Proving Viability of Small Displacement Turbocharged Power

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ABSTRACT

For the 2016 Society of Automotive Engineers (SAE) Clean Snowmobile Challenge (CSC), the University at Buffalo (UB) Clean Snowmobile Team has made significant strides to reduce the environmental impact of a snowmobile while retaining the performance, cost, and reliability that riders and manufacturers require. This year the UB CSC Team has returned to gasoline powered engines with an Arctic Cat Bearcat 3000LT chassis and a 700cc, liquid-cooled, electronically fuel injected (EFI) four-stroke. This chassis was chosen for its durability and long-track maneuverability paired with the small displacement four-stroke engine it provided the perfect platform to build from a clean slate. Significant improvements were made in the exhaust and intake system as well as re-mapping the fuel system in order to achieve lower emissions with increased performance.

An intercooled intake system was paired with a Borg-Warner KP39 turbocharger for decreased hydrocarbon formation, lowered exhaust gas temperatures, and increased power output. Emissions control was addressed by employing an Magnaflow catalytic converter. Fuel control was addressed with a Dobeck AFR+ engine control system to improve our emissions through fuel mapping. Through these improvements, the 2016 UB CSC team has proven that small displacement, turbocharged power is a viable solution for today's snowmobile market.

INTRODUCTION

Based off of research conducted over the past decades, there is a clear correlation between the uses of internal combustion engines to a negative impact on our environment. Due to rising awareness and concerns, there has been a significant increase in regulation when it comes to exhaust emissions of recreational vehicles. This rise has thus sparked a trend in the pursuit of not only more fuel efficient recreational vehicles, but also in the demand for decreased emissions. This trend, which is strongly present in the recreational snowmobiling industry, has caused a drive to develop new technologies in an effort to combat exhaust emissions, aiming to make snowmobiles quieter, cleaner, and more fuel efficient. The Clean Snowmobile Competition is a collegiate competition, designed for student members of SAE, where teams are given the task of re-engineering a current model snowmobile in production in order to reduce emissions and environmental impact. Stated by SAE, the CSC's purpose is defined as: "[The development of] a snowmobile that is acceptable for use in environmentally sensitive areas. The modified snowmobiles are expected to be quiet, emit significantly less unburned hydrocarbons, carbon monoxide and particulate matter than conventional snowmobiles, without significantly increasing oxides of nitrogen emissions" [1]. The CSC uses an E-score in order to evaluate all snowmobiles in the competition; this E-score, defined by the equation below, uses Hydrocarbon (HC), Carbon Monoxide (CO) and NOx measurements to quantify and rank the emission outputs of participating snowmobiles.

$$E - Score = \left(1 - \frac{HC + NOx - 15}{150}\right) * 100 + \left(1 - \frac{CO}{400}\right) * 100$$

Equation 1: E-Score Equation for Emissions Testing

Spark ignited snowmobiles remain to be the most commonly produced snowmobiles on the market. The Internal Combustion (IC) class was created in an effort to allow collegiate students the ability to directly affect the snowmobile industry, while also working to protect our environment. Staying congruent to the goal of the CSC competition, the IC snowmobile is put through multiple emissions tests, while also performing up to certain expectations that are desired by manufacturers and operators. The standard performance expectations of the IC class are a trail speed of 45 miles per hour (MPH) on a smooth trail, an acceleration of 500 feet within 10 seconds from a standing start, and the ability to run for at least 100 miles before refueling. Re-engineered snowmobiles must be designed to maintain their original reliability, while also using cost effective solutions that positively affect emissions, economy, and noise reduction problems. After considering all these constraints, the University at Buffalo CSC Team re-engineered a utility four-stroke snowmobile with supporting systems in order to produce a snowmobile that produced lower emissions, was cost effective, efficient, and also reliable.

DESIGN CONSIDERATIONS

To effectively redesign a snowmobile, the UB CSC team identified three pivotal design factors. It was imperative that these three factors were met throughout the transformation process of the snowmobile. The factors and their perspective expectations are defined below.

The Environment

The UB CSC team determined that the environmental impact of the snowmobile was to be considered with the utmost importance. It directly relates to the primary objective of the Clean Snowmobile Challenge, which is to design a snowmobile that is acceptable for use in environmentally sensitive areas such as National Parks [6]. The specific objectives are as follows.

- Significantly reduce the emission of unburned hydrocarbons and carbon monoxide
- Decrease noise during operation
- Improve the fuel economy of the snowmobile

Numerous strides were taken to achieve these objectives, which include the implementation of emissions control devices, design for efficiency, and weight reduction wherever applicable.

The Operator

The snowmobiles marketability was also an important factor considered by the UB CSC team. With the intent to design a touring snowmobile to be used on groomed snowmobile trails, it was vital to meet all of the following expectations of the snowmobiles operator.

- Comfortable and enjoyable to operate
- Easily maintain a riding speed of 45 mph
- Does not require a lot of work or attention to maintain
- Travel long distances without needing to refuel
- Withstand demanding terrain

If these basic reliability and performance characteristics are not fulfilled, the snowmobile will not be adopted in today's market. To address this design factor the team focused on increasing engine power output, improving handling, and decreasing fuel consumption. The operator design considerations were mainly reflected in the engine turbocharger and intake systems as well as the selection of skis on the machine.

The Manufacturer

The aspect of manufacturing was also an important consideration while designing the snowmobile. It was necessary to eliminate non-value adding material and production costs to the snowmobile without damaging the quality of the machine. The most important requirements are accounted for below.

- Minimize initial production costs
- Improve durability to minimize life cycle costs and warranty claims

To reduce the overall cost of the snowmobile, the UB CSC Team emphasized cost effective solutions such as minimizing part counts, fabrication amount, and overall system complexity. This resulted in the use of more readily available mass produced parts. Lean manufacturing principles such as limiting defects were also closely studied in an effort to successfully bring the snowmobile design into a mass production environment.

ENGINE CONTROL UNIT

When introducing a force-induction system to a previously naturally aspirated engine, special attention must be paid to the fuel input into the combustion cycle. To achieve the proper fuel management, the UB CSC elected to utilize an EFI control unit. The control unit chosen was the Dobeck Performance AFR+ system. The standard engine uses the engine control unit (ECU) to modulate and control the fuel delivered to the engine for good combustion. The AFR+ control unit is an EFI controller that works in conjunction with the stock ECU, interrupting and modulating the injector signals to achieve AFR set points. The factory narrowband oxygen sensor was replaced with a Bosch wideband O2 sensor to collect data for the Dobeck controller. The wideband sensor in the exhaust was used by the UB CSC team to calibrate and tune the fuel injection to the engine to achieve maximum horsepower while maintaining low emissions.

Using the data from the wideband, the AFR+ control system modulates to achieve the desired AFR set points that have been pre-programed into the unit. The UB CSC team has determined that in low-load scenarios, in order to achieve optimum efficiency, the AFR set points have to be in the range of 15.5:1-17:1 parts air to fuel. Furthermore, the system has been fine-tuned for optimal efficiency at all rpms and throttle inputs. In low-load scenarios, the AFR is leaner than the stoichiometric ratio for gasoline to maximize the cruising efficiency. Wide open throttle scenarios will remain in a safe AFR target range to retain an acceptable level of power and reliability. The advertised power ratings of the 2017 Arctic Cat Bearcat 3000LT was 60 hp and 40ft-lbs of torque. The UB CSC team tested the provided power limits of the snowmobile on their DYNOmite Land & Sea dynamometer. Through testing it was shown that the fully stock Arctic Cat Bearcat 3000 LT generated the expected 40 ft-lbs of torque at 4800 rpm but only 50 hp at 7000 rpm shown in Figure 1.

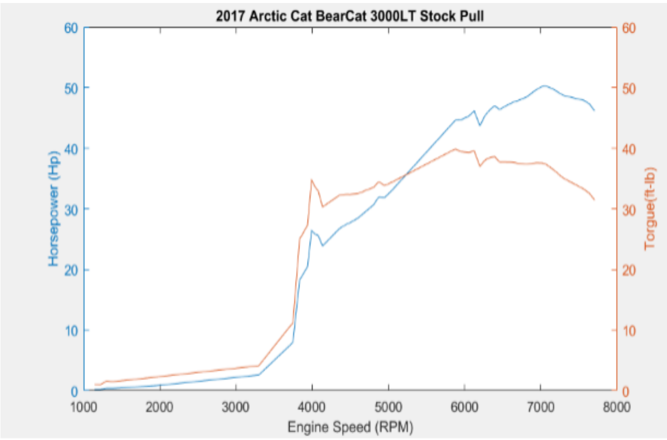

Figure 1: 2017Arctic Cat BearCat 3000LT Baseline Engine Output

Regardless of the discrepancy between the advertised ratings and the UB CSC teams tested numbers, the team set its benchmark at improving peak hp by 50% over stock and peak torque by 50% over stock. Given the use of the Borgwarner KP39 turbocharger and the AFR+ engine management system, the theoretical peak horsepower gain was expected to be 30 hp and the theoretical peak torque increase was expected to be 20 ft-lbs.

EXHAUST SYSTEM

Reduction of harmful emissions from internal combustion engines can be achieved in two ways. Primarily, reduction of toxic exhaust gas emissions can take place inside the engine by running a lean air to fuel ratio (AFR). Secondarily, toxic exhaust gas emissions can be reduced by utilizing after-treatment in the exhaust system [2]. The UB CSC design team addressed both the primary and secondary approaches of reducing harmful exhaust gas emissions by custom fabricated a turbocharger system to allow for higher power output with less fuel and by utilizing a high flow Magnaflow catalytic converter to reduce the output of carbon monoxide (CO), nitrogen oxides (NOx) and hydrocarbons (HC).

The Arctic Cat Bearcat 3000 LT came equipped with a naturally aspirated four stroke engine. In order to prove the theory of small displacement yet high power output, the UB CSC team decided to create a force-induction system via the use of a BorgWarner KP39 turbocharger. A custom exhaust system was built to mount the turbocharger. There are two basic types of manifolds, log style and tubular style. Log style manifolds are generally found in OEM applications and they are usually cast. Welded tubular style manifolds are almost exclusively found in the aftermarket world. Manifold design on turbocharged applications is deceptively complex as there many factors to take into account and trade off. Utilizing the generously provided knowledge of Full Power Performance, a local custom fabrication shop in Buffalo, NY, and our conversation with them about how to make the most efficient manifold design, the following design guidelines were developed.

- Maximize the radius of the bends that make up the exhaust primaries to maintain pulse energy
- Make the exhaust primaries equal length to balance exhaust reversion across all cylinders
- Avoid rapid area changes to maintain pulse energy to the turbine
- At the collector, introduce flow from all runners at a narrow angle to minimize "turning" of the flow in the collector
- For better boost response, minimize the exhaust volume between the exhaust ports and the turbine inlet
- For best power, longer primary lengths should be used
- For best emissions, shorter primary lengths should be used

Using Solidworks 3D modeling software, a variation of a log manifold as well as a tubular manifold were drawn, and flow simulation was performed.

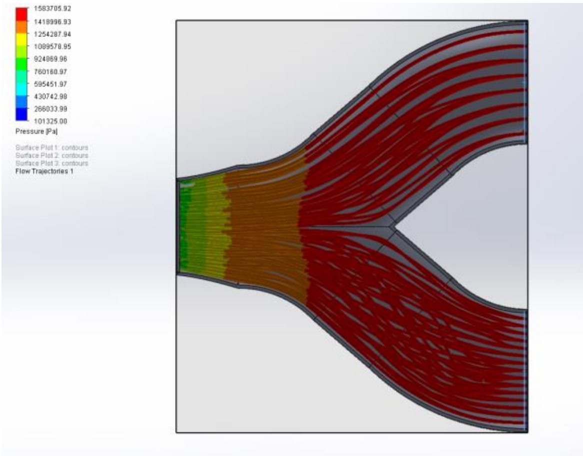

Figure 2: Tubular Manifold CFD Results

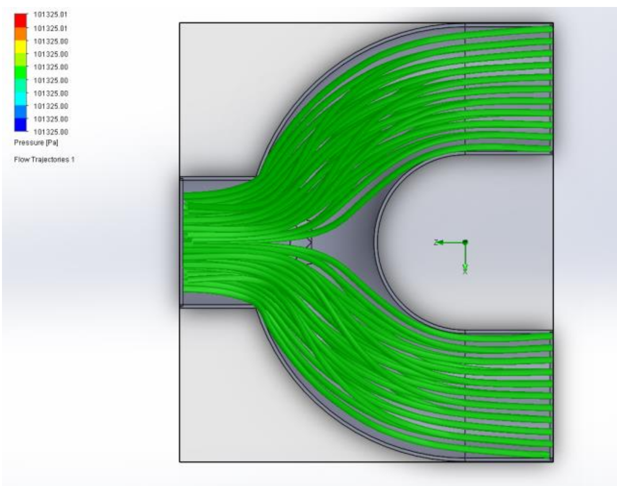

Figure 3: Log Manifold CFD Results

Based on the flow simulation shown above in Figure 2 and Figure 3, the exit pressure from the tubular manifold is higher than that of the log manifold. Higher fluid pressure going into the turbo would lead to better boost response from the turbo, thus the tubular manifold was chosen and fabricated [4]. The total length of the exhaust manifold was kept relatively short at 6.5 inches to allow for higher exhaust gas temperatures to be maintained so the catalytic converter could be properly activated.

Implementing a catalytic converter into the exhaust system of an internal combustion vehicle comes with challenges. In order to have a properly operating system, the catalyst must see exhaust gas temperatures (EGT) of between 1200°F-1400°F thus the need for a short tube manifold. To monitor the EGT and ensure proper activation of the catalyst a pyrometer was installed in between the turbo exhaust outlet and the catalytic converter. Further testing needs to be performed but initial speculation shows the EGTs at roughly 1300°F which would ensure proper catalyst activation.

INTERCOOLER SYSTEM

The UB CSC design team has proven that clean diesel technology is a viable possibility in many years past. Drawing off of this knowledge, it is known that in a forced-induction system, providing cooler air to the combustion cycle of an engine will allow for a cleaner more efficient burn of the fuel. In diesel engines, low temperature combustion (LTC) is used in diesel engines to control NOx emissions. NOx is created from a high-temperature flame inside the engine. NOx emissions are not only toxic, but once released into the atmosphere and exposed to sunlight, they react with other pollutants to create ground-level ozone, or smog [5]. Utilizing this knowledge, the UB CSC team designed an air to air intercooler system to be paired with the turbocharger system. The intercooler received the hot compressed air from the turbocharger and cooled it before entering into the intake system of the engine. Using Solidworks Flow Simulation technology the intercooler was designed and tested to ensure that exit temperatures would be lower than input temperatures.

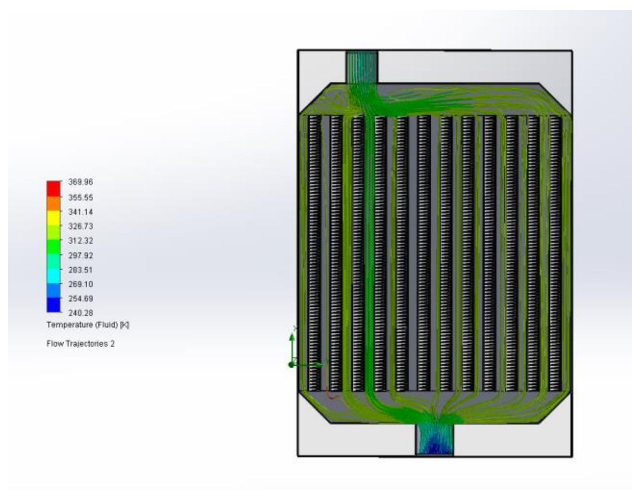

Figure 4: Intercooler Flow Simulation

CONCLUSION

Creating a forced induction system on a previously naturally aspirated snowmobile provided the UB CSC team with the unique opportunity to directly control and limit the power production in turn the emission profile of the Arctic Cat Bearcat 3000 LT. The UB CSC team made design decisions to effectively ensure that emissions of harmful CO, NOX and HC were reduced and the peak power was increased. The UB CSC Team accomplished this through the design considerations of the operator, environment, and the manufacturer applied to various systems of the snowmobile as follows.

- The snowmobile was selected to prove the efficiency of small displacement, turbocharged power
- The power profile of the engine was increased utilizing the Borgwarner KP39 turbocharger
- Calibration of the engine was performed using the AFR+ engine control system to optimize emissions and power output through extensive theoretical and experimental research, producing a theoretical gain of 30 hp and 20 ft-lbs of torque
- An intercooler was refined to properly cool the intake charge, reducing NOx, and deliver the cooled air charge to effectively increasing power output.
- Tailpipe emissions were reduced by the use of a Magnaflow catalytic converter, maintaining high catalyst efficiencies with a specially designed exhaust system and calibration.

Based on the above points, the 2017 UB CSC snowmobile design definitively proves the viability of small displacement turbocharged power. The combination of performance, low emissions, high reliability, and high fuel economy makes the 2017 UB CSC snowmobile an ideal snowmobile.

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ACKNOWLEDGEMENTS

The University at Buffalo thanks the following sponsors for helping us pioneer the development of a clean and efficient diesel powered snowmobile.

UB Engineering Machine Shop	Arctic Cat
UB Student Association	BorgWarner
UB SEAS Department	Custom Laser
SolidWorks	NYSSA
Klispie Motorsports	Autometer
DEI	Camoplast Solideal
Pfeifer Industries	Ballistic Battery
Peter Dietrich	Specialist Components

SPECIAL THANKS

Our team would also like to thank the following individuals for their support and knowledge provided to our club:

- Dr. Jason Armstrong, UB SAE Faculty Advisor
- UB Engineering Machine Shop Personnel

ABBREVIATIONS

SAE	Society of Automotive Engineers
CSC	Clean Snowmobile Challenge
UB	University at Buffalo
NOx	oxides of nitrogen
WOT	wide-open throttle
HC	hydrocarbons
CO	carbon monoxide
EGT	exhaust gas temperature
ECU	engine control unit
CVT	Continuously Variable Transmission