Proving Viability of Small Displacement Turbocharged Power

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ABSTRACT

For the 2018 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 continued its entry in the Internal Combustion class with the 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 along with an increased performance.

An intercooled intake system was paired with a BorgWarner KP39 turbocharger for decreased hydrocarbon formation, lowered exhaust gas temperatures, and increased power output. Emissions control was addressed by employing a Flowmaster catalytic converter. A Motec M130 engine control unit was implemented to control fuel injection, timing, and tuning through a specifically designed fuel map. Through these improvements, the 2018 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.

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

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. The UB CSC Team opted for a full standalone ECU to replace the one from the factory. This gives the team full control over every engine parameter during the tuning process. The ECU of choice was the Motec M130 due to its compact size and good fit within budget limits while also providing more than enough functions for the team's purpose. The Motec M1 Tune Software has many features to aid in having precise control throughout the various tuning maps. To aid in the tuning process, a Wideband O2 sensor and pyrometer were installed to make sure the engine is operating optimally and within a safe range to increase its lifespan and efficiency.

The UB CSC team has determined that in low-load scenarios, in order to achieve optimum efficiency, the Air Fuel Ratio (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 (WOT) 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 horsepower (hp) and 40 foot-pounds (ft-lbs) of torque. The UB CSC team tested the provided power limits of the snowmobile using a 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.

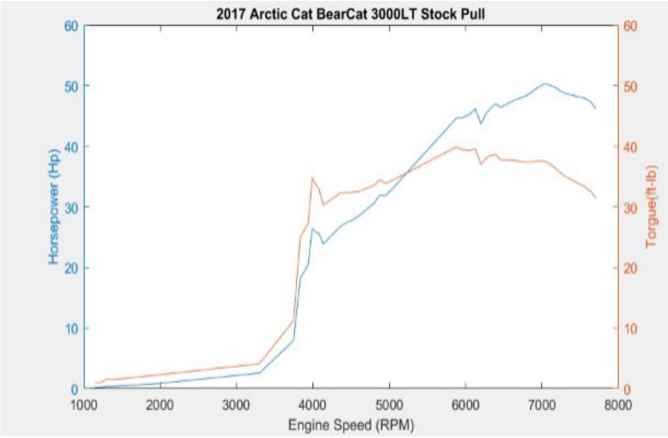

Figure 1: 2017 Arctic Cat BearCat 3000LT Baseline Engine Output

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 rigorous tuning with the 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 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 fabricating a turbocharger system to allow for higher power output with less fuel and by utilizing a high flow 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. The team felt it was important to keep the turbocharger mounted as close to the engine as possible. This would ensure the fastest and hottest exhaust gasses are entering the turbine. However, this limited the type of manifold designs available. To avoid clearance issues with surrounding panels, we opted to use a log style manifold to keep it compact. The primary tubes on the manifold were kept short to maintain high exhaust gas speeds.

To increase the effectiveness of the KP39, the stock wastegate was removed and an external wastegate was added in order to gain precise control over the intake air pressure. A Precision Turbo 38mm external wastegate was chosen due to its compact size, control over boost, as well as for proper control over exhaust pressures used to turn the turbine in the exhaust housing.

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 ensuring proper catalyst activation.

Lastly, to ensure the exhaust exiting the sled is quiet, the team opted for a turbo style muffler. The muffler chosen is manufactured by Dynomax. It was chosen do to its high flow characteristics while still being quiet. The team elected to go that route to reduce the cost of the snowmobile. Instead of developing a new muffler which includes high development costs and a relatively low volume production, this option gave the team very satisfying results while greatly reducing the cost and weight of the snowmobile due to the mufflers design and the fact that it is already being manufactured in high volume. The stock muffler weighed 20 lbs while the new dynomax muffler comes in at only 6 lbs. That means 14 lbs of weight was saved in the muffler alone.

Figure 2: Dynomax Turbo Muffler [7]

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].

The team considered 2 types of intercoolers, both air to air and air to water. Both options have their pros and cons. The air to air cooler is simple and doesn't require any external components. While it is relatively small, the fact that it needs to be exposed to high airflow, its mounting locations are limited. An air to water intercooler and be more compact, and be mounted anywhere because it utilizes coolant instead of air to cool the intake charge. However, an external coolant system with reservoir, pump, and hose would be needed to ensure the coolant is cold enough to cool the intake charge. Because of these extra components, the system would become bulky, adding unnecessary weight to the snowmobile. Therefore, 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.

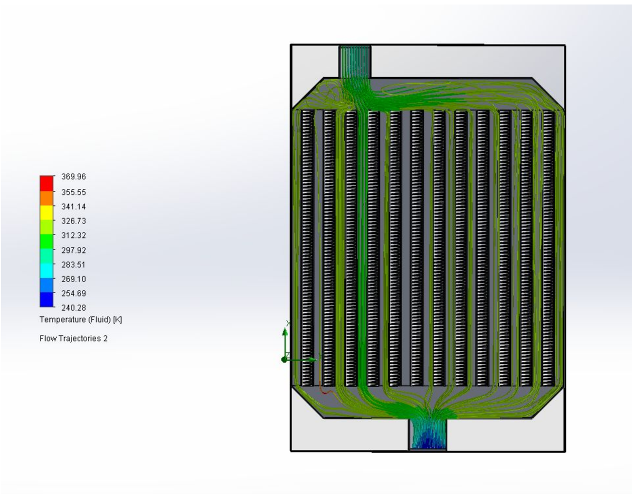

Figure 3: Intercooler Flow Simulation

To complete the intercooler and charge piping, our team elected to install a Turbosmart Kompact 20mm blowoff valve in the charge pipe to relieve the system of excess pressure when the throttle is rapidly released. This will prolong the life of the compressor in the turbocharger.

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 Motec M130 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, reduce NOx emissions, and deliver the cooled air charge to effectively increasing power output.
- Tailpipe emissions were reduced by the use of a 3-way catalytic converter, maintaining high catalyst efficiencies with a specially designed exhaust system and calibration.

Based on the above points, the 2018 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 2018 UB CSC snowmobile an ideal snowmobile.

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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
AFR	Air Fuel Ratio