# 4-Stroke Port Injected Turbocharged Snowmobile Design Clean Snowmobile Challenge 2015 Design paper

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## ABSTRACT

As engineering students from the snowmobile's origin province, Team QUIETS has decided to take on the challenge of modifying and improving the image of the snowmobile. With growing concerns regarding emissions controls and noise from recreational vehicles such as the snowmobile, we are using a 2012 Ski-Doo 600 ACE 4 stroke engine for our researches to mitigate these factors. Our modifications include the implementation of a turbocharger, an entirely redesigned exhaust system, an EGR system and a new engine management system in order to improve exhaust emissions and noise reduction. These changes allow our snowmobile to surpass the stock engine power output while being quiet and economic. The modified snowmobile now has a peak power output of 85 horse power (HP) and 76 foot pounds (ft-lbs) of torque at 7200 RPM. This student club is a great example of what a group of 22 students with common goals can accomplish.

## INTRODUCTION

Team QUIETS is proud to present our 2015 Clean Snowmobile Challenge's submission. This year, we are pushing further the turbocharged 4-stroke engine design. We believe that this will allow us to achieve the great handling and acceleration characteristics we enjoyed with the two-stroke engine, with much more reliability, while considerably reducing emissions and noise. 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 we look forward to show our improvement at the CSC 2015.

## SNOWMOBILE DESIGN AND MODIFICATIONS

### Snowmobile Engine

#### Comparison and Selection

The snowmobile engine selection had to be according to our objectives. We are looking for a small light engine block with good fuel economy and the reliability to withstand harsh engine calibration. With the help of forums on behalf of the FCMQ (Federation of Snowmobile Clubs of Quebec), we were able to determine the needs of the rider. Environmental issues are not a big concern in the region of Quebec, the main attraction from the buyer's point of view is power and fuel economy. Usually, these two qualities do not go hand in hand, but with the use of small turbo charged engine block with available table switching modes, buyers could get a good compromise on both desires. Theoretically, a 600 Ace turbocharged will have a better fuel economy then its new older brother, the 900 Ace, which is a naturally aspired engine. Going for small turbo charged engine pushes the snowmobile industry to follow the automotive industry where we can witness a rising amount of models available with smaller turbo charged engine blocks with better fuel economy.

***Table 1. Snowmobile Comparison***

| | **900 Ace** | **E-tec** | **600 Ace Turbo** |
|---|---|---|---|
| Displacement | 900 cc | 600 cc | 600 cc |
| Stroke | 4 Stroke | 2 Stroke | 4 Stroke |
| Hp | 90 | 121 | 100 |
| Fuel Consumption | 23 mpg | 21 mpg | 24 mpg |

## Engine Control and Calibration

For the 2015 edition of the CSC we upgraded our engine management computer (EMC) to a Motec M400. We made this decision to solve some of the weaknesses of the Megasquirt 3. First of all, we were having important reliability issues with our previous computer. We chose Motec because of the proven reliability of the platform in many racing applications over the past years.

The Motec M400 offers features that are very similar to that of the Megasquirt. These include lambda closed loop control, high speed data logging, boost control and many more. By switching to the M400 we also benefit from added functionalities such as the ability to create custom fuel and ignition compensations for different situations. We are also able to fully control our new electronic throttle system.

Another important aspect of our decision to switch to Motec is the easy access to technical support. The company's technical support was extremely helpful and we had answers to our questions very quickly. After consulting our school's formula SAE team, which also uses Motec, it seemed obvious this EMC was the one to choose for our prototype.

We believe that completely replacing the snowmobile's EMC 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 getting engine to run up to its maximum potential RPM which is 7200 RPM. The engine calibration had to be perfect in order to avoid damaging the engine the high amount of heat caused by the turbo. Our task was greatly assisted by the embedded closed loop lambda control system as seen on figure 1.

Lambda Table (Lambda)

| Load % \ RPM | 0 | 1000 | 2000 | 4000 | 6000 | 8000 | 10000 |
|---|---|---|---|---|---|---|---|
| 200,0 | 0,80 | 0,80 | 0,80 | 0,76 | 0,75 | 0,75 | 0,75 |
| 180,0 | 0,80 | 0,80 | 0,80 | 0,80 | 0,75 | 0,75 | 0,75 |
| 160,0 | 0,85 | 0,85 | 0,85 | 0,85 | 0,80 | 0,75 | 0,75 |
| 140,0 | 0,90 | 0,90 | 0,90 | 0,90 | 0,90 | 0,80 | 0,75 |
| 120,0 | 0,95 | 0,95 | 0,95 | 0,95 | 0,95 | 0,95 | 0,80 |
| 100,0 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 |
| 80,0 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 |
| 60,0 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 |
| 40,0 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 |
| 20,0 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 |
| 10,0 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 |

***Figure 1. AFR Table (Engine Load vs RPM)***

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.

## Calibration Strategy

Running the engine at a stoichiometric ratio of 1 for Lambda is ideal for maximum efficiency and emission's control. But to maximize fuel economy, a lean combustion is required. To save on fuel, the programmed closed loop AFR target during cruising speed will rise to 1.02, meaning that between 5000 and 6000 RPM and between a TPS position of 15 to 30%, the engine will be running on a lean air/fuel mixture.

The programmed AFR value was calculated with the help of the specific fuel consumption (SFC) in g/KW-hr represented by the equation (1).

$$SFC = \frac{\dot{m}}{P} \quad (1)$$

Where m is the fuel flow in g/h and P is the engine's power output in kW. On a test bench, while keeping the engine at a constant speed and load, it is possible to witness the variation of the SFC by changing the AFR. Testing various ratios will trace a curve on a graph on figure 2.

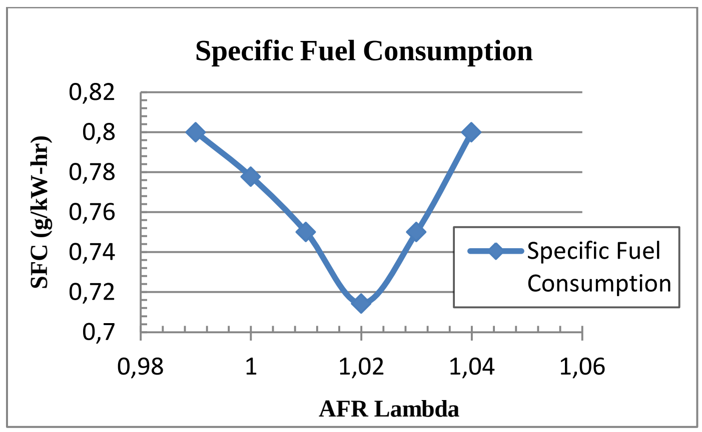


***Figure 2. Engine's Specific Fuel Consumption***

So by following this curve, we can establish the correct AFR for each operation point running with a lean air/fuel mixture.

## Engine Emissions Control

Regarding emissions found in exhaust gases, only three types of particles really cause a problem for 4 stroke engine. According EPA standards, our engine should pass a 5-mode resulting in an E-score greater or equal to 100. According to the following formula:

$$E = \left(1 - \frac{(HC + NO_x) - 15}{150}\right) * 100 + \left(1 + \frac{CO}{400}\right) * 100 \quad (2)$$

The compilation of the measured brake specific emissions (g/Kw-hr) of HC, NOx and CO will require a score greater than 100. To accomplish this goal our team has opted for implement two types of emissions control systems. Since most of engine's running point aim for a stoichiometric efficiency (λ=1), a good majority of the exhaust gas emissions can be treated with the help of three way catalyst. A catalyst composed of a stainless steel casing and of a stainless steel substrate from the company Aristo and Emitec coated layers of platinum, rhodium and palladium. This single bed three-way catalytic converter system offers conversion efficiency between 80-95% depending of the engine's operating conditions and air/fuel ratio as seen in the table below.

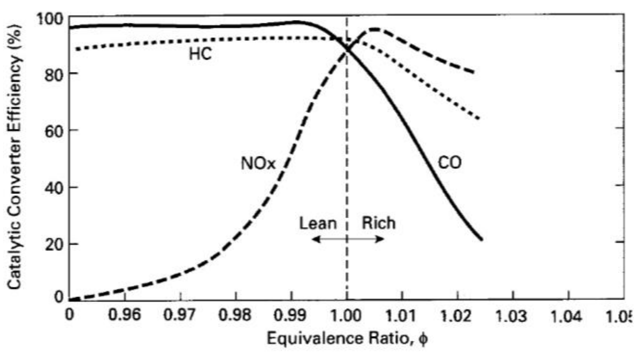


***Figure 3. Catalytic Converter Efficiency vs Air/Fuel Ratio***

By referring our engine calibration to the figure 3, we can notice that a maximum of the catalytic converter's efficiency is achieved at an air/fuel ratio of phi=1. Going back to our engine control from the previous section, our fuel/air ratio (phi) will drops to 0.98 during cruising speeds of 45 mph in order to improve the snowmobile's fuel efficiency. But while saving on fuel, our engine's emissions were altered. As seen on figure y, decreasing the value of phi causes a reduction in HC and CO particles, but an increase in NOx.

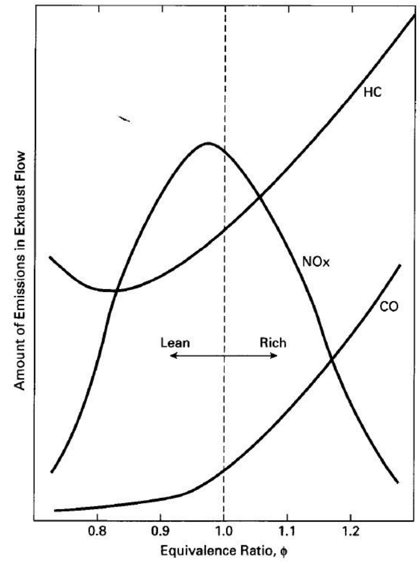


***Figure 4. Amount of Emissions in Exhaust Gases vs Air/Fuel Ratio***

Not only that, but the lean air/fuel mixture reduces the efficiency of the catalytic converter. A test was run to show the effects of running an engine lean on fuel on NOx formation. The tests were carried out at an engine speed of 3500 RPM and with a 30% throttle position opening.

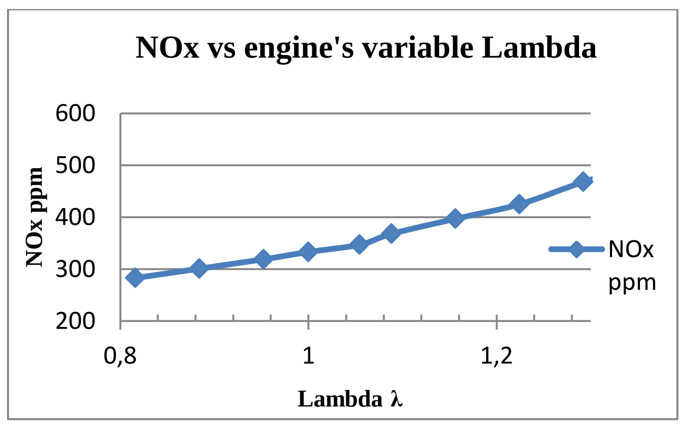


***Figure 5. NOx ppm vs Engine Lambda of operation (at 3500 RPM at 30% TPS)***

By observing the results illustrated on the figure 5, we can conclude that a lean running engine produces a non-negligible augmentation of NOx. As seen in figure 1, the catalytic converter will still be efficient for HC and CO particles with a lean burning engine but conversion efficiency for NOx will drop drastically. Looking at NOx formation, we can identify three sources contributing to its formation. The first and major source of NOx formation is due to heat peaks in the combustion chamber, the second source is due to the reaction of nitrogen with hydrocarbon radicals. The last source of NOx formation is due to the nitrogen found in the fuel itself. Since the heat peaks in the combustion chamber is considered the most significant source for NOx formation, a consideration was taken to eliminate the two other sources and working on reducing the flame temperature of the combustion. By looking at the figure 6 illustrating the Zeldovich NOx formation model, we can observe the direct link to flame temperature and NOx formation rate.

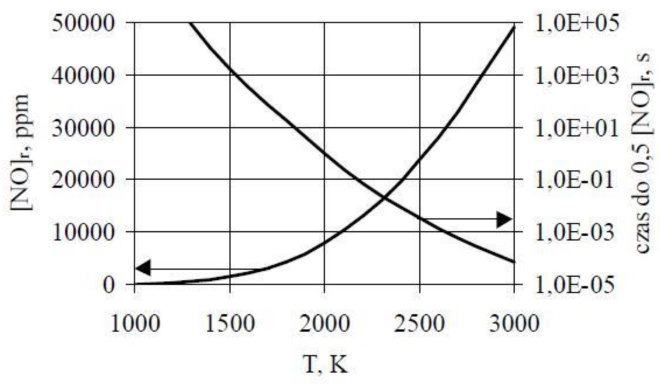


***Figure 6. NOx ppm vs flame temperature (NOx formation according to the Zeldovich model)***

With such a comparison, the inevitable solution for this problem would be to implement an EGR system in order to reduce the combustion flame temperature. By re-circulating a certain percentage of the exhaust gases, the quantity of oxygen available for the combustion is reduced and replaced with inert gases such as CO and CO2. To be able to get the approximate quantity required, a comparison method is used to calculate the amount of energy on the reactive side of the combustion chemical equation versus the amount of energy on the product side of the equation.

$$C_8H_{18} + O_2 + N_2 \rightarrow CO_2 + CO + O_2 + H_2O + N_2 \quad (3)$$

By using the first rule of thermodynamics, a balanced energy equation can be established. For this comparison method, we consider that there is no work exchanged (W), no kinetic energy (Ek), no potential energy (Ep) and no heat exchanged with surrounding environments (combustion chamber).

$$Q - W = \Delta E = \Delta H + \Delta Ec + \Delta Ep \quad (4)$$

$$\Delta E = \Delta H \quad (5)$$

$$\Delta E = \text{H product} - \text{H reactive} \quad (6)$$

What we have left is the difference between the enthalpy of the reactive and the enthalpy of the products. In other words, the enthalpy of the products is equal to the enthalpy of the reactive.

$$H\ product = H\ reactive \text{ (Units kJ/kmol)} \quad (7)$$

$$[\sum np\ (h°f + (h - h°))product = \sum nr\ \left(h°f + (h - h°)\right)reactive]$$

We can now work with the equation above to compare the enthalpy by estimating a combustion flame temperature for the reactive. We have h°f representing the formation enthalpy of the molecules, h represents the enthalpy of a molecule at a known temperature and h° represents the enthalpy at a reference temperature. By starting with a flame temperature of 1600 K, we can assume that the actual temperature will be much higher, therefore, it is possible to iterate to a higher flame temperature until the enthalpy of the products is equal to the enthalpy of the reactive. This temperature will give us the peak temperature of the combustion for a given combustion formula.

***Table 2. Theoretical Adiabatic Fuel Temperature (K)***

| TPS (%) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **40** | 1620 | 1680 | 1600 | 1580 | 1560 | 1560 |
| | **35** | 1620 | 1680 | 1600 | 1600 | 1560 | 1560 |
| | **30** | 1620 | 1660 | 1580 | 1580 | 1560 | 1560 |
| | **25** | 1620 | 1660 | 1580 | 1580 | 1560 | |
| | **20** | 1600 | 1640 | | | | |
| | **15** | 1600 | | | | | |
| | | **3250** | **3750** | **4500** | **4750** | **5250** | **5500** |
| | | **RPM** | | | | | |

In table 2, we can find the theoretical adiabatic flame temperature of combustion for the operating cells of the EGR valve. With these temperatures, we can now fix a reduction objective which in our case is 200K. The new combustion equation with re-circulated gases is as described below with x representing the percentage of gases re-circulated.

$$C_8H_{18} + O_2 + N_2 + x(CO_2 + CO + O_2 + H_2O + N_2) \rightarrow CO_2 + CO + O_2 + H_2O + N_2 \quad (8)$$

The actual quantity of exhaust gases re-circulated is determined with the difference in pressure between the intake of the EGR valve and the out port, and the EGR valve position. By using Bernoulli's equation of energy, we can isolate the fluid speed variable which will vary with the valve's position.

$$Z_1 + \frac{P_1}{\gamma} + \frac{v_1^2}{2g} + H_p - H_m - H_L = Z_2 + \frac{p_2}{\gamma} + \frac{v_2^2}{2g} \quad (9)$$

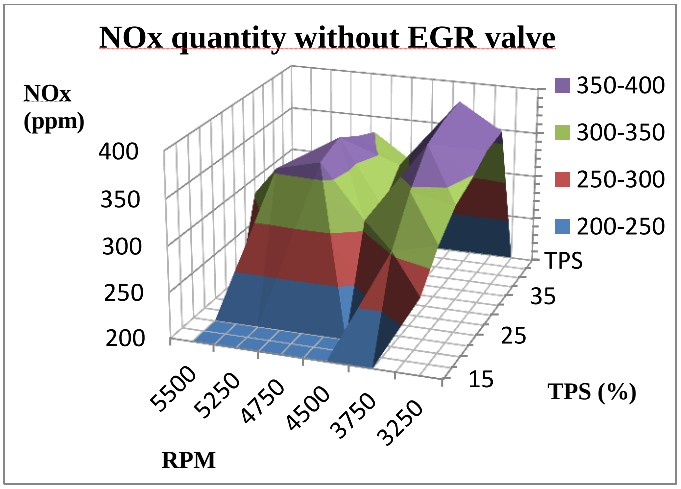


*Figure 7. NOx Quantity with no EGR Valve*

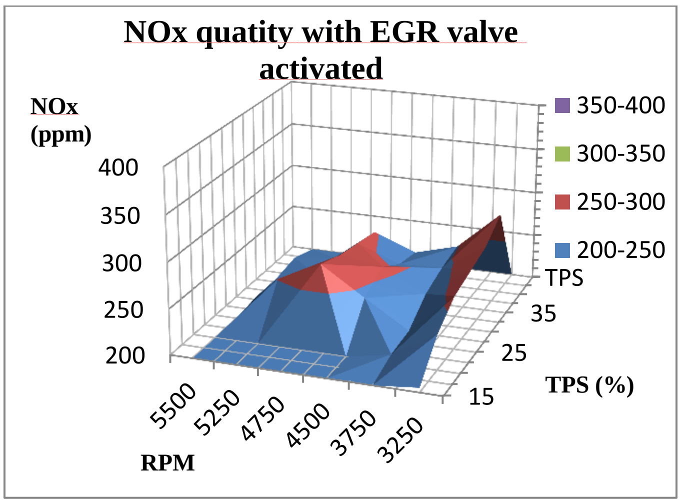


*Figure 8. NOx Quantity with Active EGR Valve*

By comparing figure 7 and 8, the effects of the EGR valve on NOx have been proven very effective. The achieved global NOx reduction of 23% in the EGR's operating range proves that the reduction in the flame temperature is directly linked to the reduction of NOx.

Following the emissions data collection, a rise in HC particles and a loss in power were noticed. The air fuel ratio also dropped resulting in a rich combustion. To explain these variances, the following equation representing the flame's front speed shows the effects of re-circulated gases.

$$S_L(x_b) = S_L * (1 - 2.06 * {x_b}^{0.77}) \quad (10)$$

Were SL is the flame speed and xb is the percentage of re-circulated gases. With a greater quantity of re-circulated gases, the flame speed reduces. To compensate, more spark advance is needed to allow more complete flame propagation and to be able to harvest the maximum amount of power from the fuel.



## Turbo selection

This year, the ETS team uses a new turbocharger. In fact, after some calculations, it was determined that the MGT1238Z fit better with the new power goal. To achieve 110 hp at 7250 rpm, the old turbo would have to spin way passed its max speed limit of 220000 rpm. The new setup has the potential to rotate up to 295000 rpm. To achieve the desired power goal, it has to work just below this limit, as seen on figure 10.

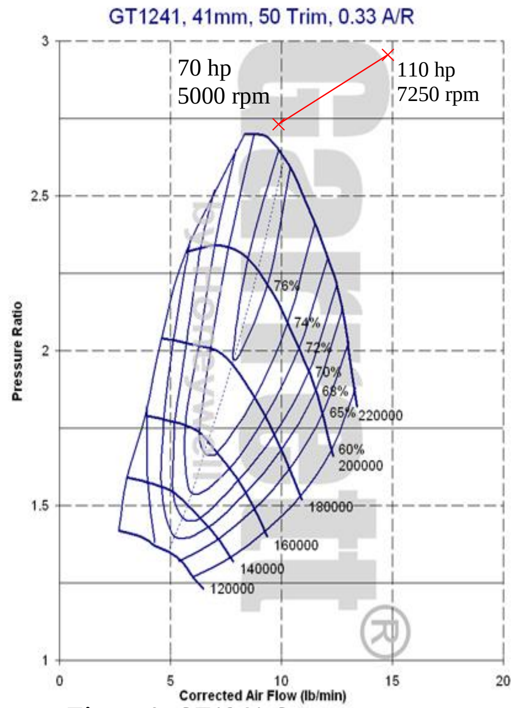


*Figure 9. GT1241 Compressor map*

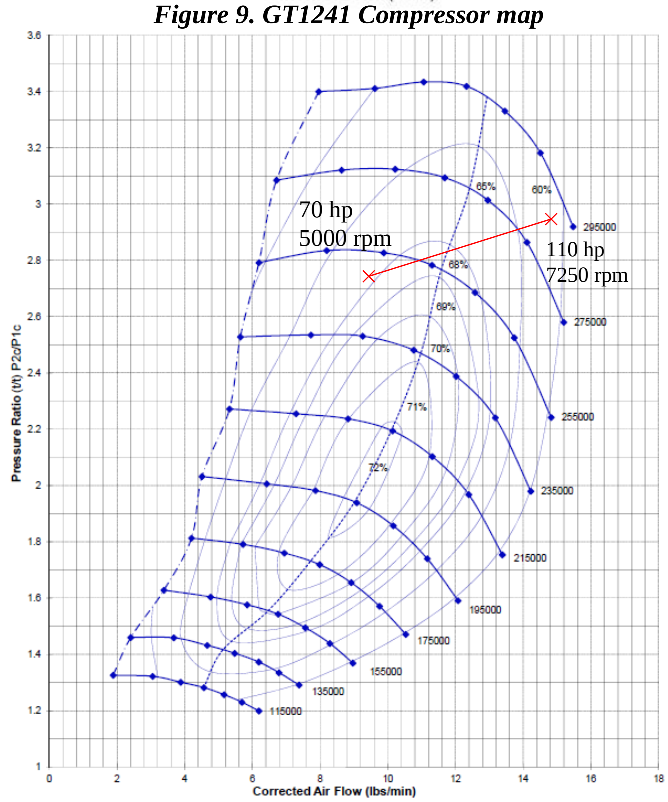


*Figure 10. MGT1238Z Compressor map*

## Electronic throttle control

The installation of an electronic throttle control is one of many upgrades done on our snowmobile this year. Also known as drive-by-wire system, this throttle body is actuated by an electric signal from the engine management system, which receives data from the throttle lever. An electronic throttle control is more efficient compared to the previous mechanical throttle control. It is also capable of controlling engine idle speed, replacing the auxiliary idle valve originally needed on a mechanical setup. The throttle lever is softer and easier to operate improving driver's comfort. This system allowed us to program selectable performance modes based on throttle body butterfly valve opening percentage. This ability to switch between modes enables significant power enhancement and extensive improvement on fuel economy. Overall, the electronic throttle control replaces a few components and its accuracy ensures flawless throttle response.

# Acoustics and Noise Reduction

## Exhaust Design

This section examines more thoroughly the thought process behind the design of the exhaust system. For the most part, this year's product is based on last year's concept. Since the previous exhaust yield good improvement over stock, it served as a base for the new system.

The casing of the new muffler is very similar to the previous one. As a matter of fact, only minor exterior modifications were made in order to improve fitting of the part in the snowmobile as well as facilitate its assembly. Some examples of the improvements implemented include, but are not limited to: dimension constraints, substitution of wide radius bends for simple bends, addition of bends in some strategic points in order to limit welding, etc. The biggest alteration to the design is the fact that the front panel is now removable. This allowed us, during testing period, to properly examine the quality of the absorbent material used; improper isolation was a major flaw we encountered during last year's competition. The following figures compare the previous version of the muffler with the new one.

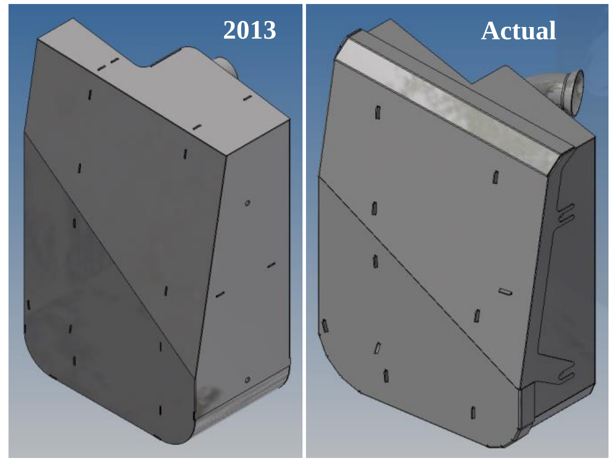


***Figure 11. New and Old Exhaust Muffler Design***

The interior of the silencer is also very similar to that of last year's. Exhaust gases follow the same path through the various sections. The only notable modification is the replacement of the pair of resonators parallel to the center tube in the middle section, with three different length resonators fixed vertically to the said center tube. The length of each resonator has been determined experimentally in order to mitigate the desired sound frequencies. This being said, the more present 600Hz, 700Hz and 850Hz are now greatly dampened. Furthermore, the slight design rework allows the elbow at the entry of the muffler to serve as an additional resonator. Sections 1, 2 and 3 are purposely filled with sound dampening material in order to lessen the noise generated by the entire frequency range. This process performs significantly well with higher frequencies. Figure 12 illustrate the interior design of the two latest exhaust designs.

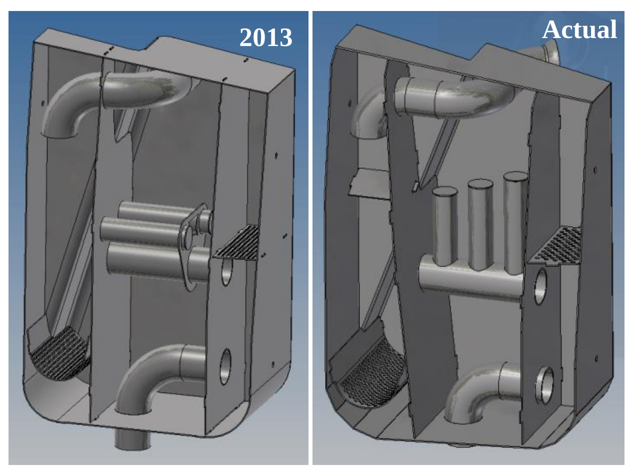


***Figure 12. Muffler's Interior Design***

With the sole purpose of optimizing the length of the resonators and reducing noise, many acoustic tests were performed on the motor. These measurements were conducted on an exhaustless engine at various rotation speeds (from 4000RPM to 7000RPM by increments of 500RPM). The 3D graph from figure 19 in the Appendix C points out these results. These results indicate that the engine generates most of its strong frequencies between 150 Hz to 900 Hz. By adjusting the resonator's length, it will be possible to increase the exhaust system's efficiency and eliminate the targeted frequencies.

### *Resonator length calculation*

A simple equation allows us to determine the necessary length of a resonator in order to eliminate the desired frequencies:

$$f = \frac{c}{4 * L} \quad (11)$$

However, in practice there is a phenomenon called edge effect which slightly distorts the expected results. Indeed, the edge of a resonator influences the path of a wave in a way that simulates a longer tube length then what it really is. Thus, to counter this deviation, the resonator must be slightly shorter than what the theoretical value suggests. Table 3 in Appendix A shows the difference between speculated theoretical frequencies and experimentally observed frequencies for the resonators present in the exhaust system.

The substantial difference between the expected and obtained results is what encouraged us to modify the sound reduction system of the exhaust. Thereby, we were able to match the desired frequencies by adjusting each resonator's length inside the muffler and therefore increase its efficiency. Appendix B shows the measurements for each resonator. It wasn't possible to experimentally measure the frequency in the resonator at the entry of the muffler which explains why it wasn't modified.

### *Final Results*

Finally, we ran new tests with the new exhaust fitted to the engine and were able to achieve the results found in the 3D graph from figure 20 in Appendix C. On a global point of view, the noise level is reduced throughout the entire sound stage. Moreover, it seems that engine speed only slightly affects noise intensity. It is nonetheless hard to quantify noise reduction by simply comparing the figure 19 and figure 20. Thus, the figure 13 shows the logarithmic difference between the exhaustless engine and the one fitted with this year's exhaust.

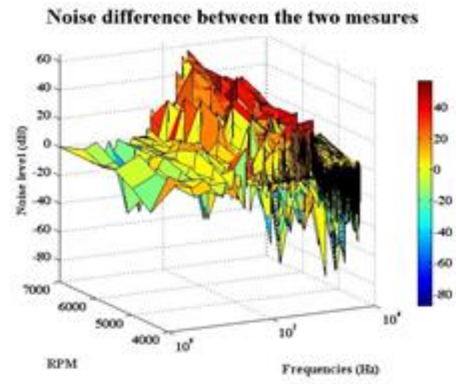


***Figure 13. Noise Reduction from 2015 Exhaust***

The exhaust seems to be more effective in the 200 to 1000Hz range, which specifically corresponds to the loudest zone of the sound stage. Therefore, the resonators and absorption chambers have adequately been optimised. However, the major improvement noticed in the 200 Hz range remains unexplained, since our sound reduction methods did not aim this frequency. It would be important and even necessary to push our research a step further in order to understand which element affects this particular frequency.

## Track Test bench and Noise Analysis

For the past years, Club QUIETS has successfully designed exhaust systems that reduce noise to a point where the track becomes the major noise source of the snowmobile. With this in mind, the club has decided to build a test bench for which the sole purpose is to study this aspect. The project being established on a long term base, this year's objective was to build the test bench and conduct the first sound tests.

### *Test bench Description*

The test bench consists mainly of a steel structure that supports the chassis of the snowmobile. It is held by the front suspension mounting points as well as by the rear reinforcement bar. The structure itself is equipped with auto blocking wheels that allow the bench to be moved around easily. An electric motor is located where the combustion engine usually sits and it drives a belt. A hinge holds the motor in place and uses the weight of the motor to properly tension the belt. Finally, the belt transmits the power directly from the motor to the track's sprocket. Figure 14 shows the test bench while fitted with the drive system.

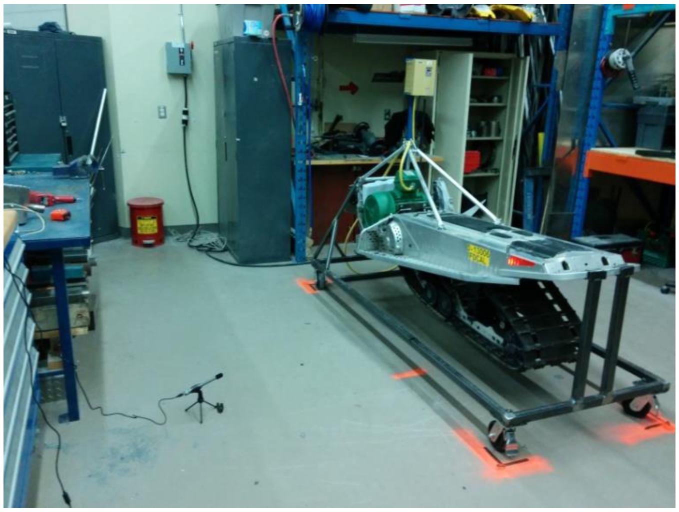

*Figure 14. Track Acoustic Test bench*

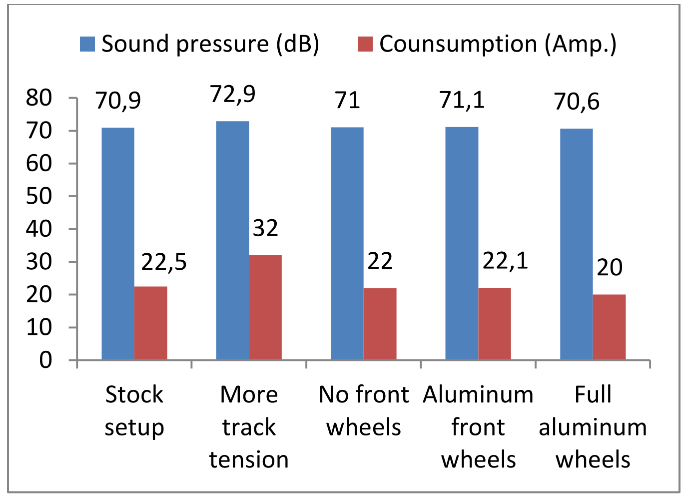


*Figure 15. Sound test results*

### *Acoustic Results*

Since sound tests have a great importance in the competition, we have decided this year to focus on the noise made by our snowmobile. We started out on the sound test bench that was built last year. We have refined it to reduce the sound it is responsible for, and obtain results with a better precision concerning the snowmobile. All the tests were made according to a strict protocol to ensure the repeatability of our results. For example, the snowmobile was in the same position to maintain the same distance with the microphone each time. Also, the speed of the electric motor was controlled by a drive to ensure a constant cruising speed of 30mph.

This test bench allowed us to analyse different components and pieces, and identify which were best for noise reduction. You can see the different results we have obtained in the figure 15. It is important to consider these results are relative to each other, and not absolute, since the microphone was not calibrated, since the noise produced by the environment during the tests was maintained constant.

To confirm the result from the test bench, we have reproduced the conditions of the competition on a snowmobile trail on a lake to verify different types of wheels, tracks and isolation materials. The measures were then taken according to the exact description of the sound tests.

According to the results, the best setup is to keep the manufacturer recommended tension and to change to aluminum wheels.

## SUMMARY/CONCLUSIONS

The design of our new four-stroke turbocharged engine is an exciting step for team QUIETS. Since the turbocharged 600ACE has already shown its potential, we can proudly say that our innovations are still going further. The implementation of a modified intake and exhaust manifolds, improved exhaust muffler design, simplified wire harness and an efficient EGR valve put this sled ahead of stock model regarding efforts to offer maximum performances, while reducing noise and exhaust emissions. Our few years of tests and experience with turbocharged snowmobiles lead us a step forward in the right direction toward the design of an eco-friendly, yet powerful snowmobile.

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# DEFINITIONS/ABBREVIATIONS

| | |
|---|---|
| CO | Carbon Monoxide |
| CO2 | Carbon Dioxide |
| EGR | Exhaust Gas Re-circulation |
| EGT | Exhaust Gas Temperature |
| EMS | Engine Management System |
| HC | Hydro Carbon |
| H2O | Hydrogen Dioxide |
| Hz | Hertz |
| MPH | Miles per hour |
| NOx | Different groups of nitrous oxides |
| RPM | Rotations per minute |

## APPENDIX A

***Table 3. Resonator Length Adjustments***

| | Length | Theoretical | Experimental | Difference |
|---|---|---|---|---|
| $R_{Entry}$ | 95 | 897,37 | | |
| $R_1$ (Short) | 90 | 947,22 | 853 | -9,95 |
| $R_2$ | 110 | 775,00 | 704 | -9,16 |
| $R_3$ (Long) | 133 | 640,98 | 587 | -8,42 |

# APPENDIX B

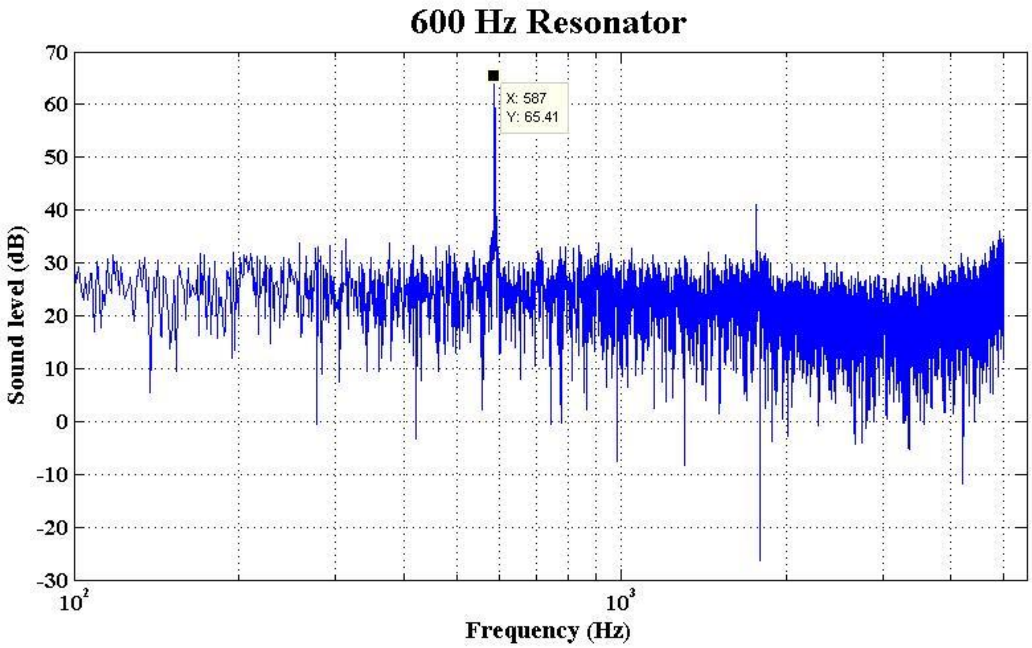


*Figure 16. Resonator for 600 Hz*

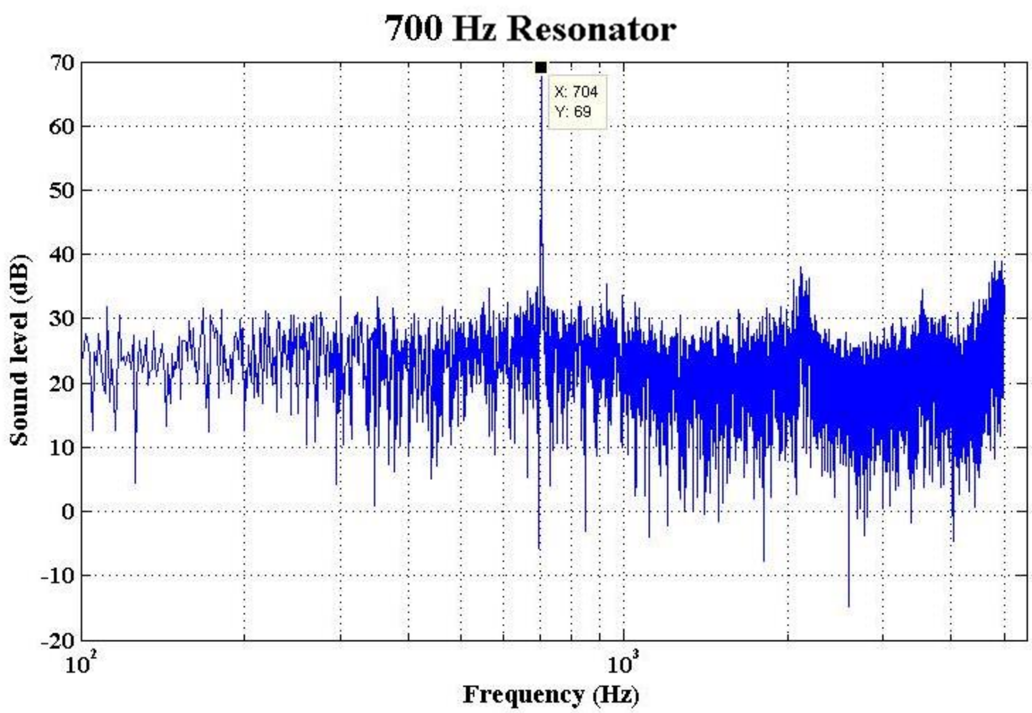


*Figure 17. Resonator for 700 Hz*

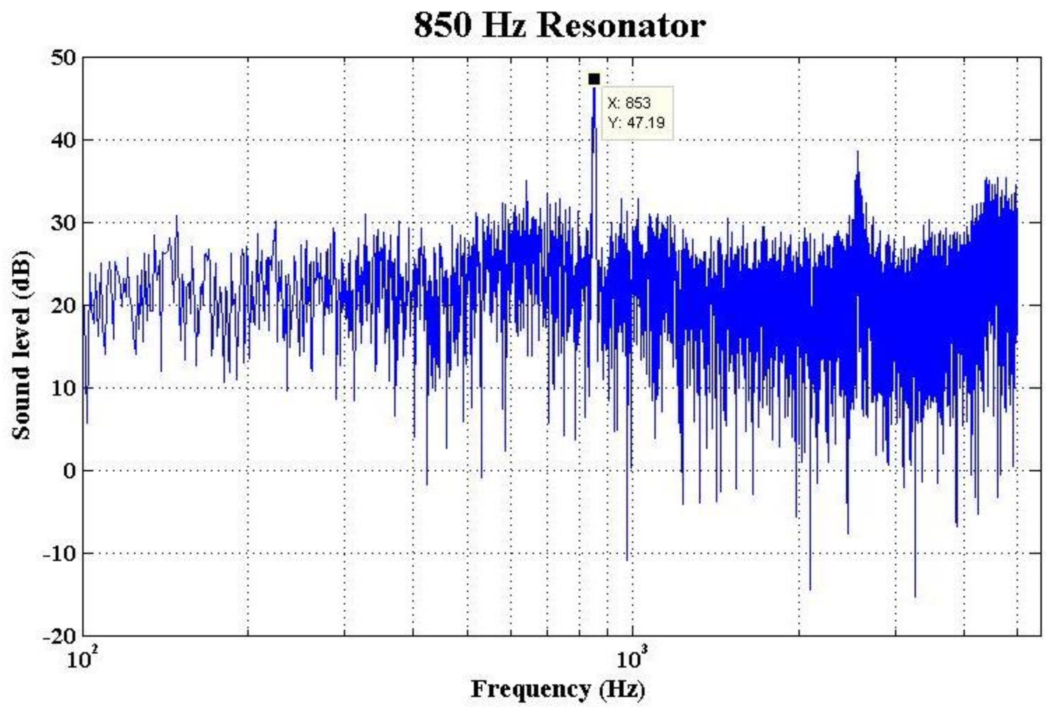


*Figure 18. Resonator for 850 Hz*

## APPENDIX C

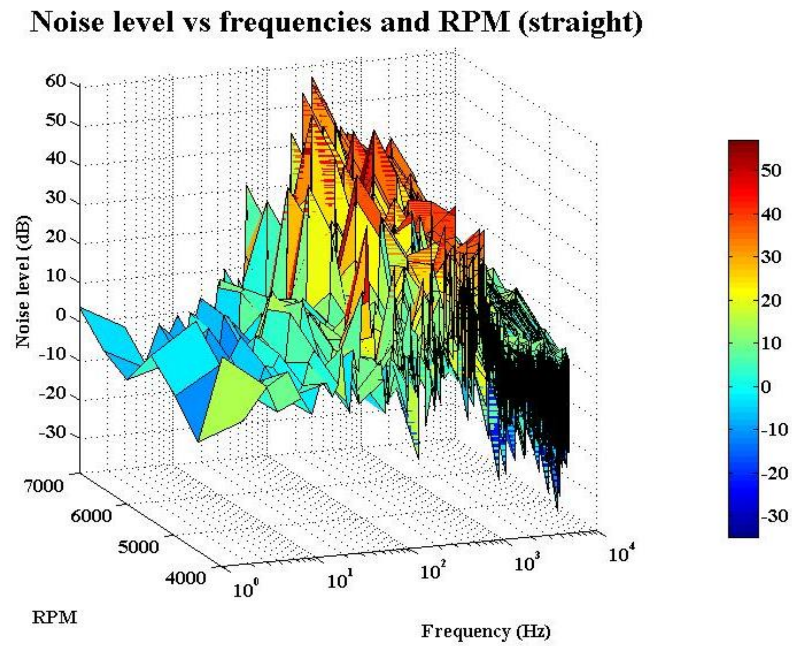


*Figure 19. Engine Noise Level with no Muffler*

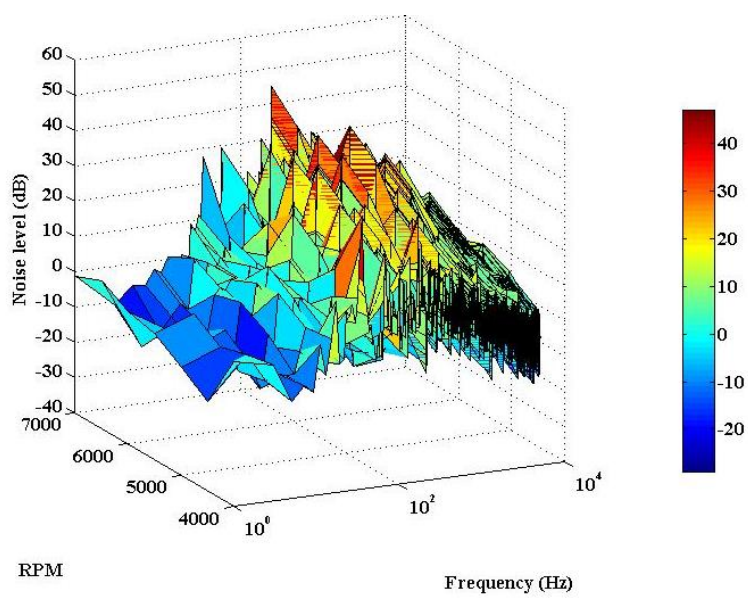


*Figure 20. Engine Noise Level with 2015 Exhaust System*