2015-RIT-IC

Design for Six-Sigma Applied to High-Efficiency, Low Emissions Snowmobile

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ABSTRACT

Rochester Institute of Technology Clean Snowmobile Team applied design for six-sigma methodology to develop a low-emissions snowmobile for the 2015 SAE Clean Snowmobile Challenge. The DMADV process was chosen to guide product development.

The resulting design uses a 2013 Polaris Rush 600 Pro-R chassis and a modified Weber 750cc engine. This engine was outfitted with a variable nozzle turbine (VNT) turbocharger, a continuous discharge ignition system, low-pressure EGR, and fueled by 16-32% Bio-isobutanol blended gasoline.

No emissions in-service data was collected, but engine dynamometer testing showed a BSFC of 284 g/kW*hr and a peak power output of 107 hp.

INTRODUCTION

The Society of Automotive Engineers (SAE) Clean Snowmobile Challenge (CSC) allows collegiate design teams to address vehicle emissions, noise, and efficiency concerns of the snowmobile industry by developing innovative, robust, and economical design solutions. These cleaner, quieter, and more fuel-efficient snowmobiles are targeted for use on environmentally sensitive land, such as National Parks or other protected areas[i]. These designs are also valuable exercises in exploring technology in advance of the release of more stringent regulations on emissions, noise and fuel consumption.

The Clean Snowmobile Challenge is a week-long competition consisting of intense dynamic and static events, where design teams demonstrate the performance of their snowmobiles and justify their engineering decisions. However, these events are not the only trying parts of the competition. The CSC's short design cycle time combined with the constraints and limitations of a team's finances and resources can be just as, if not a more difficult challenge to manage. The risks associated with these challenges, as well as the high emphasis placed on innovative project management led the RIT Clean Snowmobile Team (RIT CST) to implement a Design for Six-Sigma 'DMADV' process at the systems and subsystem level.

SIX-SIGMA DMADV PROCESS

Six-Sigma is first and foremost, a quality improvement system, with many tools available for different applications. The most common application being a process improvement tool – the DMAIC process (Define, Measure, Analyze, Improve, Control), which is commonly employed in manufacturing, design, and business. However, this tool only works on improving an existing process, not if one is to be developed from the ground up - this is where the DMADV (Define, Measure, Analyze, Design and Verify) process can be utilized.

DMADV places an emphasis on designing things correctly the first time. This leads to highly optimized systems, lower development costs, higher product quality, reduced design time – and ultimately a more satisfied customer[ii]. A comparison between DMAIC and DMADV can be seen in Figure 1. Just as with DMAIC, The DMADV process is broken down into five phases, where specific tools are used to ensure the design will be successful – a brief overview of these phases is below:

1. **Define** – Define the design objective of the system, as well as the scope and time-line of deliverables.
2. **Measure** – Measure customer feedback and determine customer requirements.
3. **Analyze** – Analyze concepts and innovative technology to find competitive advantage. Benchmark competitor's products and create competitive analysis.
4. **Design** – Design subsystems to add value to system. Simulation, models, and prototypes guide design.
5. **Verify/Validate** –. Verify the design with testing.

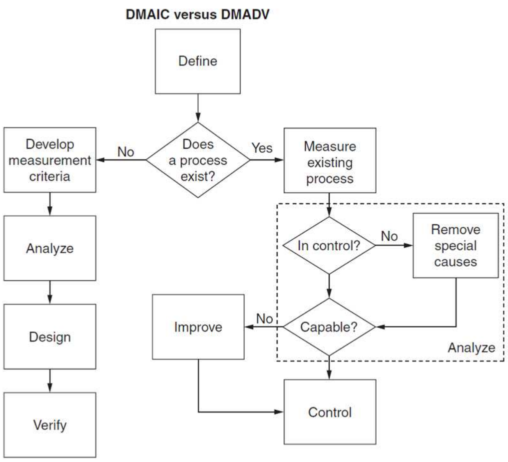


Figure 1: Comparison of DMAIC and DMADV Six-Sigma processes[iii]

Define Phase

Project Charter

RIT CST's objective was to design a snowmobile which would be optimized for the scoring matrix of the 2015 SAE Clean Snowmobile Challenge. Emphasis was placed on innovation, while ensuring the snowmobile would still be fun and reliable.

Scope of the project was limited to a current production chassis no older than 2011 from one of the four major manufacturers, and all designs must meet the 2015 CSC rules, while remaining "in the spirit of the competition".

A Gantt chart with soft, hard, and dependent deadlines was created to establish a project timeline. The final deliverable product was required to be in competition March 2, 2015.

Measure Phase

Voice of the Customer (VOC)

Voice of the Customer (VOC) is simply what is needed for a successful design – this is typically created through communication with the customer, external market research, surveys, and from internal data. The VOC can be "stated" or "unstated" depending on if the customer directly names their need. It is vital to measure the VOC correctly, as it will guide the design throughout the DMADV process.

For this application, the score matrix from the 2015 rules was used as the stated needs in the VOC. An additional need was added from section 9.4.1 in the rulebook, stating "Innovation is weighted more heavily in the scoring sheet than in past competitions." While this was not explicitly listed in the score matrix, it was considered to be an "unstated" customer need. The needs for static events were removed since they did not directly apply to the design of the snowmobile.

Critical to Customer (CTC)

To ensure that RIT CST created the Critical to Customer (CTC) accurately, the 2015 CSC score matrix was analyzed and events were reconsolidated into a simplified matrix with clear design objectives. Each objective's score was used to calculate its weight.

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

Pareto Chart

Because RIT CST's Critical to Customer needs were derived directly from the CSC scoring matrix, the maximum points for each need were used to calculate their respective importance. A Pareto chart of customer needs was then created to help better understand the importance of each CTC. The Pareto chart (Figure 2) shows that the emissions, noise, fuel-efficiency, and reliability of the snowmobile accounted for 80% of the total score.

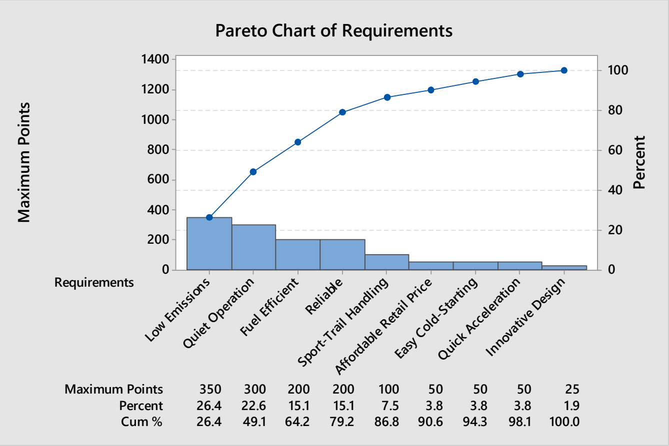


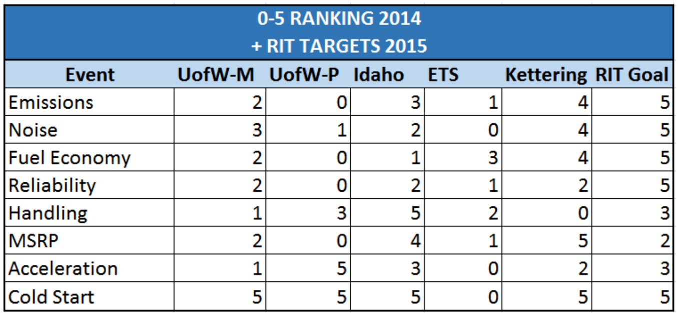
Figure 2: Pareto chart of 'Critical to Customer' characteristics

Analyze Phase

RIT CST invested a considerable amount of effort into the Analyze phase, where the team investigated which customer needs returned the largest satisfaction, and if there was a chance for RIT to develop a snowmobile with non-traditional technology and gain a competitive advantage.

Competitive Benchmark

RIT CST analyzed the final scores of top five gasoline-powered snowmobiles from the 2014 Clean Snowmobile Challenge and ranked their relative performance 1-5[iv]. This allowed RIT to identify design trends of the leading teams, as well as identify potential areas of improvement. RIT CST then strategically chose a combination of high-value and low-effort requirements to excel at, and estimated their relative performance after re-normalizing the benchmark scores. These results can be seen in Table 1.



0-5 RANKING 2014 + RIT TARGETS 2015						
Event	UofW-M	UofW-P	Idaho	ETS	Kettering	RIT Goal
Emissions	2	0	3	1	4	5
Noise	3	1	2	0	4	5
Fuel Economy	2	0	1	3	4	5
Reliability	2	0	2	1	2	5
Handling	1	3	5	2	0	3
MSRP	2	0	4	1	5	2
Acceleration	1	5	3	0	2	3
Cold Start	5	5	5	0	5	5

Table 1: Normalized final rankings of 2014 CSC top 5 finishers.

Quality Function Deployment (QFD)

A system-level quality function deployment matrix was then created using the competitive analysis, CTC, and design targets from the winners of each event in the 2014 CSC.

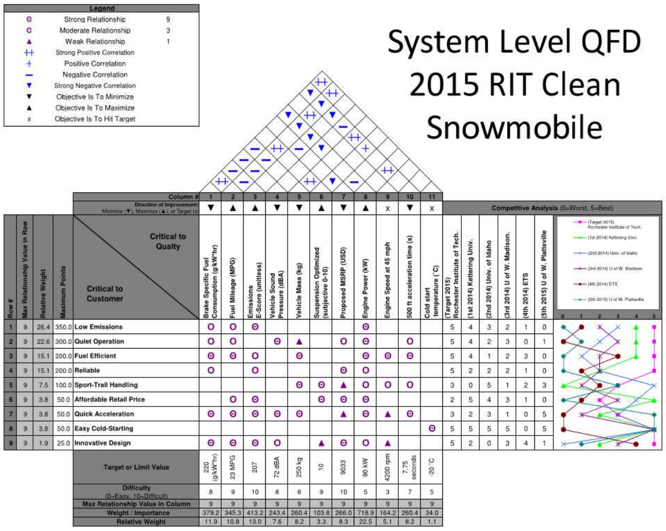


Figure 3: Quality Function Deployment (QFD) of 2015 RIT Clean Snowmobile

The QDF relates the Critical to Customer characteristics to the Critical to Quality (CTQ) characteristics, and places objective importance on each CTQ. It is also a visual aid to see the relationships between different CTQs. These relationships were chosen using logic and understanding of their respective theory – however a much more complex interaction may have been observed if the time and resources were available to complete a design of experiments (DOE).

The "Relative Weight" row shows how important each CTQ is to the overall performance of the system, based off how strong, and how many interactions with CTCs and CTQs there are. This relative weight should be thought of as a system sensitivity rather than how important it is for the CTQ to meet its target. 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 that it has so many negative impacts other CTQs 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.

Again, a Pareto chart was created to show the importance of each CTQ characteristic, and to give RIT CSC insight on where to focus our resources. Figure 4 shows that the largest payoffs will be seen in getting an optimal response from Engine Power, Emissions E-score, Brake Specific Fuel Consumption, and Fuel Mileage.

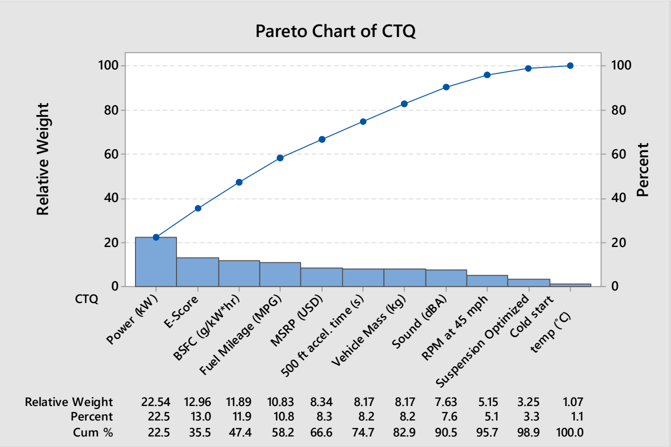
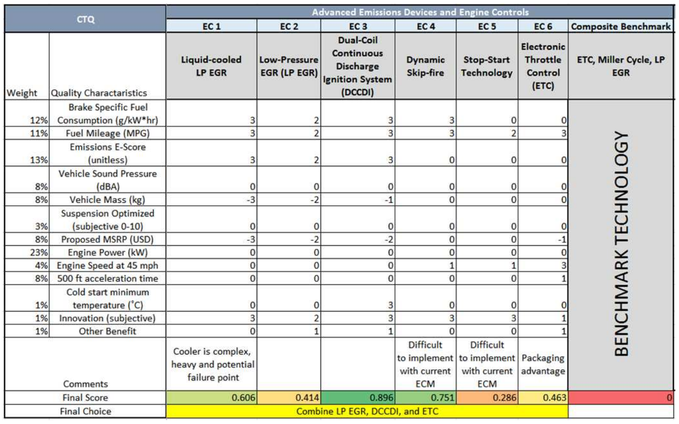


Figure 4: Pareto chart of Critical to Quality Characteristics.

Pugh Matrix

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.

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 5.



CTQ		Advanced Emissions Devices and Engine Controls						
		EC 1	EC 2	EC 3	EC 4	EC 5	EC 6	Composite Benchmark
Weight	Quality Charactaristics	Liquid-cooled LP EGR	Low-Pressure EGR (LP EGR)	Dual-Coil Continuous Discharge Ignition System (DCCDI)	Dynamic Skip-fire	Stop-Start Technology	Electronic Throttle Control (ETC)	ETC, Miller Cycle, LP EGR
12%	Brake Specific Fuel Consumption (g/kW*hr)	3	2	3	3	0	0	BENCHMARK TECHNOLOGY
11%	Fuel Mileage (MPG)	3	2	3	3	2	3	
13%	Emissions E-Score (unitless)	3	2	3	0	0	0	
8%	Vehicle Sound Pressure (dBA)	0	0	0	0	0	0	
8%	Vehicle Mass (kg)	-3	-2	-1	0	0	0	
3%	Suspension Optimized (subjective 0-10)	0	0	0	0	0	0	
8%	Proposed MSRP (USD)	-3	-2	-2	0	0	-1	
23%	Engine Power (kW)	0	0	0	0	0	0	
4%	Engine Speed at 45 mph	0	0	0	1	1	3	
8%	500 ft acceleration time	0	0	0	0	0	1	
1%	Cold start minimum temperature (˚C)	0	0	3	0	0	0	
1%	Innovation (subjective)	3	2	3	3	3	1	
1%	Other Benefit	0	1	1	0	0	1	
Comments		Cooler is complex, heavy and potential failure point			Difficult to implement with current ECM	Difficult to implement with current ECM	Packaging advantage	
Final Score		0.606	0.414	0.896	0.751	0.286	0.463	0
Final Choice		Combine LP EGR, DCCDI, and ETC						

Figure 5: Pugh Matrix of emissions devices and engine control strategies.

Design Phase

The next step in the DMADV process is the Design Phase, where concepts are fully developed into components. This is where simplified models, simulations, and prototypes are used to guide the design of each respective component and system.

Design Summary

The highest scoring concepts were taken from the subsystem Pugh Selection Matrices and RIT’s 2015 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 2 alongside the 2014 Clean Snowmobile Composite Benchmark.

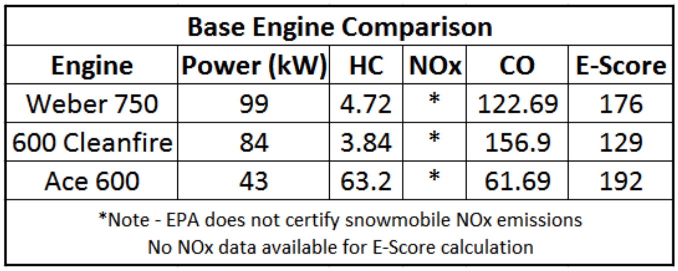
Design Summary		
Category	**2015 RIT**	**Composite Benchmark**
Base Chassis Selection	Polaris Rush 600 Pro-R	Ski-Doo MXZ Sport
Base Engine Selection	Weber 750cc Turbo	600 ACE w/ turbo
Shock Selection	Walker Evans	Motion Control
Turbocharger	Honeywell GT1749V	MGT1238Z
Aftertreatment	Oxidation Catalyst	3-way catalyst
Advanced Emissions Devices and Engine Controls	LP EGR, ETC, Dual-Coil Continuous Discharge Ignition (DCCDI)	ETC, Miller Cycle, LP EGR
Fuel Strategy	Lean-Burn	Lean-Burn
Noise Treatment	Combine Absorbtive and Resonant	Stock
Flex-Fuel Modifications	Closed-loop lambda-based correction	Fuel-Quality Sensor
Ski Choice	Curve XS	C&A RZ
Track Choice	Camoplast Ice Attak XT	Camoplast Ice Attak XT
Driveline Modification	Slydog Bogey Wheels	Stock Bogey Wheels
Lighting Modification	External LED housing	Halogen (Stock)

Table 2: RIT design summary and composite benchmark

Base Engine and Design Strategy

The base engine selected for the 2015 RIT Clean Snowmobile was the Weber 750 MPE in the turbocharged high-output snow 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 lubrications while minimizing windage losses on rotating components.



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 3: Base engine comparison.

In stock form the Weber 750 HO exceeds the power limit imposed in section 4.2.1 of the 2015 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[v].

SwRI HEDGE-II explored 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 tailpipe emissions through lower temperature combustion. To achieve high dilution levels an external EGR was utilized with a continuous discharge ignition system. The EGR was cooled and used as a charge dilutant, and a variable geometry turbocharger was used to provide low-speed and high-speed boosting. This research was the inspiration for RIT CST's powertrain design and we believe will be the future of light-duty engines[vi].

Turbocharger Selection

RIT CST evaluated several traditional waste-gate turbochargers, but found that a variable-geometry turbine would be required to get both low-speed and high-speed boosting. A Honeywell GT1749V was selected after matching both the compressor and turbine to the Weber 750 MPE's expected operating range.

The GT1749V's compressor was analyzed first. This compressor is a 45 trim wheel with 0.46 A/R ratio housing, and had a shaft speed limit of 190,000 RPM. When RIT CST's boost targets and mass-flow rates are plotted on the compressor efficiency map (Figure 6), it is noted that the boost threshold is met by 3000 RPM, and that boost must be tapered off to remain under the SAE CSC power limit.

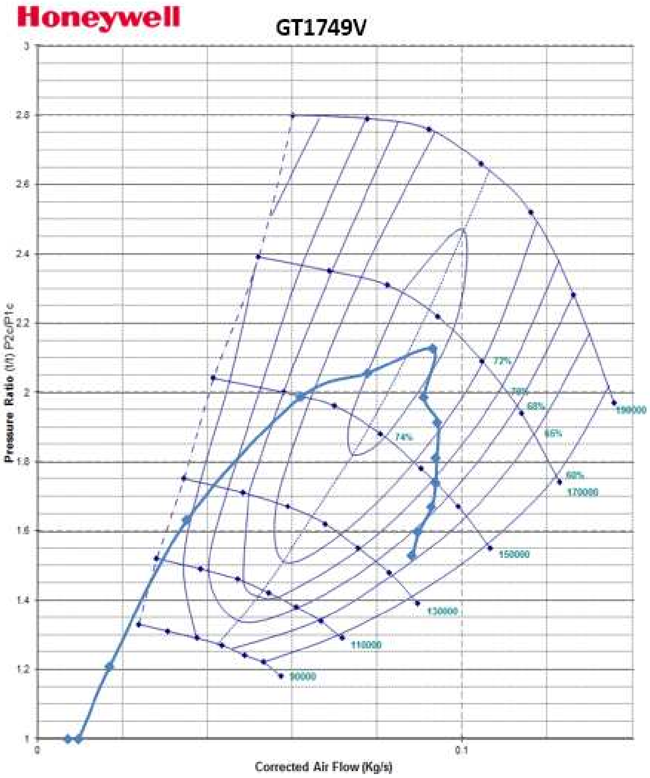


Figure 6: GT1749V compressor performance map.

Mass flow rate of air was calculated from idle speed to redline (1500-8000 rpm) using ideal-gas law and was plotted on the isentropic efficiency map of the compressor. Isentropic efficiency was then referenced from the map and added to the ideal gas equation to calculate the final air mass flow rate. These numbers were then corrected to the compressor test conditions using Equation 1.

$$W_C{}^* = \frac{W\sqrt{T_{1C}1/545}}{P_{1C}/13.95}$$

The corrected mass flow rate was used to look up shaft speed at a given pressure ratio, and was also corrected to test conditions using Equation 2

$$N_C = \frac{N_{phy}}{\sqrt{T_{1C}/545}}$$

Corrected mass flow rate and corrected shaft speed were then used to calculate the compressor power required to meet boost and mass air flow requirement using Equation 3.

$$Lc = \frac{W_C \times C_p \times T_{1C} \times \left\{ (\pi_C)^{\frac{\gamma-1}{\gamma}} - 1 \right\}}{\eta_C}$$

The exhaust mass flow was then calculated by adding the expected fuel mass, assuming Lambda of 1.20. The exhaust mass flow rate was then corrected to turbine test conditions using Equation 4.

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

Corrected exhaust mass flow, and compressor wheel speed was then used to calculate a corrected turbine shaft speed as shown in Equation 5.

$$N_T = \frac{N_{phy}}{\sqrt{T_{1_T}/518.4}}$$

Corrected exhaust mass flow rate, corrected turbine shaft speed, and turbine efficiency were then used to calculate the power converted by the turbine in Equation 6.

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

The power consumed by the compressor is compared to the power converted by the turbine. This power balance confirms that the expected boost levers are realistic for a given load and speed. The results of this comparison can be seen in Figure 7.

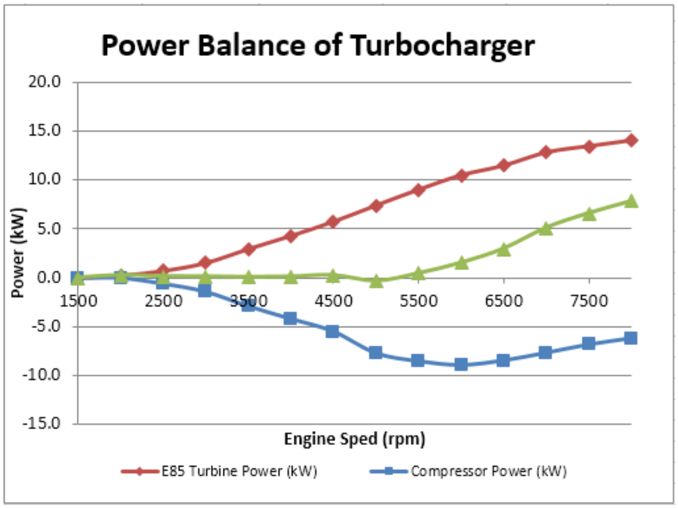


Figure 7: Turbocharger power balance.

Corrected exhaust mass flow rate and pressure ratio were then plotted on the isentropic efficiency map the turbine as shown in Figure 8.

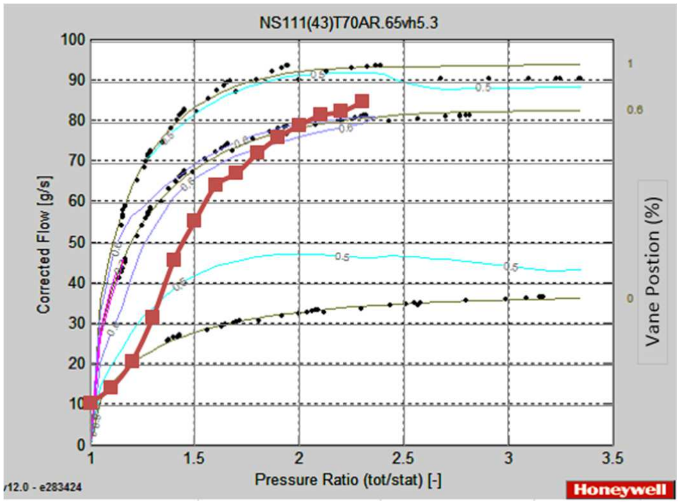


Figure 8: GT1749V turbine efficiency map

The installation and of this turbocharger took considerable design effort, as the turbine housing came equipped with an integrated exhaust manifold for a different automotive application. This required the RIT CST to modify the turbine housing by cutting the runners off and welding on a custom single-runner flange. Because a CAD model was unavailable, and the organic geometry was difficult to model, a Creaform 3D scanner was used to import the part mesh directly into Solidworks where a flow-optimized solution could be designed. The initial form factor and RIT CST's solution are pictured below.

Figure 9: 3D scan, CAD design, machined flange, and assembled turbine housing.

Dual-Coil Continuous Discharge Ignition (DCCDI)

RIT CST decided that in order to reach high dilution levels without a significant decrease in combustion quality, a more robust ignition system would have to be developed. A system similar to SwRI's Dual-Coil Offset was proposed and designed using readily available production components.

SwRI's research showed that the extended duration spark was shown to dramatically increase the lean-limit and EGR dilution limit of the engine[vii]. This is accomplished by creating a continuous current across the spark plug gap and by maintaining the glow discharge stage of the ignition process as shown in.

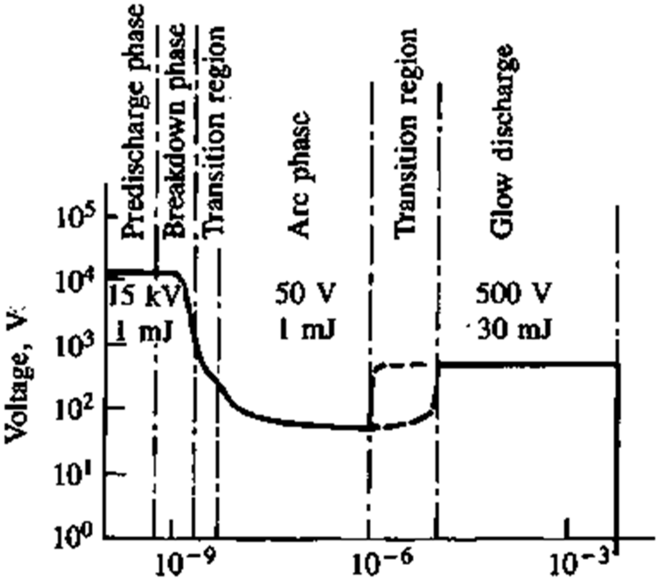


Figure 10: Phases of the spark-ignition process[viii]

This system utilizes 2 ignition coils per spark plug, and fires them in an alternating pattern to create a high-energy long-duration spark. These coils are fired out of phase through a diode assembly to prevent the secondary windings from back-feeding each other.

To dwell the ignition coils quickly and be able to rapidly fire them multiple times during one combustion cycle. The decision was made to operate the coils at an elevated voltage using a 24V step-up converter. This brought the coil dwell time down to 1.5ms from 5.3ms. The coils also begin dwelling before they fully discharge so that they can fire more rapidly, as shown in Figure 11.

Figure 11: DCCDI 5V trigger signal from external module.

The control strategy was then chosen next. Because of limitations on the flexibility of programming the ECM an additional ignition module would control the DCCDI dwell and spark duration, while the ECM would output a fixed pulse width signal. Because engine speed and pulse width are known, the DCCDI module can still calculate ignition angle to +/- 0.2 degrees.

The inputs to the module are cylinder 1 & 2 ignition triggers from the ECM, ignition voltage, and manifold absolute pressure from a secondary sensor. This allows 3D look-up tables based on engine speed and load to be created to control spark duration, and a 2D table to be created for open-loop coil dwell control.

Four LS3 coil-near-plug ignition coils were selected for packaging and performance reasons. It was determined that the stock fine-tip iridium spark plugs would suffice for this design, but the spark plug gap was opened up from 0.7 mm to 1.0 mm to promote kernel growth[ix].

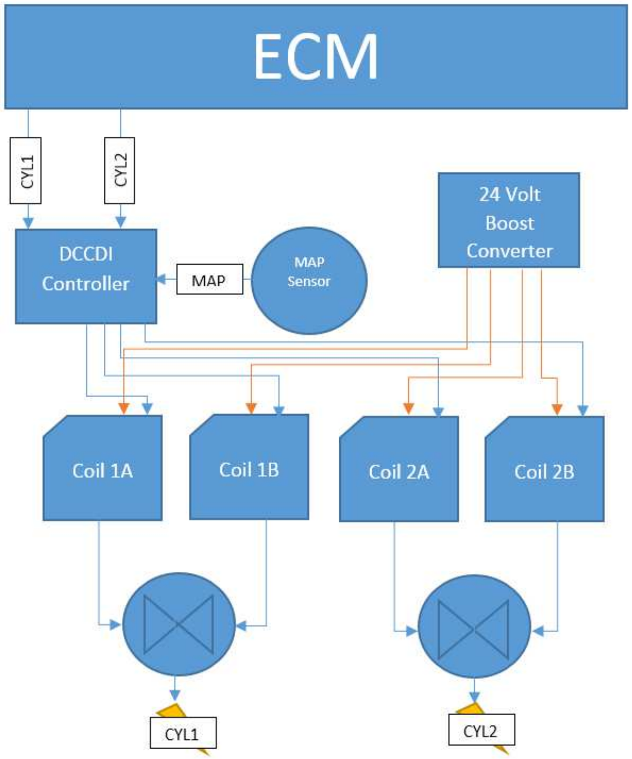


Figure 12: System diagram of DCCDI

Low-Pressure EGR

A low pressure EGR system was designed using existing automotive light-duty diesel components that would allow for RIT CST to explore the dilution limit of the engine. A decision was made to simplify the system as much as possible, so no EGR cooler was installed. But, because the EGR flows through the charge-air cooler it was estimated that based on the lower flow rates and high effectiveness of the stock charge-air cooler during testing, that an additional EGR cooler would be excessive. This is a design choice that RIT CST intends to explore in the future.

A poppet valve regulates EGR flow by changing flow area depending on load and engine speed. Mass flow can be estimated using Bernoulli's equation, but because pressure differential and gas temperature is dependent on operating condition system is empirically calibrated purely based on position.

To ensure that an adequate pressure differential is available to allow EGR flow at all times, an external module controls an up-stream normally open throttle body. When EGR is flow desired, the module closes the throttle slightly to impart a 5-15 kPa vacuum before the compressor inlet. The vacuum is kept minimal to reduce pumping losses and prevent oil leakage through the compressor seal.

Electronic Throttle Control

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.

Aftertreatment

An Aristo oxidation catalyst was chosen as an exhaust aftertreatment device for RIT's snowmobile because of the decision to operate largely in a lean-burn fuel strategy. The NO_X conversion efficiency of 3-way catalysts is poor during lean operation, so RIT decided to maximize their HC and CO conversion for small amount of space available for a catalyst. Low temperature combustion from high charge dilution was the method chosen to minimize NO_x.

Muffler Design

When designing a quiet muffler the goal is to limit sound as much as possible while trying to maintain low backpressure. High backpressure will limit the power of the engine or in severe cases not allow the engine to operate. Internal combustion engines create sound pulses from combustion that move from the exhaust valve to the exit of the exhaust. Therefore it is important to ensure that the muffler will absorb the sound pulses generated by the engine but also allow the exhaust air to flow with limited restrictions.

There are two main muffler designs that are utilized to make a quiet internal combustion engine, an absorption muffler and a reactive muffler. The absorption style muffler uses perforated tubing with sound damping material wrapped around it. As the exhaust gas pulses throw the muffler the absorbing material will absorb the pulses therefore quieting down the engine. A reactive muffler utilizes different chambers that direct and resonant the exhaust gas though different passages in the muffler to slow down the gas and reflect some of it back toward the engine. The chambers are designed to resonate at a certain frequency and reduce the noise at that frequency. For the RIT clean snowmobile both sound absorbing chambers and resonant chambers were utilized. In order to reduce the most noise produced by the Weber 750cc engine, 133 hertz was targeted as that is the primary firing frequency of the engine.

It was determined that due to space limitations after the weber 750cc engine swap a stock Polaris Rush muffler would not fit in its normal location. Therefore instead of modifying the stock shells to fit it was chosen to create a simpler square box design. 16 gauge 304 stainless steel was bent and welded together to create the shells of the muffler. Creating custom shells allowed the muffler to be integrated into the chassis and fit perfect with the weber engine.

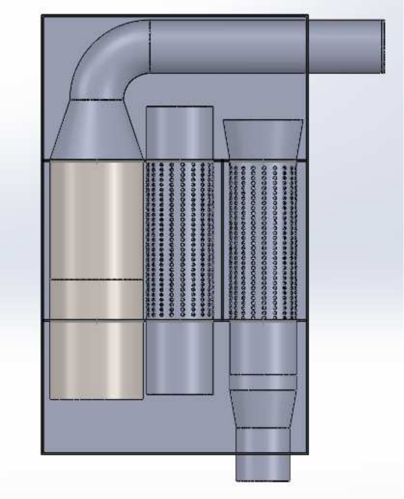


Figure 13: CAD model of RIT designed muffler. Note internal catalysts.

The muffler contains four different internal chambers. Two of these chambers are absorption chambers with two and a half inch perforated tubing wrapped in sound absorbing material. The other two are resonant chambers that allow the gas to free flow throughout the chamber before entering the next chamber. The muffler also uses two catalytic converters welded back to back. The exhaust gas first passes though the catalysts before entering the first chamber. The catalysts are made of palladium and Rhodium and are designed to initialize an oxidation reaction with both carbon monoxide and hydrocarbons. These Catalysts help reduce emissions of the snowmobile and by using two of them in series, their life will be extended.

To ensure the muffler would not create too much back pressure and would have good flow patterns, CFD was performed on the 3D model before fabrication. In order to simulate the engine exhaust gas a sine wave was entered into the CFD package to simulate the pulses created from combustion. The results showed that the muffler would indeed not create too much back pressure and that the exhaust gas would indeed slow down and become absorbed by the muffler.

Base Chassis Selection

The chassis selected for RIT CST's snowmobile was the 2013 RUSH Pro-R. This chassis boasts Polaris's innovative Pro-Ride progressive rear suspension, and an advanced bonded aluminum construction. The Pro-R model was chosen over the base Rush because the upgraded Walker Evans shocks gave an additional handling benefit that RIT CST decided was needed to help offset the additional weight of the Weber 750 engine.

Figure 14: 2014 Polaris Pro-Ride chassis.

Skis

Curve Industries XS Skis were chose for their superior trail performance. This is credited to their unique parabolic profile which allows the ski to "carve", similar to an aggressive downhill mountain ski. They also feature "variable geometry" pockets on both sides of the keel, which are intended to funnel and compact snow into a temporary rail and allowing the ski rise above the snow rather than push through it. These skis are also customizable with accessories and different colored components, which makes them attractive to the consumer.

Figure 15: Curve XS Skis. Note parabolic profile and control features on bottom of ski.

Track

RIT CST chose Camoplast's Ice Attak XT track, Camoplast's newest pre-studded track with an improved lug design. Compared to Camoplast's previous Ice Ripper XT the Ice Attak XT's lug design delivers better traction on groomed trails, as well as hard packed and icy conditions. When compared traditional studs the factory studs are much quieter, less likely to be ripped out, and are much easier to install. Its 1.22" lug height also provides for better handling and stability than the stock Ripsaw's 1" lug. This track also features

Camoplast's new optimized rubber compound for superior traction on groomed trails.

Figure 16: Camoplast Ice Attak XT pre-studded track.

Shocks

By comparing the stock Walker Evans Clicker shocks, to Fox Float EVOL shocks, and Motion Control shocks, the stock Walker Evans Clicker shocks bettered the competition due to no increase in MSRP and the amount of adjustability they have. These shocks were valved and sprung for the approximate 80 pound increase in weight due to the increase in motor weight.

Bogey Wheels

By comparing the Sly Dog bogey wheels to the stock Polaris bogey wheels, the Sly Dog bogey wheels bettered the competition by reducing friction, which RIT CST believes will return both better in-service fuel economy and faster acceleration. The Sly Dog bogey wheels are designed as an airfoil which blow snow into the skid and decrease the coefficient of friction between the hyfax and the track clips. They are also available in different colors which makes them an attractive customizable option to consumers.

Lighting

RIT CST decided to install a headlight delete kit and replace the stock halogen bulbs with an external high-efficiency LED unit. This was done to increase the amount of space under the hood, for aesthetic reasons, and because LEDs required only 20W as compared to the original bulb's combined 120W.

Verify/Validate Phase

The verify/validate phase of the DMADV process is where the finished designs are tested and their performance is evaluated. The performance of many of the subsystems are closely tied together and their performance is dependent on them being evaluated as a larger system. This dictates that the verify/validate phase be conducted at the system level. Due to RIT CST's limited resources, some aspects of design were not able to be measured and will not be presented in this paper – these aspects are specifically noise, emissions, in-service economy, and handling.

ENGINE CALIBRATION AND DYNO TESTING

RIT CST calibrated and evaluated their engine on a Borghi & Saveri FE600 eddy current dynamometer with Superflow data acquisition. Because of a data collection issue, the fuel flow data from the MAX model 2013 piston-type flow meter was not recorded. All fuel flow data was calculated from air fuel ratio and mass-air flow from a MoTeC LSU 4.0 sensor and Superflow 6" airflow turbine respectively.

Turbocharger

Mass air flow data was collected during calibration, and overlaid onto the GT1749V compressor map. There is a strong correlation to the flow and pressure ratios calculated in the design phase. The compressor is shown to operate at its highest efficiency at peak engine power which reduces charge air temperature, and is beneficial for BSFC as well as under-hood temperature. The VNT turbine allows for a very low boost threshold as expected, but the compressor does operate very close to the surge line as shown in Figure 17. It is not expected to cause reliability issue due to the loading characteristics of the belt CVT.

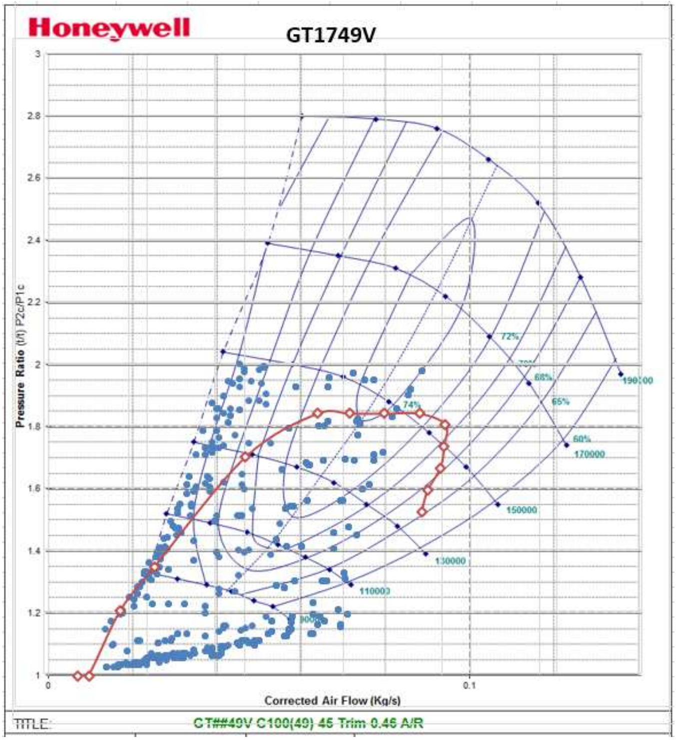


Figure 17: Compressor efficiency map with test-data points overlaid.

Engine Performance

RIT CSC's modified Weber 750cc was shown to produce up to 140 hp during calibration, depending on boost level and fueling strategy. This shows that this engine package is flexible and can be highly competitive with existing sport-trail oriented snowmobiles on the market. Boost was then reduced to lower power output to CSC-legal levels. Final power output characteristic can be seen in Figure 18. The engine produces significant power at low speeds due to the low boost threshold of the GT1749V.

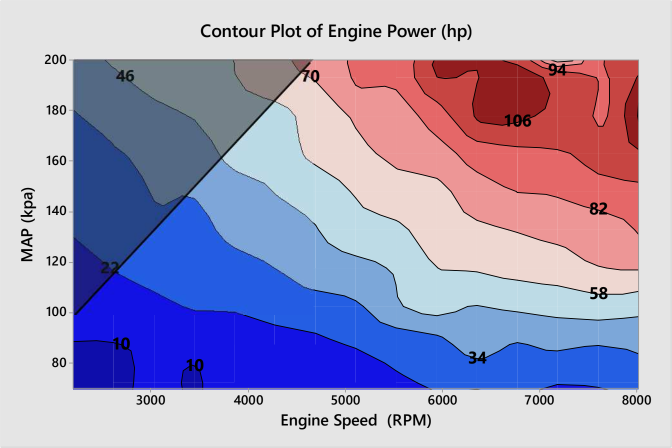


Figure 18: Manifold absolute pressure (MAP) vs engine speed (RPM) vs engine power (hp) contour plot.

Brake Specific Fuel Consumption

A BSFC plot was created based on manifold pressure and engine speed. The contour lines show that the engine operates at its highest efficiency between 180-200 kPa and 6000-7500 RPM.

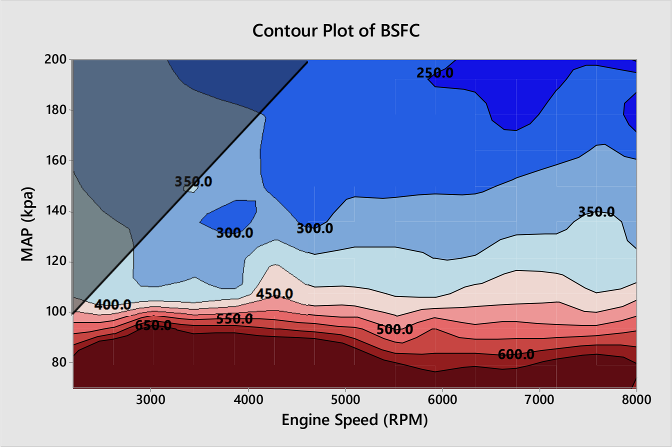
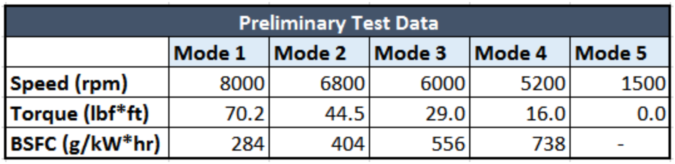


Figure 19: Manifold absolute pressure (MAP) vs engine speed (RPM) vs efficiency (BSFC) contour plot.

This power and efficiency data was then used to calculate the speeds, loads, and BSFCs of the 5-mode emissions test. These results are shown in Table 4.



Preliminary Test Data					
	Mode 1	**Mode 2**	**Mode 3**	**Mode 4**	**Mode 5**
Speed (rpm)	8000	6800	6000	5200	1500
Torque (lbf*ft)	70.2	44.5	29.0	16.0	0.0
BSFC (g/kW*hr)	284	404	556	738	-

Table 4: 5-mode test results

SUMMARY/CONCLUSIONS

RIT Clean Snowmobile Team's 2015 snowmobile appears to meet or exceed the design targets that were established using the DMADV process, however many aspects of the design were not able to be validated due to limited resources. The design's results for the 2015 Clean Snowmobile Challenge will provide valuable data for the 2016 design, and will function as our validation.

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