. Due to this use, the RIT Clean Snowmobile Team decided to use the DMADV process to design a new snowmobile for this year's competition.

The DMADV process is composed of five phases, which each have their own goals and purposes. Listed below is a breakdown of each phase:

1. **Define** – During the Design stage the main objective is to set the main objectives of the system being deigned. Also, during this phase the scope of the project and time line of major events are established.
2. **Measure** – During the Measure stage, customer feedback is collected and customer requirements for the product are determined.
3. **Analyze** – During the Analyze stage, customer requirements are transformed into required product specifications. Also, concepts and innovative technology are analyzed to find competitive advantages. This is done by benchmarking competitor's products and creating a competitive analysis.
4. **Design** – During the Design phase, subsystems are designed to meet the product specifications determined to give the greatest advantage during the analyze phase. Simulation, models, and prototypes guide design.
5. **Verify** – During the Verify Stage, the designs are tested to ensure that they are working correctly and meet customer requirements.

Define Phase

To define the objectives and scope of the snowmobile being designed, the RIT CST turned to the SAE CSC Rulebook. The rulebook calls for the snowmobile to have reduced emissions and a reduced noise signature, as well as improved fuel efficiency.

As the rules state, the scope of this project is limited to model year 2012 to 2016 production snowmobile chassis, manufactured by one of the four major snowmobile manufacturers. Along with this, the rules also limit the snowmobile to a maximum power of 130 horsepower [2].

To establish a project timeline, a Gantt chart was created to establish a schedule of deadlines. The completed snowmobile was required to be in competition on March 7th, 2016.

Measure Phase

One ideology used in the DMADV process is Voice of the Customer (VOC), which is simply what the customer desires in the final product. To find these requirements, normally market research is conducted in the form of customer surveys and interviews. Depending on the responses to the surveys and interviews, customer requirements are established and ranked by importance based on the feedback. However, due to the SAE CSC Rulebook defining the "customer requirements" for the CSC, the RIT CST used the scoring rubric as the requirements for the snowmobile and the maximum possible score for each event to rank the requirements by importance. However, static events were eliminated from the requirements, as they have no influence on design decisions.

These customer requirements found with the VOC are then restructured into Critical to Customer (CTC) categories. This restructuring creates categories that have clear design objectives, which can be targeted by individual technical specifications during the analyze and design phases. Table 1 displays the CTC categories and their maximum point value. The maximum point values are combinations of the CSC rules maximum points that could be awarded to an area of each event. For example, the maximum points for fuel efficiency are a combination of the maximum scores for the Brake Specific Fuel Consumption, In-Service Fuel Economy and Fuel Economy and Endurance events.

Table 1. Critical to Customer Point Distribution

Critical to Customer	Maximum Points
Low Emissions	350
Quiet Operation	300
Fuel Efficient	200
Reliable	200
Sport-Trail Handling	100
Affordable Retail Price	50
Quick Acceleration	50
Easy Cold-Starting	50
Innovative Design	25

Figure 1 displays a Pareto chart of the CTC requirements, which was created in order to display the importance of each CTC in relation to the others. According to the Pareto Principle, it is beneficial to target the requirements that make up 80 percent of the total value of a whole [3]. Applying this to the Pareto chart, the RIT CST discovered that it would be most advantageous to target the CTC requirements of low emissions, quiet operation, fuel efficient, and reliable.

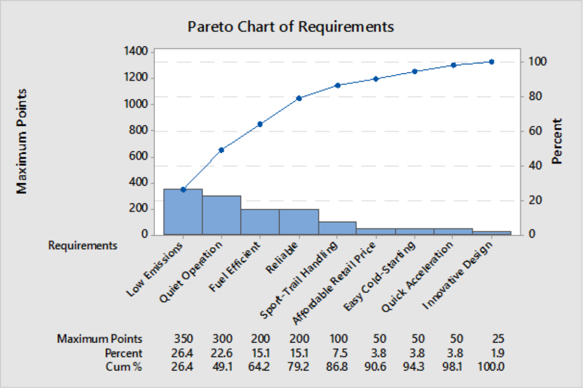


Figure 1. Pareto Chart of Critical to Customer Requirements

Analyze Phase

After finding the CTC and deciding which areas to target, the RIT CST began the analyze phase of the DMADV process. During this phase, the CTC were transformed into technical specifications for the sled by using Lean Six-Sigma tools, such as competitive benchmark, quality function deployment and a Pugh Matrix. These tools allowed the team to set specific performance based goals and to decide what technologies to implement in order to reach these goals.

Table 2. Critical to Customer Point Distribution

2015 Competative Benchmark with RIT CST 2016 Targets (0 = Worst, 5 = Best)						
Requirements	U of W. Madison. (1st 2015)	Kettering Univ. (2nd 2015)	ETS (3rd 2015)	U of Minn. Duluth (4th 2015)	Univ. of Idaho (5th 2015)	RIT Targets for 2016 CSC
Low Emissions	4	3	1	2	0	5
Quiet Operation	3	4	1	0	2	5
Fuel Efficient	4	5	2	0	1	3
Reliable	5	5	0	5	5	5
Sport-Trail Handling	4	0	2	1	5	3
Affordable Retail Price	1	4	5	0	4	2
Quick Acceleration	1	0	2	5	4	3
Easy Cold-Starting	5	5	5	5	5	5
Innovative Design	0	0	0	0	0	5

With the competitive benchmark analysis complete and the CTC and design targets identified, a quality function deployment (QFD) was completed in order to set technical goals for the snowmobile design. The completed QFD is shown in Figure 2. This relates the CTC categories into Critical to Quality (CTQ) characteristics. The QFD also displays the relationships between each CTC and CTQ. These relationships were established by the team’s understanding of the CTQ and how they affect the CTC.

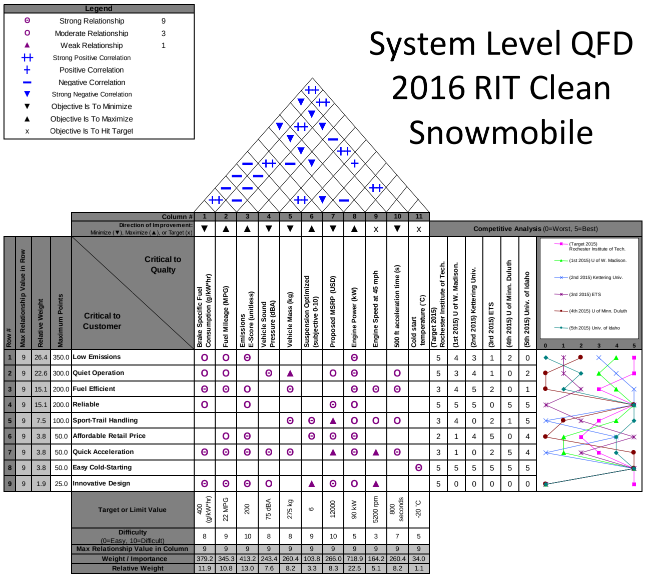
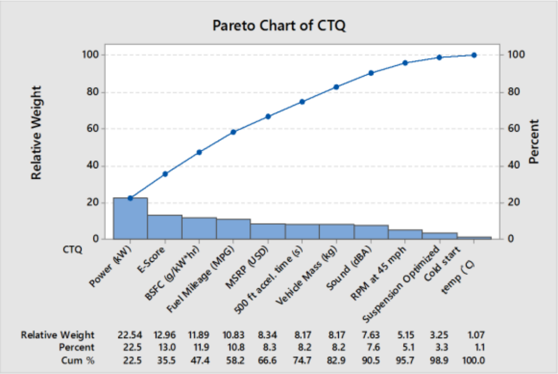


Figure 2. System Level Quality Function Deployment

The QFD allowed the RIT CST to calculate the “relative weight” of each CTQ, which quantifies how important each characteristic is to the overall performance of the snowmobile as a system. These weights were calculated based on the maximum points possible for the CTC, the amount of relationships between the CTCs and CTQs, and the strength of those relationships. The purpose of the relative weight is not to show the importance of the CTQ, but to display how sensitive the system is to a change in that CTQ. For example, engine power has the highest importance, and the direction of improvement is ‘maximize’. However, this weight does not mean that power is the most important thing to optimize – rather it indicates that power has so many negative impacts on CTCs that the system is most sensitive to this CTQ. In other words, it is most important to set engine power to a level which will give you the emissions, efficiency and sound responses that are desired.

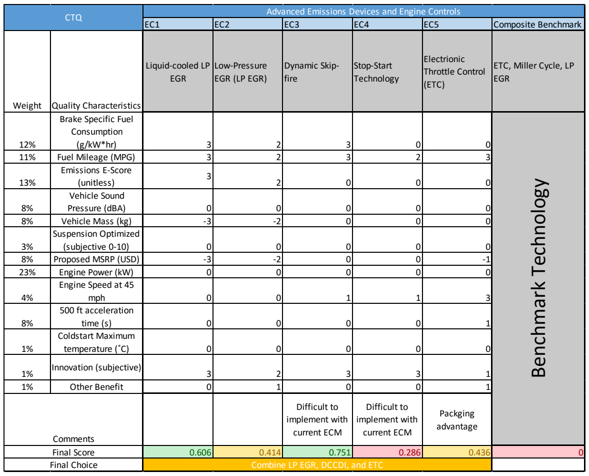
To assist in identifying the CTQ requirements to target, another Pareto chart was created to display where to focus the RIT CST’s resources. By again applying the Pareto Principle to this Figure 3, the most important CTQs to optimize are Engine Power, Emissions E-score, Brake Specific Fuel Consumption, and Fuel Mileage.



Relative Weight	22.54	12.96	11.89	10.83	8.34	8.17	8.17	7.63	5.15	3.25	1.07
Percent	22.5	13.0	11.9	10.8	8.3	8.2	8.2	7.6	5.1	3.3	1.1
Cum %	22.5	35.5	47.4	58.2	66.6	74.7	82.9	90.5	95.7	98.9	100.0

Figure 3. Pareto Chart of Critical to Quality Characteristics

A Pugh Matrix was used to compare existing technology and identify opportunities to introduce new innovative designs and gain a competitive advantage for the 2015 Clean Snowmobile Challenge. Typically, a Pugh Matrix compares a single benchmarked technology or product to potential concepts for a future product design. These concepts are then weighed against the benchmark for each CTQ, and a winner is objectively identified with a -3 to +3 “worst to best” scale. However, RIT CST decided to create a composite of the top 5 snowmobiles for this system-level application and benchmark RIT’s 2015 concepts against it.



CTQ		Advanced Emissions Devices and Engine Controls					
		EC1	EC2	EC3	EC4	EC5	Composite Benchmark
Weight	Quality Characteristics	Liquid-cooled LP EGR	Low-Pressure EGR (LP EGR)	Dynamic Skip-fire	Stop-Start Technology	Electrionic Throttle Control (ETC)	ETC, Miller Cycle, LP EGR
12%	Brake Specific Fuel Consumption (g/kW*hr)	3	2	3	0	0	Benchmark Technology
11%	Fuel Mileage (MPG)	3	2	3	2	3	
13%	Emissions E-Score (unitless)	3	2	0	0	0	
8%	Vehicle Sound Pressure (dBA)	0	0	0	0	0	
8%	Vehicle Mass (kg)	-3	-2	0	0	0	
3%	Suspension Optimized (subjective 0-10)	0	0	0	0	0	
8%	Proposed MSRP (USD)	-3	-2	0	0	-1	
23%	Engine Power (kW)	0	0	0	0	0	
4%	Engine Speed at 45 mph	0	0	1	1	3	
8%	500 ft acceleration time (s)	0	0	0	0	1	
1%	Coldstart Maximum temperature (˚C)	0	0	0	0	0	
1%	Innovation (subjective)	3	2	3	3	1	
1%	Other Benefit	0	1	0	0	1	
Comments				Difficult to implement with current ECM	Difficult to implement with current ECM	Packging advantage	
Final Score		0.606	0.414	0.751	0.286	0.436	0
Final Choice		Combine LP EGR, DCCDI, and ETC					

Figure 4. Example of Pugh Matrix for Advanced Emissions Devices and Engine Controls

Individual Pugh Matrices were created for each subsystem, and a final product design summary was created from the output. An example subsystem Pugh Matrix is shown in Figure 4.

The highest scoring concepts were taken from the subsystem Pugh Selection Matrices and RIT CST’s 2016 system design summary was created. This summary is an overview of the technology and concepts that RIT CST decided to pursue for use in the 2015 Clean Snowmobile Challenge. The design summary can be seen in Table 3 alongside the 2015 Clean Snowmobile Composite Benchmark.

Table 3. Design Summary

Design Summary		
Category	2016 RIT	Composite Benchmark
Base Chassis Selection	Polaris PRO RMK	Ski-Doo MXZ Sport
Base Engine Selction	Weber 750cc Turbo	600 ACE w/turbo
Shock Selection	Walker Evans	Motion Control
Turbocharger	Honeywell MGT1238Z	Honeywell MGT1238Z
Aftertreatment	3-way catalyst	3-way catalyst
Advanced Emissions Devices and Engine Controls	LP EGR, ETC	ETC, Miller Cycle
Fuel Strategy	Lean-Burn	Lean-Burn
Noise Treatment	Combine Absorbtive and Resonant	Stock
Flex-Fuel Modifications	Closed loop lambda sensor correction	Fuel quality sensor
Ski Choice	Curve XS	C&A RZ
Track Choice	Camso Cobra	Camso Ice Attack XT

Design Phase

After establishing the most desirable technologies, the RIT CST continued into the design Phase, where concepts were fully developed into components. This is where simplified models, simulations, and prototypes were used to guide the design of each respective component and system.

Engine

The base engine selected for the 2016 RIT Clean Snowmobile was the Weber 750 MPE in the turbocharged high-output configuration. In stock form this engine boasts an impressive power density of 1.54 kW/kg, as well as brake specific emissions that nearly meet minimum CSC levels. RIT CST believed that this engine could provide the best combination of power, reliability, efficiency and emissions required to be successful in the Clean Snowmobile Challenge. The Weber 750 MPE had several design features that made it attractive for this application. Frictional losses are minimized by the extensive use of roller-bearings in components such as the camshaft and gear-drive, and a dry-sump oiling system ensures reliable lubrication while minimizing windage losses on rotating components.

Table 4. Base Engine Comparison

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					

In stock form the Weber 750 HO exceeds the power limit imposed in section 1.3.4 of the 2016 CSC rules. The RIT CST decided that the best way to maintain acceleration performance while minimizing fuel usage and emissions production was a high-dilution strategy demonstrated by Southwest Research Institute's HEDGE-II (High-Efficiency Dilute Gasoline Engine, Stage II) research consortium [4]. This strategy included a low-temperature combustion and the dilution limits of a boosted gasoline engine. The results were 10-30% improved BSFC through reduction of pumping losses and improved combustion phasing, elimination of low-speed knock, and reduced emissions through lower temperature combustion. This research was the inspiration for RIT CST's powertrain design believe it will be the future of light-duty engines [5].

Figure 5. Weber 750 MPE Engine

Simulation

In order to make informed design decisions RIT CST created a 1-D engine simulation using GT-Power, a software developed by Gamma Technologies. This software provides the ability to simulate for different scenarios the engine will face during the competition. It can be used to optimize design parameters and improve the design. Predictive combustion modeling allows the team to focus on improving the efficiency of the combustion process. It also aids in determining properties and composition of exhaust gas. The model was refined using dyno data from the 2015 engine build and updated to reflect changes for 2016. This model was used to validate design changes including intake manifold design, muffler design, turbocharger selection, and implementation of the cooled EGR system. The use of simulation software allowed the RIT CST to compare design changes in order to select the best option without the expense of physical engine testing. Engine simulation also allowed the team to investigate the effects of running different fuel mixtures and EGR percentages in a quick and easy manner. The model is not sufficiently refined to provide absolute measurements, however, it is a very useful tool for exploring comparative differences. In the future, RIT CST plans on integrating chassis, clutching, and coolant system models to provide a comprehensive model of the snowmobile.

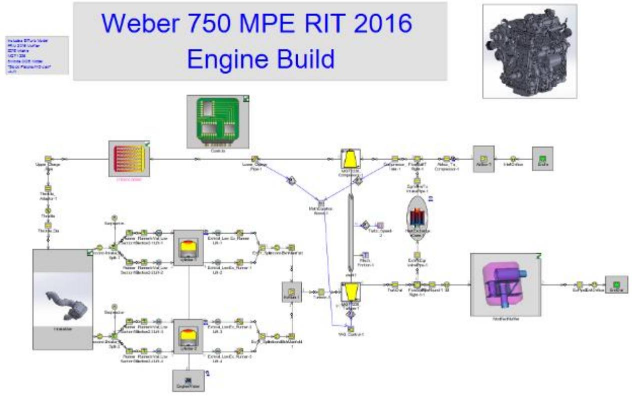


Figure 6. RIT CST Simulated 2016 Engine Build

Turbocharger Selection

For the 2016 build, RIT CST selected an internal wastegate turbocharger, the Honeywell MGT1238Z. In 2015 the team ran a GT1749V, a variable geometry turbocharger from Honeywell. This proved to be a poor match due to uncontrolled boost levels. Even when low boost was commanded, approximately 27 psi of boost would result. There was difficulty controlling the vanes with the hydraulic actuator. Also, high exhaust temperatures caused the vanes to seize. RIT CST is still interested in the technology, but until a better control strategy is developed and the effects of EGR are fully understood, a wastegate turbocharger will be the best option. A wastegate turbocharger provides the control and durability characteristics the RIT CST desires.

The MGT1238Z selection was determined through engine simulation. A simulation was executed to optimize the turbocharger for optimal performance in the 5-mode emissions event outlined in section 9.6.3 of the 2016 rules. Due to the high weight this event is given in the point structure it was determined to be the best event to optimize for. Additionally, EGR was set up to range from 0-20% and ethanol content was varied per the rules of the competition (0-75%). This provided the team with a full range of possible conditions under which the engine would be running. Results were plotted on both the compressor map as well as the turbine map. The plots indicate the MGT1238Z being a very good match for RIT CST’s 2016 engine build.

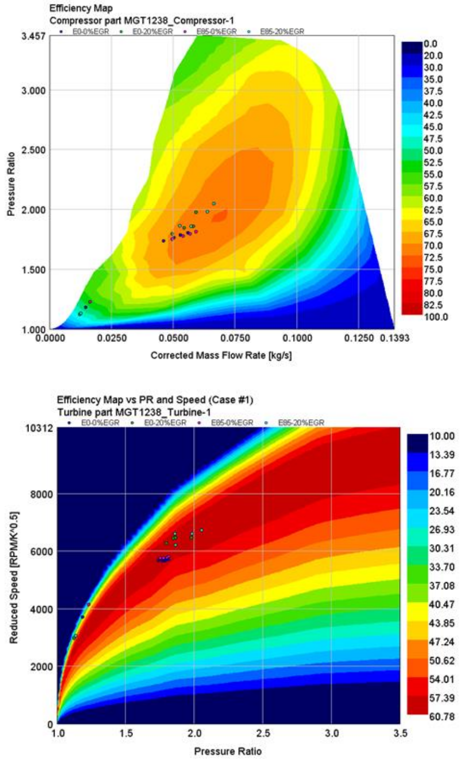


Figure 7. MGT1238Z Compressor and Turbine Maps with Simulation Data

Electronic Throttle Body

A single Delphi electronic throttle body (ETC) replaced the stock dual manual throttle bodies mounted between the intake plenum and cylinder head. The ETC was mounted upstream of the intake plenum for packaging reasons, allowing the plenum to be mounted directly to the intake runners and creating clearance between the plenum and gas tank. RIT CST acknowledges the change intake runner design changes the tuned length, but this compromise was required to fit the engine into the Polaris Rush chassis.

Electronic throttle control was selected because it allows the ECM to filter throttle changes and reduce the amount of acceleration enrichment required during normal operation. It also allowed for the air-flow profile of the throttle body to be linearized to the sensor output from the thumb throttle.

Intake Manifold Design

In the 2015 engine build, the RIT CST design included a flow restriction after the throttle body as a result of using a stock intake plenum with the ETC. Additionally, the rubber hose which connected the throttle body to the plenum contained a spring that while necessary to prevent collapse, was also disruptive to flow. For the 2016 design new intake manifold was created to remove this restriction and also provide more clearance to the gas tank.

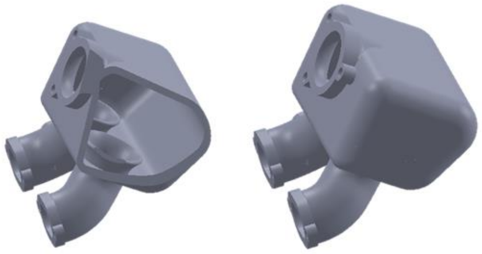


Figure 8. 2016 RIT CST Intake Manifold Design

Through simulation RIT CST was able to determine that plenum volume did not have a significant impact on volumetric efficiency, power, and torque, so it was designed to be 1.6L (as opposed to 1.5L stock) as a result of packaging. Integrating the runners allowed for a smooth transition and improved packaging. Flow simulation was conducted to ensure that both cylinders were receiving the same amount of air. Removing the flow restriction showed an increase in power of 3kW over the 2015 design.

Cooled Low Pressure EGR

A cooled low pressure EGR system was utilized for implementing the high-dilution strategy. EGR is deemed to be a crucial component in controlling combustion temperature. Low pressure EGR takes exhaust gas after the turbocharger turbine and inserts it into the intake system before the turbocharger compressor. The RIT CST 2015 build did not include a properly functioning cooled EGR system and as a result exhaust gas temperatures were far too high and component failures resulted. For the valve itself, a poppet valve regulates EGR flow by changing flow area depending on load and engine speed. Flow simulation was conducted on the valve to determine the amount of air that can flow through the valve in various positions and the system is empirically calibrated based on position. The valve is mounted directly to the turbocharger compressor which provides a vacuum to draw the exhaust gas into the intake system.

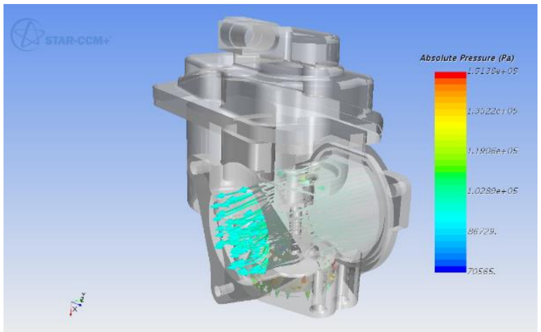


Figure 9. EGR Valve Flow Simulation

The system is equipped with an EGR cooler to reduce the temperature of the gas. RIT CST discovered in 2015 that the charged air cooler did not provide the cooling capacity expected, therefore it was necessary to cool the EGR before it enters the intake air. A crowded bulkhead prevented the appropriate amount of air from reaching the charged air cooler. Also high temperature gas at the inlet of the turbocharger compressor could lead to a failure of the aluminum compressor wheel. As a result, it was deemed necessary to implement an EGR cooler in the 2016 design. The cooler will be used to lower EGR temperature to approximately 70°C, which is near the condensation temperature of exhaust gas [6]. Due to gas temperature approaching the condensation temperature of exhaust gas [6]. Due to gas temperature approaching the condensation point, a concern is resulting corrosion due to Nitric Acid. This is an issue RIT CST is familiar with from past experimentation with cooled EGR. To help counteract this, exhaust gas is now extracted after the catalyst which reduces NOx emissions that cause the corrosion. Also the cooler is placed at a lower elevation than the valve to prevent condensation from draining into the intake system and potentially damaging the turbocharger.

Muffler Design

For the 2016 competition, RIT CST developed a new muffler design intended to significantly reduce noise output. In doing that, a compromise must be made between noise suppression and exhaust back-pressure. The challenge faced in design is that those two are often directly related such that a muffler with better sound performance is likely to provide greater back-pressure. The muffler was developed using GEM-3D and GT-Power for simulating many different design iterations.

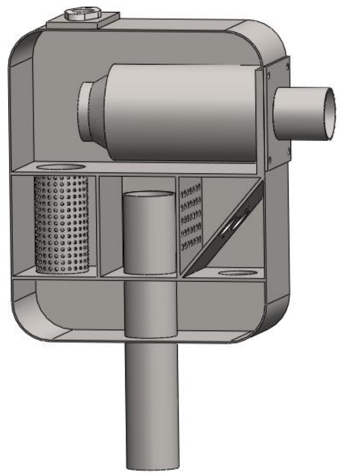


Figure 10. 2016 RIT CST Muffler

The muffler was designed with several chambers and baffles designed to cancel out different frequencies. This is a very effective method for canceling out sound waves [7]. Software allowed RIT CST to iterate through changes in chamber volumes, baffle geometry and placement as well as hole and pipe diameters in a quick and cost effective manner.

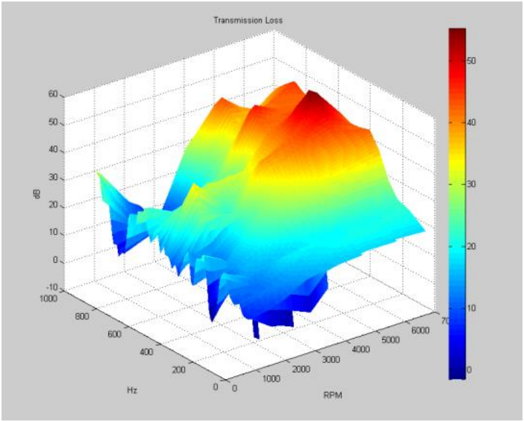


Figure 11. Simulated Muffler Performance

RIT CST reduced the size of the muffler for 2016 in order to reduce the risk of melting side panels. Also, the catalyst is sleeved into the muffler as a removable section so it can be changed out quickly and easily in the case of a catalyst failure. During the 2015 competition the team suffered a catalyst failure and due to their fixed nature, no corrective action was possible. The 2016 design was compared to the 2015 version and performed notably better in sound suppression with only a slight increase in added back pressure.

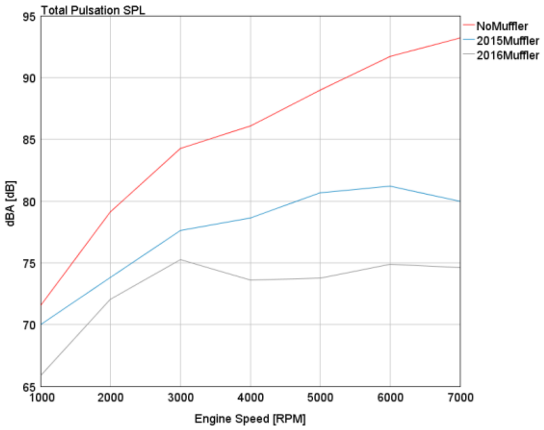


Figure 12. Muffler dB Comparison

Aftertreatment

RIT CST selected a 3-way catalyst for the 2016 Clean Snowmobile Challenge. The catalyst was chosen to reduce emissions in the form of HC, CO, and NOx. A 3-way catalyst was selected due to the high amount of NOx that are formed in the combustion chamber during operation. The precious metals used will allow for a reduction in NOx to form O_2 and N_2, an oxidation of CO and O_2 to form CO_2 and final HC to be converted into CO_2 and H_2O. This will reduce the overall emissions make the snowmobile more environmentally friendly.

Operating with Flex Fuel

Ethanol “flex-fuel” operation over an operating range of 0-85% ethanol/gasoline blend is required as per Section 1.2 of the 2016 CSC rules, with no user input to the engine management system required. This flexibility is friendlier for the consumer, since they do not need to worry themselves with what blend of gasoline they have purchased, and to the environment, since these Flex-Fuel engines can take advantage of the emissions, performance, and renewable-energy benefits of ethanol fuels. However, there are several challenges to implementing flex-fuel strategies due to the large differences between gasoline and ethanol’s chemical properties. First, the large difference in stoichiometric air-fuel ratio of E0 and E85 (14.7 and 9.76 AFR, respectively) and the significant differences in distillation curves requires the fuel delivery to adapt to changing mixture on-the-fly. The fuel system must be properly sized to support the additional injected mass of fuel to both achieve stoichiometry and to promote vaporization into a combustible mixture. Vaporization is especially important for cold-start performance in low-temperature applications, such as a snowmobile. Second, ethanol has a significantly higher octane rating than gasoline, promotes lower in-cylinder temperatures due to its vaporization characteristics, and has different combustion characteristics that require different ignition strategies. The engine control system must be capable of adjusting ignition advance to MBT (Maximum Brake Torque) or KLSA (Knock-Limited Spark Advance) depending on the ethanol/fuel mixture. This is important in order for the engine to always run at optimal efficiency, emissions, and for thermal/durability constraints.

To achieve flex-fuel capable fuel control, RIT CST chose to minimize system cost while still retaining a high-performance system by leveraging the Technical Services Entrol 88 engine controller’s closed-loop and block-learn memory capability, without adding any additional flex-fuel sensor. For this strategy to work, a closed-loop lambda sensor control is used at idle. The ECM uses the feedback from the lambda sensor to trim the injected fuel mass to the desired Air-Fuel Ratio, specified during calibration. The lambda sensor feedback system is used to control how much fuel is injected [8]. This strategy only works when the engine has entered into closed-loop mode, so is not a robust method of fuel control for all situations.

However, this short-term trim is constantly monitored over the engine’s runtime and the ECM determines (by the magnitude and duration of error) what the multiplier values in blocks of the fuel table should be. This is called “Block-Learn Memory (BLM).” RIT CST chose to leverage the BLM tables in a different way than intended. Rather than use the whole resolution of the speed-load table for several discrete local multipliers, the BLM for fuel was forced to contain only one cell. This allows snowmobile to trim itself at idle, apply a global fuel multiplier to all fuel tables, and effectively have a system which can detect ethanol content changes, correct them and constantly minimize error, and make predictive changes to the rest of the fuel table.

To accurately and effectively modify spark timing with respect to ethanol content, the OEM flat-response knock sensor was utilized. The Entrol 88 comes with capability to interpolate between a “high-octane” and “low-octane” fuel table, depending on severity and duration of knock. RIT CST calibrated both tables to MBT or KLSA, depending on whichever was the more conservative setting. E85 was used on the high-octane table, and E0 was used on the low octane table. This system works on the assumption that lower ethanol content fuels are more susceptible to spark knock due to a lower octane rating, and adjusts ignition timing accordingly. This system also utilizes a block-learn function which allows the ECM to command a spark advance, detect knock in a local region of the spark table, and write a block-learn modifier to prevent knock from occurring the text time the engine needs to operate in this region. The system then periodically seeks to advance timing to as close to MBT/KLSA as possible, and then updates the tables with the new feedback from the knock sensor. This method again, functions as a fully-optimized flex-fuel system which requires no additional sensors from stock configuration.

Chassis Selection

For the 2016 season, RIT CST chose a 2013 Polaris PRO RMK 155 as the base chassis due to its light weight and its bulkhead geometry. The forward bulkhead in this model is the same style used in the 2012 Rush chassis, used in past seasons. This allowed for a more familiar base for housing the Weber 750cc engine and its accessories. The largest difference is the tunnel and rear suspension. The Rush uses a progressive rate rear suspension while this year’s PRO RMK uses a traditional rear suspension housed completely under the tunnel. Another benefit was the PRO RMK’s use of an extruded aluminum drive shaft over the standard steel drive shaft found on most machines, which will help reduce overall weight. The PRO RMK’s “Quick Drive” belt driven system is the first of its kind on a production snowmobile and is 6.5 pounds lighter than a typical chain drive system.

Figure 13. 2013 Polaris Pro RMK

Skid Selection and Modification

Rather than using the 155” mountain specific skid, standard on the PRO RMK, RIT CST selected a shorter 144” rear suspension used by the 2015 Polaris Switchback Assault. A shorter rear suspension allows for smoother articulation of bumps and therefore a superior ride quality. In order to accommodate the 144” track and skid assembly under the Polaris Pro RMK 155 chassis, structural mounting points for the rear suspension were relocated. Two brackets are secured to both the inside of the tunnel and underside of the running board on either side of the chassis by steel rivets at a point where a suspension arm meets the tunnel. To mount the new skid, these brackets needed to be relocated forward by about 1.5”. This was accomplished by using a TIG welding process to install filler pieces in the weight reduction holes of the stock running boards. The filler pieces created a solid attachment point for the forward rivet in the mounting bracket. Existing holes in the bracket were utilized and new holes drilled in the tunnel for 1/4” stainless steel rivets. Existing holes in the brackets and running boards were also utilized with 3/16” rivets with the exception of the filler pieces where 3/16” holes were drilled.

Figure 14. Modified Mounting Points

Ensuring structural integrity was of the utmost importance in retrofitting the 144” skid. Rivets used from McMaster-Carr were of the sizes 1/4” and 3/16” with shear strengths of 1700lbs and 950lbs respectively. The 3/16” rivets in the running boards would be held in tension under any loading scenario resulting in a1200lb tensile strength each. Finite Element Analysis (FEA) was utilized to show how loading conditions would propagate through the tunnel and running boards. The tunnel and running board assembly was modeled using DSS SolidWorks focusing on the areas of concern. Using the SolidWorks Simulation Add-In, an FEA simulation was created. All parts were fixed together into a solid and meshed for analysis. A load of 200lbf was applied in an upward direction and a 100lbf was applied laterally on each suspension bracket to simulate a worst case loading scenario of about 447lbf acting on a diagonal to the track. The simulation was run assuming the material to be 6061-T6 aluminum and a Factor of Safety plot was created. This process was repeated for the stock configuration to provide a reference frame.

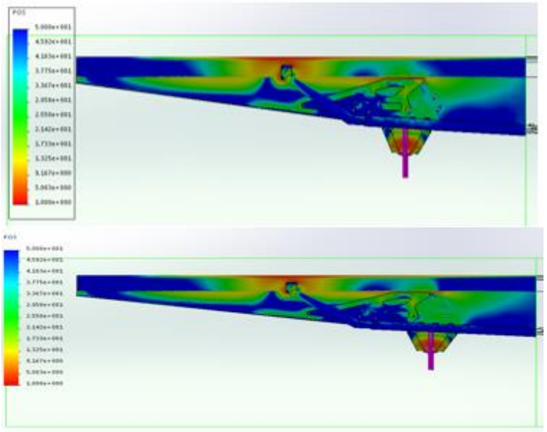


Figure 15. FEA Results (Top: Stock, Bottom: Modified)

The plot showed that safety factors in the areas of interest, ranged from 25 to above 50. However, other areas of the chassis model showed high stress levels. The same concentrations of stress were visible on both simulations and can be attributed to the simplification of the model and high loading. This evidence as well as robust design methods utilized allow for the conclusion that the rear suspension mount relocation for the RIT CST 2016 design is, as structurally sound as stock locations.

Suspension, Track, and Skis

The front suspension setup is identical to that of a 2012 Polaris Rush. This 42” wide setup allows the snowmobile to stay planted in corners and demonstrate reduced inside ski lift. Paired with Walker Evans Clicker Piggyback Shocks, the snowmobile rides smoothly over bumps and gives positive feedback to the rider.

Figure 16. 2013 Polaris Pro RMK Rear Suspension

The snowmobile is equipped with a Camso Cobra 1.325” single ply track, making it very flexible, thus improving performance in soft, unpacked snow. The complete 144” rear suspension setup is a good compromise for all types of riding as it bridges bumps on the trail and provides the ability to go off trail into deeper snow. RIT CST desires to follow consumer trends as the crossover continues to rise in popularity and manufacturers move towards longer track trail sleds (ex. 2016 Ski-doo MXZ X 129”).

Aftermarket skis were selected to improve handling. RIT CST opted for the Curve Industries XS skis, the standard trail ski offered by Curve. With a width of 7.5” the skis are considerably wider than stock skis, providing better floatation in deeper snow. They also feature a patented parabolic shape which offers razor sharp cornering, lighter steering effort, and also provides a unique look to the sled. Attached to the skis are a pair of Curve 8” Thrusters, which provide extra performance in soft loose corners.

Figure 17. Curve XS Skis

Mechanical Noise Reduction

During the 2015 Clean Snowmobile Challenge, RIT CST struggled in the noise test. The J192 level was 4 dBA higher than the control sled, resulting in a poor score. This was the result of high intensity noise levels in the higher frequencies. The dBA scale gives more weight to higher frequencies, therefore they had a large impact on the poor scoring. The highest intensity was determined to be at approximately 300Hz and independent of engine order.

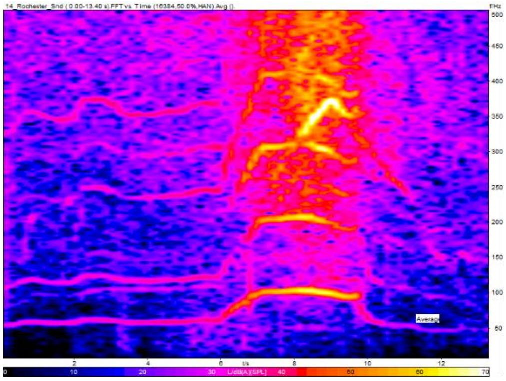


Figure 18. 2015 RIT CST Acoustic Results

In order to combat this issue, RIT CST installed adhesive sound dampening material to the underside of the tunnel. The material is designed to reduce resonance within the tunnel. The team also applied the material in the engine compartment in the area of the clutches to aid in suppression of clutch noise.

Validation Phase

Due to time and resource constraints, RIT CST was unable to produce validation results. Engine calibration will be completed before the competition. However, the calibration is not complete to provide an accurate representation of engine performance. Simulation data predicts peak power to be approximately 90hp. Peak efficiency is projected to be near 4500rpm. RIT CST is calibrating the engine for optimal performance in the 5-mode emissions test.

Summary/Conclusions

In order to develop a more efficient low-emissions snowmobile, the Rochester Institute of Technology Clean Snowmobile Team utilized the DMADV process. The goals set in the analyze phase appear to be reasonable targets and many will be achieved. Due to limited time and resources, many aspects of the design were not evaluated. As a result, the 2016 Clean Snowmobile Challenge will functionally serve as validation for the design. However, the integration of computer-based simulation positions the team better for future development.

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