# École de technologie supérieur (ÉTS)

# 4-Stroke Port Injected Turbo Engine Design

# Clean Snowmobile Challenge 2013 Design Paper



## ABSTRACT

With growing concerns regarding emissions controls with recreational vehicles such as the snowmobile, Team QUIETS has decided to the take on the challenge of modifying and improving the image of the snowmobile. The snowmobile used for the research is a 600 ACE 4 stroke engine from BRP. Modifications to improve engine mileage and the reduction of sound and exhaust emissions include the implementation of a turbocharger, a catalytic converter, a redesigned exhaust system and new engine control system. All these modifications made to the engine will allow the snowmobile to have excellent fuel efficiency, reduced sound and exhaust emissions while maintaining and even surpassing the stock engine power output. The modified snowmobile now has a peak power output of 66 horse power (HP) and 56 foot pounds (ft-lbs) of torque at 6200 RPM. The resulting global decibel level of the snowmobile in perfect trail conditions is now at 71 decibels (dB(A)), a 1 dB(A) reduction compared to the stock decibel level of 72 dB(A). The club is a great example of what a group of 16 people with common goals can accomplish.

## INTRODUCTION

Team QUIETS is very proud to present our submission for the 2013 Clean Snowmobile Challenge. This year we have changed our focus from a more efficient two-stroke engine to a turbocharged four-stroke design; we believe that this will allow us to achieve the great handling and acceleration characteristics we enjoyed with the two-stroke engine, all the while reducing emissions and noise to more competitive levels. We also believe that this year's project is considerably more economically viable than its predecessors, as it relies more on stock components and high-value modifications. We have accomplished a lot in a relatively short time, and hope that our efforts will pay off at the CSC 2013.

## ETS – CSC SNOWMOBILE DESIGN AND MODIFICATIONS

### Snowmobile Selection

Wanting to start with a completely new project for the 2013 CSC, the snowmobile selection had to be according to our objective. A small light engine block with good fuel efficiency and the reliability to withstand harsh engine calibration. Our goal was not to select a high HP and performance beast but rather a small trail snowmobile with little HP. Our choices were between our old high pressure direct fuel injected (HPDI) ETEC snowmobile and the new 600 ACE 4 stroke snowmobile.

**Table 1 - ETEC vs 600 ACE engine specs**

| | ETEC | 600 Ace |
|---|---|---|
| Displacement | 600 cc | 600 cc |
| Stroke | 2 Stroke | 4 Stroke |
| HP | 122 | 60 |
| Fuel consuption | 18 mpg | 28 mpg |

Having 122 HP and a high trail fuel consumption of 18 mpg, the ETEC was obviously not the ideal snowmobile suited for this competition and its point distribution system. On the other hand, the 600 ACE shows great potential with its good mileage and low HP which give us the opportunity and challenges to raise the engine's maximum power output while still maintaining lower fuel consumption than the ETEC.

### Turbocharger Integration

With the new 2013 CSC rules allowing us to switch between engine mapping configurations, we examined the different possibilities of easily increasing the engine's output power with minimal internal engine modifications. The best idea for this task was to integrate a turbo compressing system to the engine. The idea of a turbo compressor is to force compressed air into the combustion chamber. Having more air in the cylinder, more fuel is need to keep the combustion at a stoichoimetric level (Lamda ($\lambda$) of 1.000). The main reason for adding a turbo compressor is to achieve higher engine horse power output while minimizing the engine size. What we are looking for is higher average effective pressure (AEP). The average effective pressure allows us to compare the efficiency of the designed combustion volume at max power output. It is equal to the work per cycle divided the displacement volume of the engine and can be represented by the following equation:

$$AEP = \frac{6.28 * n_R * T}{V_d}$$

Where T is the torque, $V_d$ is the engine's displacement volume and nr is equal to 2 for 4 stroke engine and 1 for 2 stroke engines. Here is a table which compares the AEP with different types of engine systems.

**Table 2 - AEP table**

| Engine | Mass Air Flow ($Kg/m^3$) | AEP |
|---|---|---|
| Naturally aspirated | 1.19 | 100% |
| Turbo compressor with no cooling | 2.23 | 187% |
| Turbo compressor with cooling | 2.78 | 234% |

The turbo with found most appropriate for our engine was the Garrett GT1241. This small turbo and current engine configurations allows us to minimize the turbo charger's inactive time ''Turbo lag'', in order to offer boost on the majority of our engine mapping. The intake system was also equipped with a small intercooler allowing the exchange of heat through convection with cold passing air.

# Electrical and Engine Control

## Engine Management System (Hardware)

Due to financial constraints and a lack of support for the 600 ACE engine's crankshaft encoder in our version of the MotoHawk library, we opted for a Megasquirt 3 built by DIYAutoTune to serve as our engine controller this year. The Megasquirt 3 is the most advanced version of the Megasquirt series, providing almost all of the features found in other engine management computers for a fraction of the price. It is designed to be easy for anyone to implement and has a fairly large community for support as well as in-depth documentation available on the MS3 web site. Above all, the availability of (older) source code and schematics allows us to retain some of the flexibility we enjoyed with the MotoTron/MotoHawk system. We believe that the main shortcoming- non-sealed housing and connectors- will be sufficiently addressed by the strategic placement of the module in the snowmobile.

## Wiring Harness

In previous years, we designed our own wiring harness from scratch to replace the stock one. This year, we decided to implement an "adapter harness", which interfaces the stock wiring harness to the Megasquirt while still allowing us to add other peripherals (see next section) to the system. We believe that by using this approach, we can avoid minor electrical issues which have plagued us in previous years and thus increase overall reliability without losing any of the functionality provided by a custom harness. For the most part, the harness directly adapts the stock Molex connectors to the DB-37 ones used by the Megasquirt, but it also provides a secondary fuse box which taps off the main fuse and rewires the DESS key to directly control all relays. In addition, it provides a relay for the fuel pump and wires the starter button directly to the starter solenoid (Fig. 1).

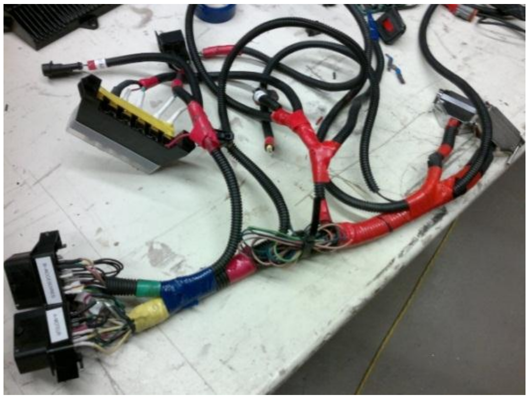


**Figure 1 - Adaptive harness**

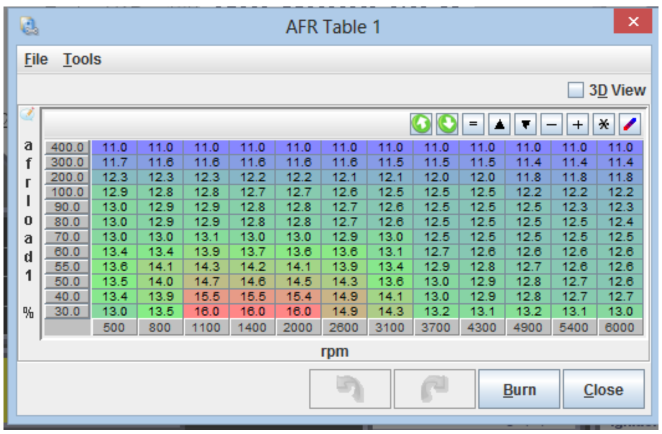
A secondary advantage of this approach is that it is trivial to return to the stock configuration; this was done multiple times to compare calibrations and the whole process was completed in less than 5 minutes.

## Additional peripherals

As much as we attempted to adhere to the 600 ACE's minimalist electrical design, it was nevertheless necessary to add several peripherals in order to achieve the desired results: The 600 ACE's stock EMS uses slight variations in engine speed in order to determine its phase, but the Megasquirt does not support this so we a cam sensor designed for the 1200 4-tec was added to the engine. We also added a flex-fuel sensor (same model as last year) in order to meet the E40-E85 competition requirement, as well as a wideband O2 sensor to improve performance and provide data logging functionality. Finally, an electronic solenoid was added to control the turbocharger's waste gate.

## Engine calibration

We believe that completely replacing the snowmobile's EMS gives us an important degree of flexibility in our projects and this year was no different. The unfortunate consequence is that, for the first year at least, one of the largest and most important tasks for our team is the calibration of the engine. This year, we had the added challenge of implementing a turbocharger so the calibration had to be perfect in order to avoid damaging the engine. Our task was greatly assisted by the auto-tuning feature provided with the Megasquirt's tuning software, as well as embedded closed loop functionality (Fig. 1).


AFR Table 1

File Tools

3D View

| afrload1 % | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 400.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 |
| 300.0 | 11.7 | 11.6 | 11.6 | 11.6 | 11.6 | 11.6 | 11.5 | 11.5 | 11.5 | 11.4 | 11.4 | 11.4 |
| 200.0 | 12.3 | 12.3 | 12.3 | 12.2 | 12.2 | 12.1 | 12.1 | 12.0 | 12.0 | 11.8 | 11.8 | 11.8 |
| 100.0 | 12.9 | 12.8 | 12.8 | 12.7 | 12.7 | 12.6 | 12.5 | 12.5 | 12.5 | 12.2 | 12.2 | 12.2 |
| 90.0 | 13.0 | 12.9 | 12.9 | 12.8 | 12.8 | 12.7 | 12.6 | 12.5 | 12.5 | 12.5 | 12.3 | 12.3 |
| 80.0 | 13.0 | 12.9 | 12.9 | 12.8 | 12.8 | 12.7 | 12.6 | 12.5 | 12.5 | 12.5 | 12.5 | 12.4 |
| 70.0 | 13.0 | 13.0 | 13.1 | 13.0 | 13.0 | 12.9 | 13.0 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 |
| 60.0 | 13.4 | 13.4 | 13.9 | 13.7 | 13.6 | 13.6 | 13.1 | 12.7 | 12.6 | 12.6 | 12.6 | 12.6 |
| 55.0 | 13.6 | 14.1 | 14.3 | 14.2 | 14.1 | 13.9 | 13.4 | 12.9 | 12.8 | 12.7 | 12.6 | 12.6 |
| 50.0 | 13.5 | 14.0 | 14.7 | 14.6 | 14.5 | 14.3 | 13.6 | 13.0 | 12.9 | 12.8 | 12.7 | 12.6 |
| 40.0 | 13.4 | 13.9 | 15.5 | 15.5 | 15.4 | 14.9 | 14.1 | 13.0 | 12.9 | 12.8 | 12.7 | 12.7 |
| 30.0 | 13.0 | 13.5 | 16.0 | 16.0 | 16.0 | 14.9 | 14.3 | 13.2 | 13.1 | 13.2 | 13.1 | 13.0 |
| rpm | 500 | 800 | 1100 | 1400 | 2000 | 2600 | 3100 | 3700 | 4300 | 4900 | 5400 | 6000 |

Burn Close

**Figure 2 - AFR Table engine load vs RPM**

An unfortunate drawback of running forced induction was that the fuel mixture had to be enriched in order to keep the pistons cool, which is sub-optimal for emissions; however, we attempted to keep the air-fuel mixture near or at stoichiometric wherever possible to ensure the catalytic converter would perform at peak efficacy. This resulted in the trade-off of consuming more fuel at part-throttle in order to reduce emissions, which is in line with what can be found in most emissions-controlled vehicles. The combination of forced induction and the addition of ethanol fuel proved to be a bit too much for the stock injectors to handle, so the maximum engine speed was limited to 6000 RPM. Nevertheless, the engine was able to produce 64 HP and 56 ft-lbs of torque at 6000 RPM thanks to the turbocharger, and the slower revolution limit also helped reduce engine noise. The ethanol fuel requirement was actually advantageous to our project, as the higher effective octane rating provided by ethanol allowed the engine to run with more spark advance and compression than would have been possible with premium-grade gasoline only. As an added precaution, the spark plugs were replaced with "colder" variants, in order to reduce the chances of detonation and pre-ignition brought on from the added spark advance.

# Exhaust Design

## Noise Evaluation

To help minimize noise emissions, a new exhaust was designed to help cut unwanted frequencies. The first step was to gather base noise emissions coming from engine for analysis and comparison.

The measurements were taken with a Larsen microphone placed 0.5 m away from the noise source according to the standard ISO 3744. The source was isolated to illuminate noise coming from the track or chain case. The measurements were taken over 10 seconds from 1500 RPM to 7200 RPM. The 2 graphs (Figure 3 and 4) bellow shows the results.

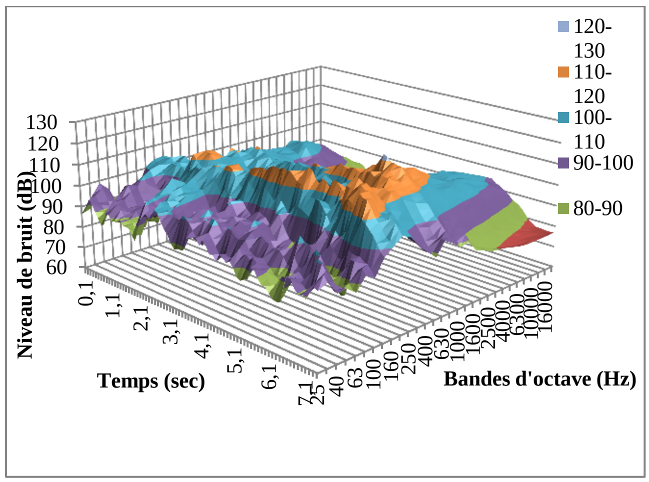



**Figure 3 - Sound level without exhaust**

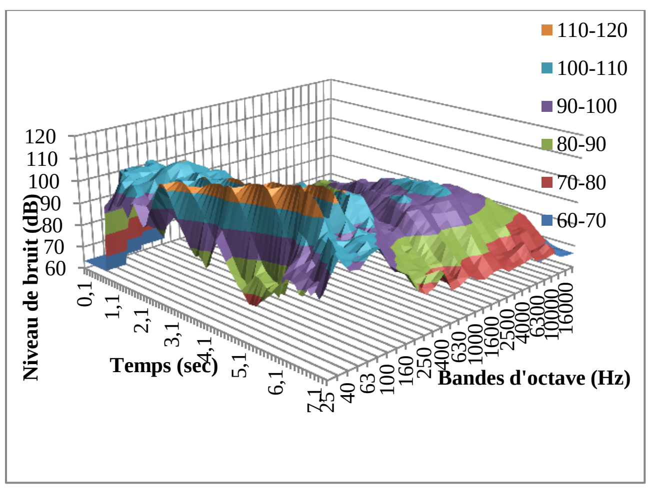



**Figure 4 - Sound level with stock exhaust system**

The comparison between these two graphs allowed us to obtain important information to be use in the exhaust design.

We can see that the frequency bands from 200 to 1000 Hz dominate the other bands as the engine RPM goes up. When you look at the graph bellow, you can see that BRP designed the exhaust system to eliminate most frequencies between 400 and 1600 Hz.

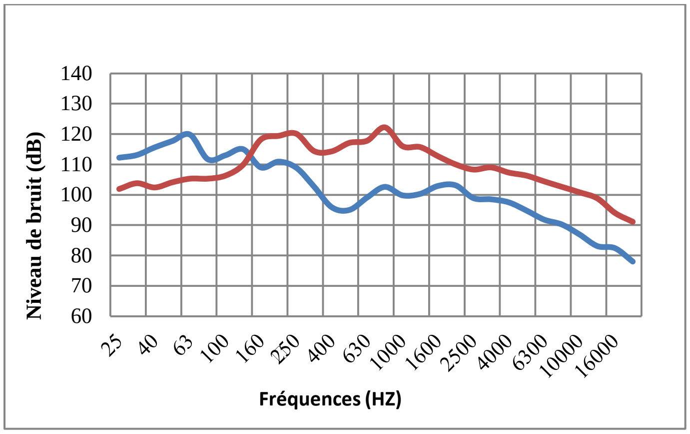



**Figure 5 - Sound level comparison,**

## Improved design

The data that we originally procured helped a lot with the design of the exhaust system. We decided to try and eliminate the 1000 Hz band which seemed to have the highest power level. The exhaust was design in three compartments to maximize the frequencies attenuation. The following image represents a cut view of our 2012-2013 concept. (See figure 6)

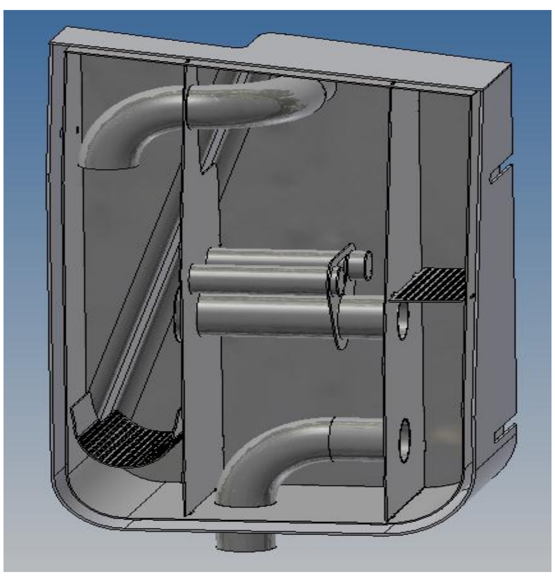


**Figure 6 - Exhaust Design 2012-2013**

To be able to reduce the targeted frequency, three resonators were used. Resonators are used to highly attenuate frequencies. The length of the resonator is proportional to the wave length. For example, the 900 Hz frequency has a wave length of 3.75 inches. So to eliminate it, we need a 3.75 inch resonator.

$$\lambda = \frac{c}{F} = \frac{343}{900 * 4} = 0.095\ m\ (3.75\ po)$$

So in our case, with the 900 Hz frequency being the highest sound level, a 3.75 inch tube was integrated to eliminate this undesired frequency. In total, three length of resonators were chosen, 3.25, 4 et 4.25 iches for the following frequencies (900, 850 and 800 Hz).

To eliminate higher unwanted frequencies are cut using mineral wool. The wool was inserted in all three chambers to absorb the high energy generated by high frequencies.

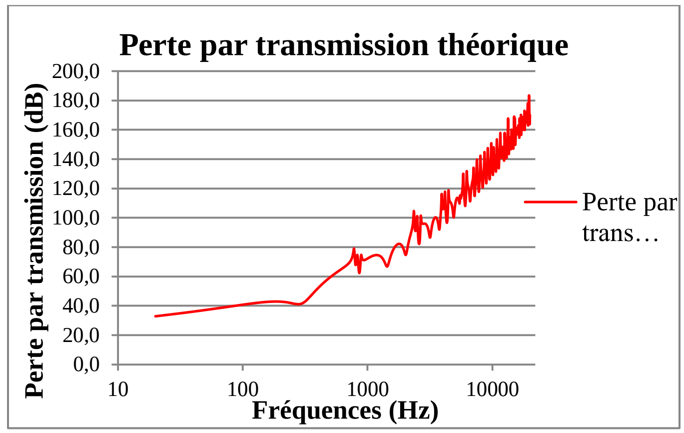



**Figure 7 - Sound transmission loss**

After simulating the exhaust with the help of a matlab program, we can now graph and examine the transmission losses. (See Figure 7) The exhaust is very efficient for eliminating high frequencies. We can also observe a reduction in the 800-1000 Hz band. The untouched lower frequencies can be neglected since these frequencies are not as influential to the human ear and will be reduced with the conversion of the decibel level form dB to dB(A).

# Air Box Intake Design

The stock air intake is designed to work under a vacuum only, and therefore there was a concern that it could rupture under the pressures produced by a forced induction system. In addition, a BRP representative informed us that the stock intake could be potentially unreliable for a turbocharged application. Therefore, we designed a new intake (See figure 8) to withstand positive pressure as well as meet the following criteria:

- Ensure that it does not collide with any other components;

- Maximize the new intake's compatibility with stock components (sensors, intake flange, coupling, injectors, etc...);
- Minimize noise related to the intake (vibration, whistling, etc...);
- Optimize the flow and velocity of air in the intake;
- Maximize fuel economy by ensuring the plenum is of optimal length;
- Maximize engine efficiency at high RPM.

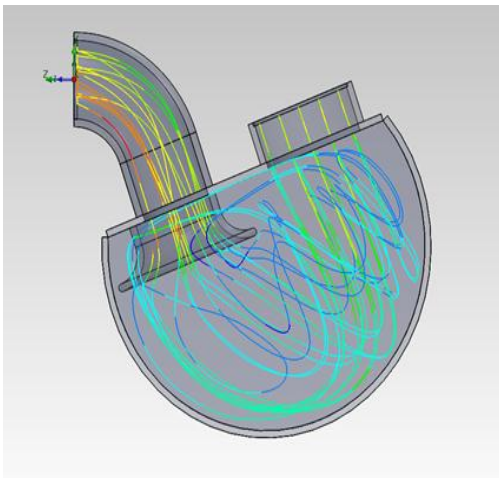


**Figure 8 - Air intake simulation (6000 RPM)**

In order to ensure that the new air intake fits correctly, it was based on measurements taken from the stock intake. By attempting to keep the overall sizing close to that of the stock intake, we were able to install it in the snowmobile without any other modifications. 1/8" aluminium with an anti-vibration coating was used to dampen any intake noise. The design also allowed for a smooth air flow, minimizing air turbulence and thus reducing noise even further. This was accomplished by ensuring that all curves in the intake had the largest radius possible. Bellmouths were also placed at the entry to the runners, to ensure that the air could easily pass from a large dimension tube to a smaller one all while raising its velocity. To improve fuel economy, the air entry was optimized to properly atomize injected fuel and thus provide a uniform combustion process. The engine's high-RPM efficiency was maximized thanks to the dimension of the runners and the length of the bellmouths.

We were able to successfully run the turbocharged engine at low boost pressure with the stock intake, and did not notice any adverse effects to engine performance upon installing the new one. This would confirm that our design goals were largely met.

## SUMMARY/CONCLUSIONS

The design our new 4-stroke turbocharged engine is a new step for Team QUIETS. Having never worked with 4-stroke engines or even turbocharged engines, we can proudly say that we have successfully implemented one of the first turbocharged 600 ACE with variable engine mapping. Although we did not have enough time to provide enough concrete results and prove that our theories and modifications worked, we are confident based on preliminary results that the work we have done is a step forward in the right direction toward the design of an eco-friendly, yet powerful snowmobile.

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## DEFINITIONS/ABBREVIATIONS

| | |
|---|---|
| dB | Decibel Level |
| CSC | Clean Snowmobile Challenge |
| EMS | Engine Management System |
| HPDI | High pressure direct injection |