4-Stroke Direct Injection Snowmobile Design Clean Snowmobile Challenge 2017 Design paper

Pierre-Olivier Langlois, Edouard Levesque
Guillaume Verner, Mathieu Verner
École de technologie supérieure (ÉTS)

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 this vehicle. With growing concerns regarding emissions controls and noise from recreational vehicles such as the snowmobile, we are using a 2016 Ski-Doo MXZ 600 ACE 4 stroke engine for our researches. Our modifications include the conversion of the engine to high pressure direct injection, the implementation of a fully programmable engine management system, the installation of exhaust after-treatment solutions and several noise reduction attempts. These changes allow our snowmobile to surpass the stock engine power output while being quiet and more efficient. The modified snowmobile now has a peak power output of 60 horse power (HP) and 50 foot pounds (ft-lbs) of torque. Many other modifications concerning the rest of the vehicle will also be presented. 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 2017 Clean Snowmobile Challenge submission. This year, we are pushing further the 4 stroke Otto cycle engine design. By converting the port injection engine to a high compression direct injection engine, we were able to considerably increase efficiency, while also increasing power output and reducing emissions. We have accomplished a lot in a relatively short time, and we look forward to show our improvement at the CSC 2017.

SNOWMOBILE BASE CHASSIS SELECTION

Rev-XS

One of the biggest improvements we made last year was to update our chassis. Since our previous platform was a 2011 Rev XP, its utility life for the purpose of the competition was coming to an end. We decided to take advantage of the great handling improvement that BRP introduced in the 2016 Rev-XS chassis.

We decided to choose the Ski-Doo MXZ Blizzard as our new platform because it was the best value for us from BRP. It comes with a lot of exclusive options and accessories that will be useful for us (more on that). Another good argument that lead us to this model was that most of the modifications that we made on the previous prototype could be transferred easily.

rMOTION suspension

One of the most significant upgrade over our past setup is the rMOTION suspension that is installed from the factory on the MXZ Blizzard. The rMOTION suspension gives the rider better maneuverability and comfort due to separate spring and shock dynamics that are paired with a fully adjustable system that lets the user tune the suspension as he likes it, either for better comfort, or more response from the snowmobile. Separate dynamics helps to reduce the impact on small bumps, and increase the capability of the suspension on bigger impact.

129’’ track

One of the biggest changes on the REV-XS chassis was the new 129” track, instead of the initial 121” we had previously. In order to try to compensate from the added drag of the longer track, we chose to reduce the length of the lugs from 1.6” down to 1”. Since the added length of the track provides an increase in traction, we think the snowmobile will have an overall similar cornering behavior to a shorter track model with taller lugs. On a different note, a longer track gives the snowmobile better stability especially at high speed on straight trails. It also provides better traction on acceleration/braking in every kind of snow and even more on un-packed snow.

Figure 1. Rev-XS Chassis and rMOTION Suspension

Pilot TS skis

BRP introduced the Pilot TS skis on some of their 2016 snowmobiles, and we took advantage of it. This feature gives the rider the ability to adjust the depth of the runners in the snow, providing better control in any situation. The driver can therefore choose which settings suits the conditions best and adjust the skis by only having to turn a knob.

Figure 2. New Pilot TS Skis With Adjustment Knob

ENGINE DESIGN AND CALIBRATION

Engine comparison and selection

The snowmobile engine selection had to follow our objectives. We were 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 a direct injection engine, buyers could get a good compromise on both desires; peak power, low-end torque and great throttle response, as well as good fuel economy while cruising. Theoretically, a 600 Ace with direct injection will have a better fuel economy then its port injection counter part. The implementation of direct injection pushes the snowmobile industry to follow the automotive industry where we can witness a rising amount of models available with GDI.

Table 1. Engine Comparison

	900 Ace	**600 Ace**	**600 ACE DI**
Displacement	900 cc	600 cc	600 cc
Type	4 Stroke	4 Stroke	4 stroke DI
Hp	90	60	60
Fuel Consumption	23 mpg	24 mpg	26 mpg

Direct Injection Conversion

The biggest change to our setup this year is the conversion of the engine to direct injection. This is a project the team has been working on for 3 years. Several mechanical challenges had to be overcome and several mistakes were made in the process. We believe it is now robust enough to be competitive which is why we are introducing our prototype at this year's Clean Snowmobile Challenge.

The first big challenge was to mount the mechanical fuel pump to the engine and find a way to actuate it. Direct injection engines operate with a very high injection pressure to maximize combustion efficiency and ensure proper fuel atomization. Injection pressures upwards of 2000 psi are common in the automotive industry. Two pump types were tested. The typical cam actuated pump and the rotary style pump. For packaging reasons, the cam actuated pump was chosen. The pump is driven off the crankshaft of the engine, by a CNC machined camshaft. An external casing was added to the main side cover of the engine to properly mount the pump to the engine and ensure proper lubrication.

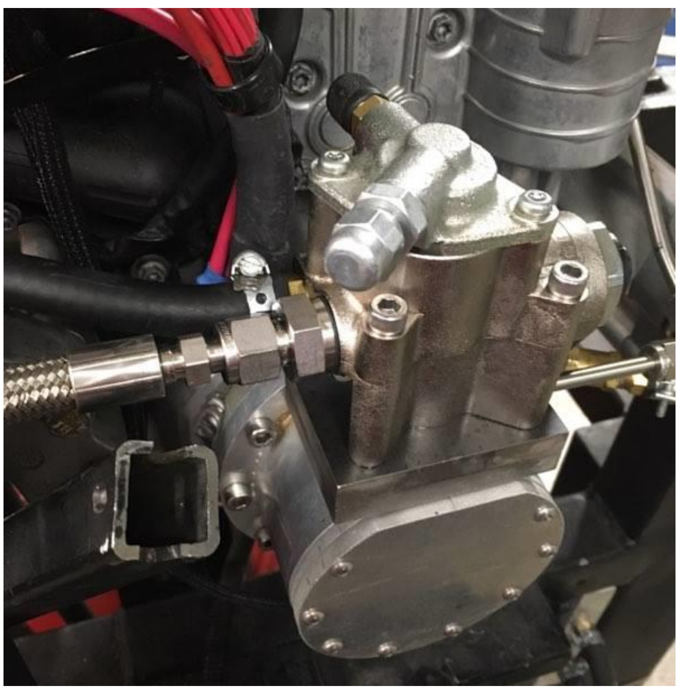

Figure 3. Crankcase Mounted High Pressure Fuel Pump

Mounting the injectors was also a challenge. The head had to be machined in order to fit the injectors, which would only fit right below the intake runners. The fit had to be perfect to ensure proper sealing of the tip of the injector in the combustion chamber. A pair of tapered seat injector holders had to be machined and matched to the head's extremely tight machining tolerances. Several fastening solutions have been discussed. For many reasons, we have decided to glue them in place with an aerospace grade high temperature and high strength composite adhesive.

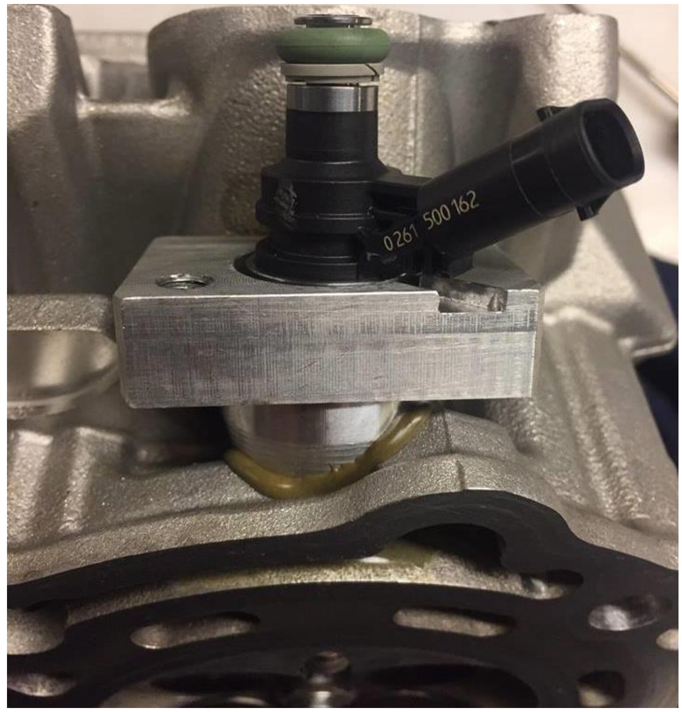

Figure 4. Injector Mounted to the Cylinder Head

The fuel rail was designed to be able to withstand pressures upwards of 10 000 psi while maintaining a security factor of more than 3. It is composed of machined high quality stainless steel Swagelok fittings and pipe, professionally and precisely welded together. A stainless steel braided hose rated for 5000 psi ensures that the high pressure fuel from the mechanical pump gets delivered to the fuel rail without leakage.

Figure 5. High Pressure Fuel Rail

Another important aspect of this conversion was the design of the pistons. The stock 600 ACE pistons required extensive design modifications in order to be adequate for use with direct injection. A bowl had to be added in the center of the piston to maximize fuel mixing in the combustion chamber as well as prevent excessive cylinder wall wetting. A cavity for the injector was also added, to prevent the injector tip from contacting the face of the piston. The top face of the piston was raised, in order to compensate for the added volume. This allows the engine to operate at the stock compression ratio of 12:1. Finally, the ring lands were reinforced to fix an inherent design flaw of the original pistons. The forged aluminum alloy construction provides higher strength than the original piston and a lower overall weight.

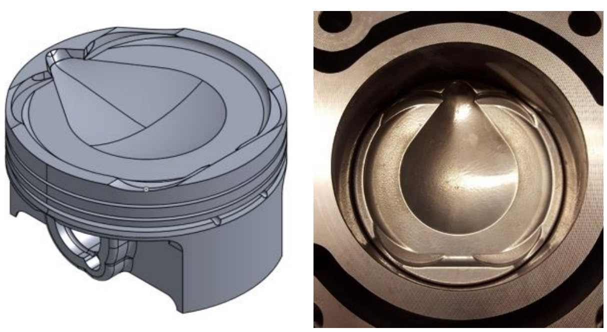

Figure 6. 3D Model of the Piston and Final Result

Finally, the intake manifold also had to be redesigned, because the factory one was causing interference with the fuel rail. Space being very restricted in that area, we had little margin to optimize the design of the part. The plenum volume is smaller than we'd like, but is the largest we can fit. Runners are also much shorter than factory, pushing the powerband to a higher engine speed range. Once again, packaging was the main issue. However, that did not stop us from producing a part worthy of our usual quality. The final iteration is a two part CNC machined and polished aluminum enclosure.

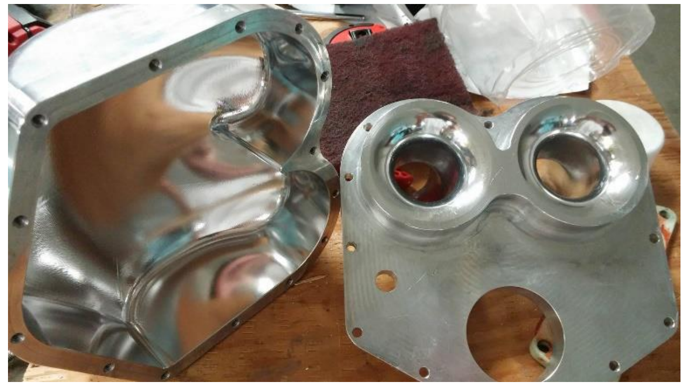

Figure 7. Two Part CNC Machined Intake Manifold

Engine Control and Calibration

For the 2017 edition of the CSC we upgraded our engine management system (EMS) to a Motec M142. We chose this EMS because of the proven reliability of the platform in many racing applications over the past years as well as it's ability to control direct injection.

The Motec M142 offers features that are very interesting from a calibration standpoint. These include lambda closed loop control, high speed data logging, flex fuel compatibility and many more. By switching to the M142 we also benefit from added functionalities such as the ability to create custom fuel and ignition compensations for different operating conditions. We are also able to fully control our electronic throttle system.

The initial calibration used on this year's prototype is simple and effective. Since this is our first competition with this new setup, we determined it was best to favor reliability over maximum performance. This being said, the engine is nonetheless calibrated at mean brake torque (MBT) wherever possible to maximize efficiency, while leaving a significant knock margin where it is needed, to ensure proper reliability. A lot of work has been put into fuel film compensations, to make the best of transient emissions and performance.

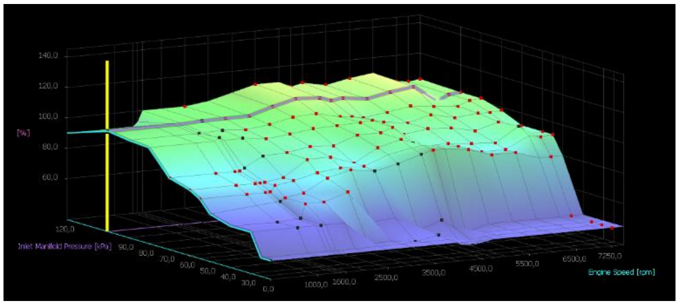

Figure 8. Engine VE Table (Engine Load vs RPM)

Calibrating with Ethanol

The addition of ethanol to the fuel used at the competition this year poses an interesting challenge when it comes to calibration. The specific energy of an 85% ethanol and 15% gasoline blend (E85) being about 30% lower than that of gasoline, the quantity that must be injected to achieve the same power output is increased by roughly 30%. Also, the fact that ethanol chemically contains Oxygen (whereas gasoline doesn't) makes for a lower stoichiometric ratio, 9.78:1 for E85 and 14.7:1 for gasoline.

However, this also has its advantages. By vaporizing a larger quantity of liquid, the heat absorbed during the reaction is also greatly increased, therefore reducing the temperature of the mixture. Colder air is denser air and so the ignition timing can be increased as the risk of knock is reduced. Thus, the combustion can produce more power with the same amount of fuel than with a warmer mixture, increasing the efficiency of the engine. This also has for effect to lower combustion heat and pressure. Lower heat and pressure decrease stress on components and contribute to better reliability. Ethanol also has a higher octane rating than gasoline, typically around 94-96 AKI for E85. Once again, more power can be made.

In our case, since the ethanol content in the fuel is unknown, a flex fuel sensor must be used to measure the percentage of ethanol in the fuel. Our calibration was done using pump gasoline with a measured ethanol content of 7%. Once the expected results were achieved, we used several blends of ethanol to properly tune our compensation curve. Starting with E85, we also tested with E60, E45, E30 and E20. Though the curve resembles a linear extrapolation, the exercise was worth the effort as a linear compensation would not have been perfectly accurate. The ignition timing compensation has also been adjusted in the same manner. As much as 6 degrees of increased timing has been added in some areas. This has a direct influence on the power our engine produces.

While not providing as much gain as with E85, lower ethanol content fuels have the same effect but at a smaller scale. They remain promising as an alternate fuel over pure gasoline whatsoever.

Engine Emissions Control

Regarding emissions found in exhaust gases, only three types of components really cause a problem for 4 stroke engines. According to EPA standards, our engine should pass a 5-mode resulting in an E-score greater or equal to 175. This score is based on 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 175. To accomplish this goal our team has opted to implement an emissions control systems. Since most of the engine's operating areas aim for a stoichiometric air fuel ratio, most of the exhaust gas emissions can be treated with a three way catalyst. Two catalysts composed of a stainless steel casing and of a stainless steel substrate from Emitec with coated layers of platinum, rhodium and palladium are used. These single bed three-way catalytic converters offer conversion efficiency between 80-95% depending on the engine's operating conditions and air/fuel ratio as seen in the figure below.

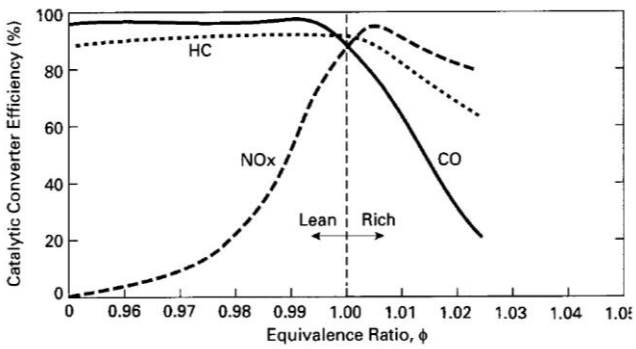

Figure 9. Catalytic Converter Efficiency vs Equivalence Ratio

Notice how efficiently the catalyst converts HC, CO and NOx when the equivalence ratio of the exhaust gases is phi 1.00. As we said previously, our goal was to fall within that window of operation. The only area of operation where the engine doesn't use a phi of 1.00 is at peak power, where it runs slightly richer, to decrease engine temperatures and increase power. As seen on figure 7, increasing the value of phi causes an increase in HC and CO particles, but a decrease in NOx.

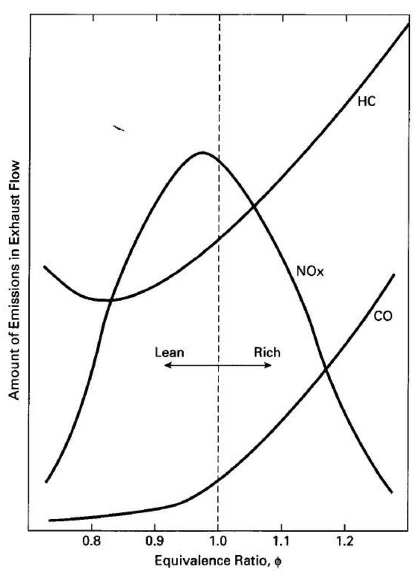

Figure 10. Amount of Emissions in Exhaust Gases vs Equivalence Ratio

In order to minimize all three pollutants, it was determined that running the engine at a lambda of 1.00 was the best solution to take full advantage of the three way catalyst.

Particulate matter emissions are also a concern for modern GDI engines, especially when running rich. We believe that by running a stoichiometric mixture, our PM emissions will be low enough to pass the requirements of the competition.

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 the ramp of the throttle opening, resulting in a smoother power delivery. This, once again, helps improve maneuverability, an important concern for our team.

ACOUSTICS AND NOISE REDUCTION

Air intake

With the same optic of reducing noise from the previous prototype, a new air intake was designed for this year's prototype. We previously noticed a fair amount of sound emerging from the front part of the snowmobile so drastic changes were needed from the previous design, which didn't have noise reduction features. The air entry was relocated and we added an expansion chamber in between the air filter and the manifold inlet. This chamber was added to the air intake pipe and its simple design essentially consists of a 5.5'' diameter by 7'' long cylinder inlet and outlet. An inlet to connect to crankcase vent is also integrated to the expansion chamber. It is also filled with sound absorbing foam to reduce the noise from the air induction. Its body is 3D printed in PEI plastic to keep the whole assembly lightweight and heat reflective.

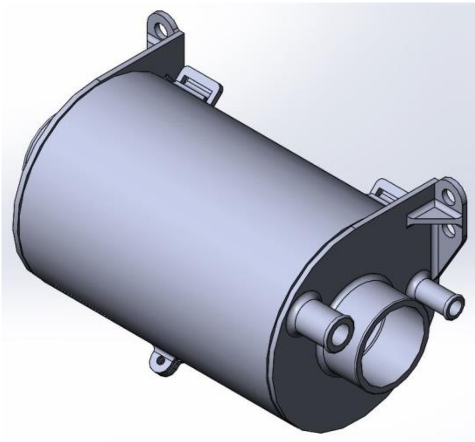

Figure 11. Air Intake Expansion Chamber

Track Sprocket Re-design

One of our main goals this year was to considerably reduce the noise coming from the track and suspension system. Compared to the last years, instead of trying to insulate the noise, we worked on reducing it from the source. We noted that a big part of the sound came from the drive sprocket, so this is why we've designed a completely new one.

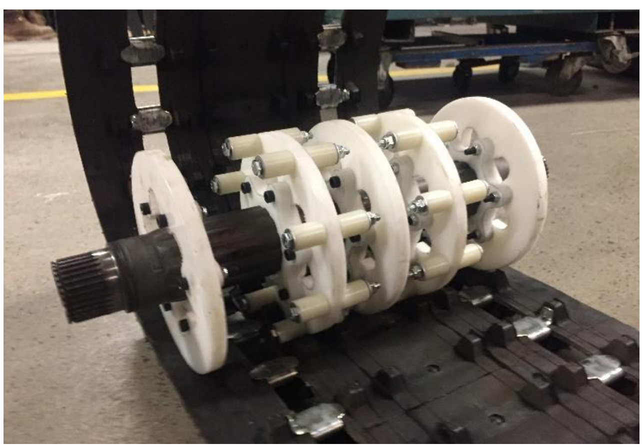

Figure 12. Custom Drive Sprocket

This system reduces the noise considerably because the drive rollers don't come in contact with the metal clips of the track. Instead, they use the rubber bosses to drive the track, similarly to BRP's Silent Drive technology. It also reduces the vibration because of the lateral discs that allow the sprocket to roll on the track and putting proper tension on it. We can see the difference of the design in the image bellow.

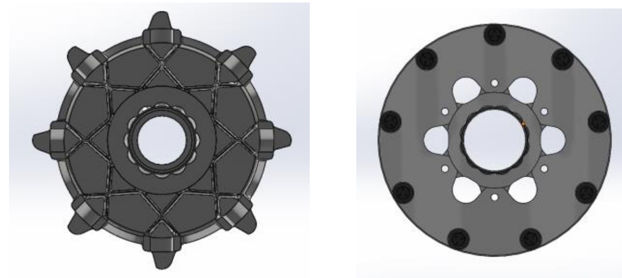

Figure 13, Drive Sprocket Comparison OEM vs Custom

This particular design offered us the chance to try different settings. For example, we've worked on different diametric pitches to reduce the noise and vibration. We've also tried different numbers of teeth to see the influence of the contact ratio, which is the number of teeth in contact with the drive lugs of the track. We thought that if a bigger contact ratio could help reduce noise and vibration for conventional gears, it could also work for our drive sprocket. This is why we chose a sprocket design with 9 teeth instead of 8.

Track Test bench and Noise Analysis

For the past years, team 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 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 22 shows the test bench while fitted with the drive system.

The electric motor's current consumption is the metric used to compare different adjustments and components. This allows great repeatability and is directly proportional to the efficiency of the drivetrain. An external decibel meter is also used to measure sound pressure.

Figure 14. Acoustic Test Bench

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 analyze different components and identify which were best for noise reduction. This year, we wanted to compare the differences between the OEM wheels and some machined aluminum wheels.

Big wheels

The big wheels are oversized wheels that go at the back of the suspension. The diameter of these wheels is generally 8” instead of 7” for the stock ones. Compared to last year, we’ve tested new wheels that are covered with a rubber layer.

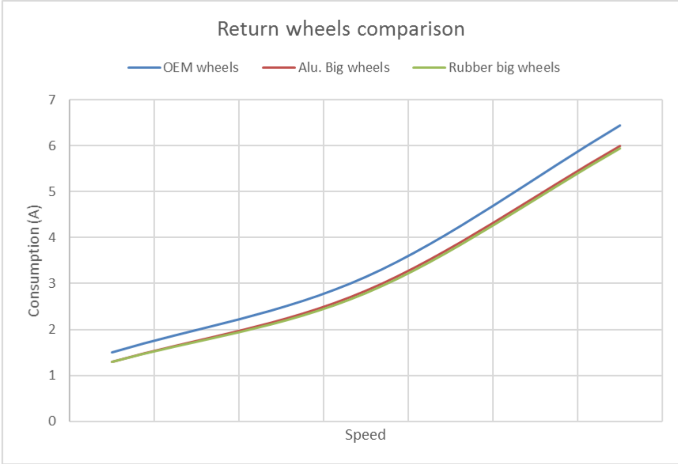

Figure 15, Big wheels’ test

The results above show us that big wheels tend to reduce the consumption of 10% compared to the stock wheels. We’ve also noted a slight reduction of 1% for the rubber coated wheels compared to the aluminum ones. The major difference of the rubber wheels is for the noise reduction. After multiple tests at different speed, the rubber wheels (OEM and big wheels) tend to be 1 to 2 dB quieter depending on conditions – a huge improvement over full aluminum wheels.

Following these results, we have performed several tests with the snowmobile in real conditions to validate the data obtained on the test bench. These tests were based on a subjective comparison of the noise level and were performed as specified in the rules of the competition. The results were similar to what we measured on the test bench.

Figure 16. Sound Test Performed Outside as per the Competition’s Rules

The rubberized aluminum big wheels seemed to stand out in the field as well. From a subjective standpoint, the rubber coated aluminum wheels sound smoother and seem to offer less resistance. This is due to the increase of the radius of curvature which has for effect to decrease the resistance of rotation. The following formula describes the effect of this theory.

$F = \frac{\pi}{2} \times \frac{1}{W} \times \frac{E" \times I}{{P_0}^2}$	F : drag force W : load E" : dynamic modulus I : inertia of belt section Po : radius of curvature

ADDITIONAL MODIFICATIONS

Murphy HV450 display

This year, we chose to upgrade to a digital dashboard. These have become very popular in the past years, because of their versatility and ease of use. Being able to display any parameter on screen on demand is a tremendous advantage for us. We are now able to display real time fuel consumption and adapt our driving based on those numbers. In addition to fuel consumption, we are able to configure maintenance reminders on the display and also fully configure it's appearance.

The display we chose is a Murphy HelmView® 450. It has a LED backlight 4.3" color display with 8 tactile buttons, that provide ease of use even with gloves or in a low light environment. It also operates on a wide range of voltages (6V to 32V), supports multiple CAN buses and has one analog and one digital input. Being designed for industrial applications, the HelmView® 450 is known for its reliability and durability. It is IP67 rated, which means it is dust tight and can survive for 30 mins immersed in 1 meter of water. It also has an impressive shock resistance of 50G in 3 axis. Finally, the broad operating temperature range of the display (-40°F to 185°F) makes it the perfect choice for a snowmobile application.

Figure 17. Murphy HV450 Display in our Custom Enclosure

SUMMARY/CONCLUSIONS

The design of our new GDI engine is an exciting step for team QUIETS. Since the GDI 600ACE has already shown its potential, we can proudly say that our innovations are still going further. Our modifications puts 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
AKI	Anti-knock index, also known as PON (Posted Octane Number)
GDI	Gasoline Direct Injection
DI	Direct Injection
HPDI	High Pressure Direct Injection