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SI 004

4-Stroke Turbocharged Snowmobile Design Paper Clean Snowmobile Challenge 2019

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Introduction

Team QUIETS is proud to present it's 2019 Clean Snowmobile Challenge submission. This year, we are pushing further the 4 stroke Otto cycle engine design. By replacing and relocating the turbocharger, we have achieved better exhaust flow and boost management. We've addressed most of the issues we've faced last year, and we look forward to showing our improvement at the CSC 2019.

Innovations

Turbocharger and exhaust manifold

For 2019, the turbo has been replaced from a Garrett GT12 to a Borg Warner KP35 and relocated. The KP35 was chosen for it's compact size and great performance, the team already runs a KP35 on our Diesel Tundra, so the KP35 was the way to go. The main reason for this change comes from an issue that happened at the 2018 CSC where the turbocharger was in the front of the snowmobile and far from the engine, which caused some stress in the exhaust system and resulted in a cracked exhaust flexible. The engine and the turbocharger were both fixed in different locations, which kept them from moving smoothly together. The new approach for 2019 is to bring the turbo as close to the engine as possible, which would also allow for more heat which would help build more boost pressure and reduce boost delay. In order to relocate the turbo close to the engine, a new exhaust manifold was designed as seen in figure 1. This setup allows the turbo to move with the engine and also results in a better throttle response.

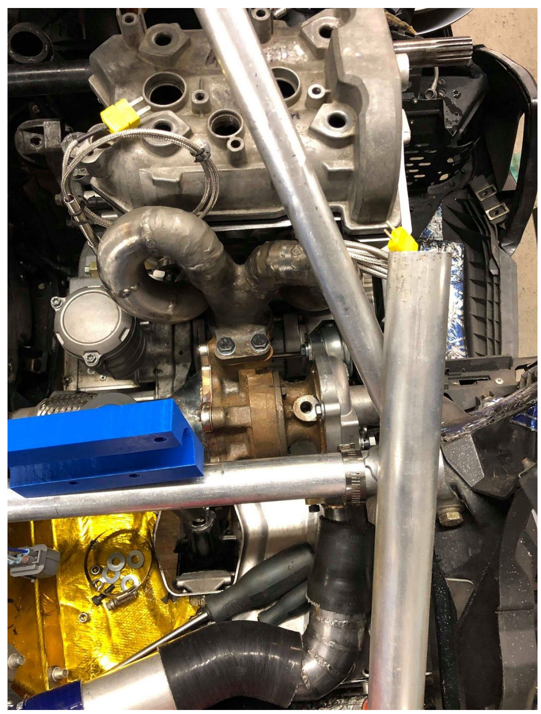

Figure 1. Turbocharger and exhaust manifold

Intercooler

Relocating the turbocharger near the engine also meant that the intercooler had to be relocated as well. Our past intercooler setup was good, but not ideal for heat management as it was very close to the engine, and far from the cold air intake. The only viable option was to relocate the intercooler in the front, close to cold air and far from the engine heat. The intercooler itself has been replaced with a smaller unit that will achieve better performances because it will get colder air. The new intercooler used is from Valeo (built as OEM for Audi) and cut in half to fit perfectly in the front grill of the MXZ. Metal plates were added to channel cold air in as much as possible (see figure 2). Calculations were made to ensure that the modified Valeo could handle the power of the MXZ and revealed a maximum power of 135 hp which is safe for our current setup. The baseline for core specification comes from Mishimoto and can be found in Appendix B along with intercooler calculations.

Figure 2. Intercooler

Steering column

With the new position of the turbocharger, we lost some considerable space in the cab for the steering column and it was in interference with the new exhaust manifold. The original steering column being a bent tube, the steering and the handlebars must therefore turn around the same axis. The bent section revolves around this same axis but with a larger radius. The clearance must take into account the movement of this part, which is greater depending on the distance between the bend and the axis of rotation. The new concept for the steering column uses universal joints to clear the engine and the turbo as seen on the figure 3. This way, the rotation of the tubes no longer generates large displacement. The maximum operating angle of the universal joints is 45 ° and this was an important constraint to respect when designing the new steering column. It was necessary to find a way to guide each tube from the frame. Now, we have gained a lot of space in the cab because there is no more displacement to consider. The steering column remains in the same position when you turn the handlebars and no steering angle was lost.

Figure 3. Steering column

Pistons Revision

Our better understanding of the physics principles of combustion has lead us to redesign the pistons used in our engine. The previous version of the piston netted the same compression as the stock pistons, which is 12:1. This design choice was made to ensure proper operation of the engine with the turbocharger. The new piston design increases the compression ratio up to 12.6:1, in an effort to increase low end torque and efficiency where the turbo doesn't operate. The knock sensor should allow the engine to properly function at high speed and load without completely sacrificing efficiency. Focus was also directed towards reducing sharp edges and angles to a minimum in an effort to reduce the potential for hot spots in the combustion chamber therefore reducing the engine's propensity to detonate or even pre-ignite. This resulted in a design that eliminates separate valve pockets favoring instead one large pocket for both intake valves, the same being true for the exhaust valves. The water drop shaped bowl has also been replaced by a spherical bowl that creates a tumbling motion within the cylinder as the piston moves upwards. This feature should help homogenize the air and fuel mixture and ensure proper combustion. This should also allow us to run stratified charges in low load conditions. Finally, the pistons have been reinforced to be able to withstand the high combustion pressures. The crown has been thickened by 27 % (an additional 2 mm) and the skirt is also 12 % thicker around the connecting rod pin. Just like the previous piston, the ring lands have also been reinforced to solve the inherent weakness of the factory part. The weight of the new piston is increased compared to the factory piston by a mere 2 %, thanks to the forged aluminium construction.

Figure 4. 2017 Piston (left) vs 2018 Piston (right)

Piston Coolers

To cope with the higher combustion temperatures caused by the increased compression ratio and the turbocharger, the team has researched options to help reduce piston temperatures thereby decreasing the risk of detonation. The idea that naturally came to mind is the addition of piston coolers (or oil squirters). Upon further inspection of the 600 ACE's engine block, we found capped off oil passages that lead to the end of the cylinders right by the crank bearings. This prompted us to search BRP parts catalogs for OEM applications using piston coolers. We found out that the 1200 4-TEC engines use piston coolers from the factory.

Figure 5. Piston Coolers Installed

We were able to retrofit these factory parts by drilling the capped off oil passages and tapping the ends to allow support via a banjo bolt. This quick modification should allow the pistons to run cooler while also helping with lubrication thereby increasing the engine's reliability.

Engine Calibration and 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 test resulting in an E-score greater or equal to 175. This score is based on the following formula:

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

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 system. 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. A catalyst composed of a stainless steel casing and of a stainless steel substrate from Emitec with coated layers of platinum, rhodium and palladium is used. This single bed three-way catalytic converter offers conversion efficiency between 80-95% depending on the engine's operating conditions and air/fuel ratio as seen in the figure below.

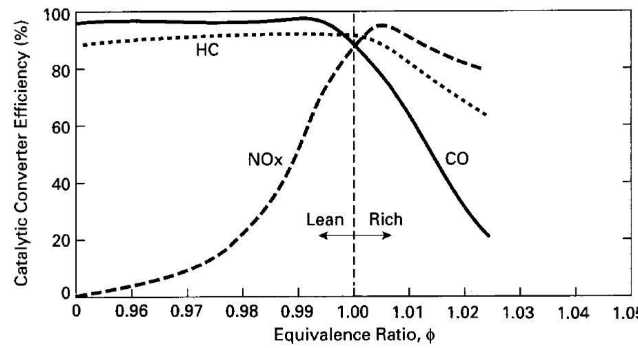

Figure 6. Catalytic Converter Efficiency vs Equivalence Ratio

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 8, increasing the value of phi causes an increase in HC and CO particles, but a decrease in NOx.

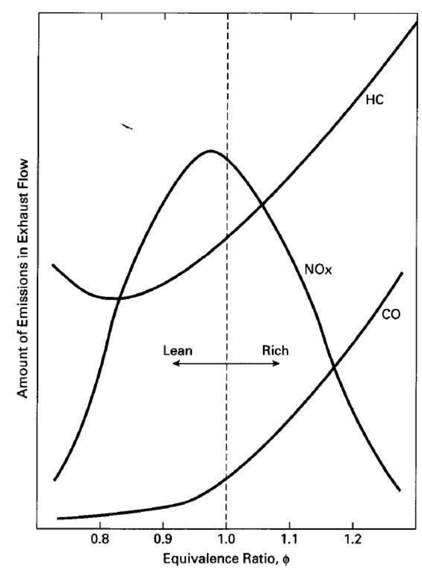

Figure 7. Amount of Emissions in Exhaust Gases vs Equivalence Ratio

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 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.

Track Sprocket Re-Design

One of our main goal is always 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.

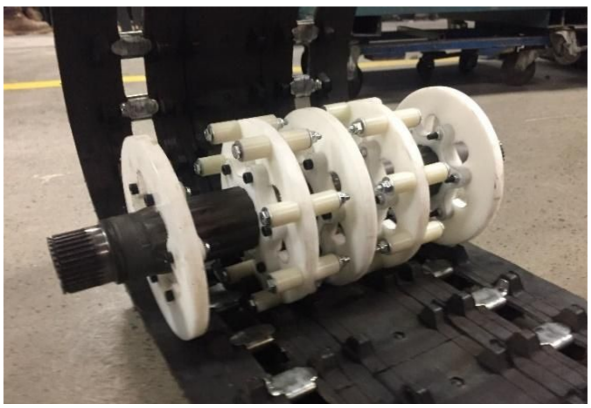

Figure 8. Custom track drive sprocket

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 below.

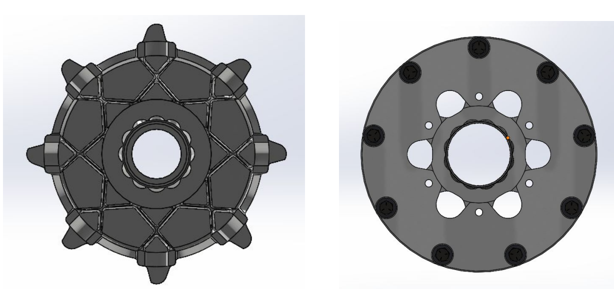

Figure 9. Drive Sprocket Comparison OEM vs Custom

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 team 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 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 10 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 10. 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 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.

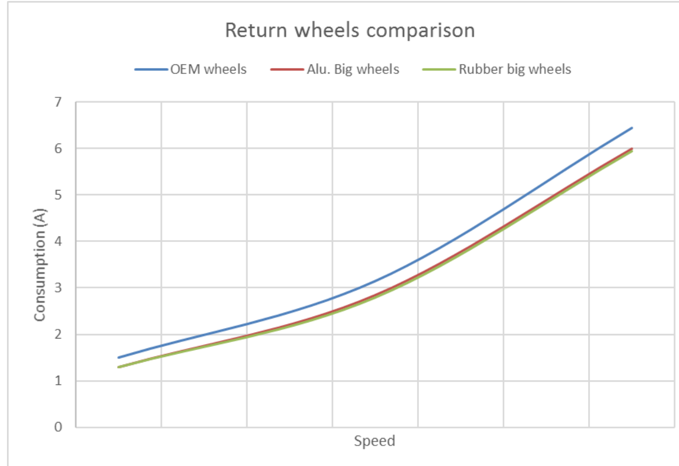

Figure 11. Big wheels’ test

The results above show 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 concerns noise reduction. After multiple tests at different speeds, 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 12. 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

Air Intake

With the same optic of reducing noise from the previous prototype, modifications were brought to the air intake. 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. This has helped quiet down the induction noise significantly. However, the team doesn’t have any data to show the difference.

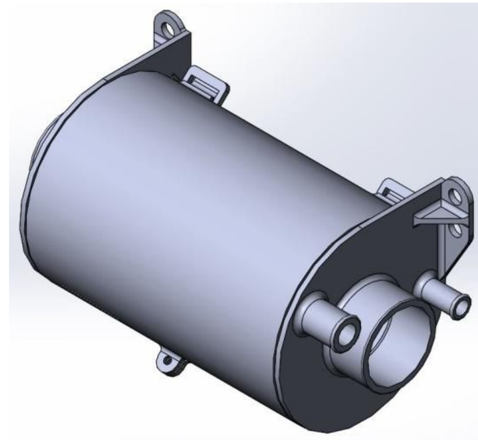

Figure 13. Air Intake Expansion Chamber

Team Organization and Time Management

Throughout the season, 1h progress meetings were held every other week to keep track of objectives as well as to discuss issues and project ideas. An initial timeline was planned, and a Gantt chart was made to help visualize time constraints. The Gantt chart is presented in appendix A. Table 1 shows team structure.

Table 1. Team Structure

Member	**Role**
Edouard Levesque	Team Captain
Jean-Daniel Meyer	Interim Captain
Mathieu Bisson	DUC everyday operations oversight
Jean-Daniel Meyer	IC everyday operations oversight

Snowmobile Description

Chassis

BRP Ski-Doo MXZ Blizzard 2016

Engine

Table 2. Engine Specifications

Manufacturer	Rotax
Model	600 ACE
Fuel	Gasoline
Type	Otto cycle (4 stroke)
Displacement	600 cc
Peak Horsepower	85hp (estimated)
Induction	Turbocharged

Track

Camso Ripsaw II 129 in

Muffler

OEM 600 ACE converted to single inlet

Catalytic Converter

Emitec 3-way catalyst, 600 cpsi, 4” dia. x 3.5” long

Skis

BRP Pilot TS

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 a stock model by offering better performance, 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.

References

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6. http://overlandconveyor.com/pdf/bsh_003_2012_reicksa_conveyor.pdf. Consulted February 18 2016.
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8. Gordon P. Blair. 1999 “Design and Simulation of Four Stroke Engines”.SAE International, 815 pages.

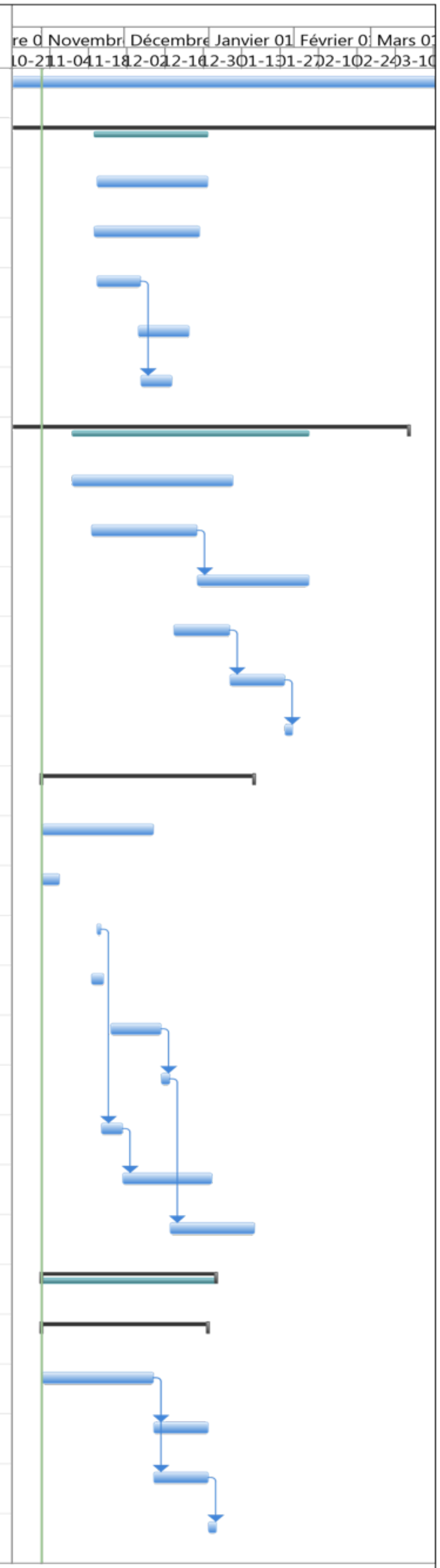
Definitions/Abbreviations

CO	Carbon monoxide
HC	Hydrocarbon
NOx	Nitrogen oxides
EPA	Environmental Protection Agency
GDI	Gasoline direct injection
PM	Particulate matter
OEM	Original Equipment Manufacturer

Appendix A

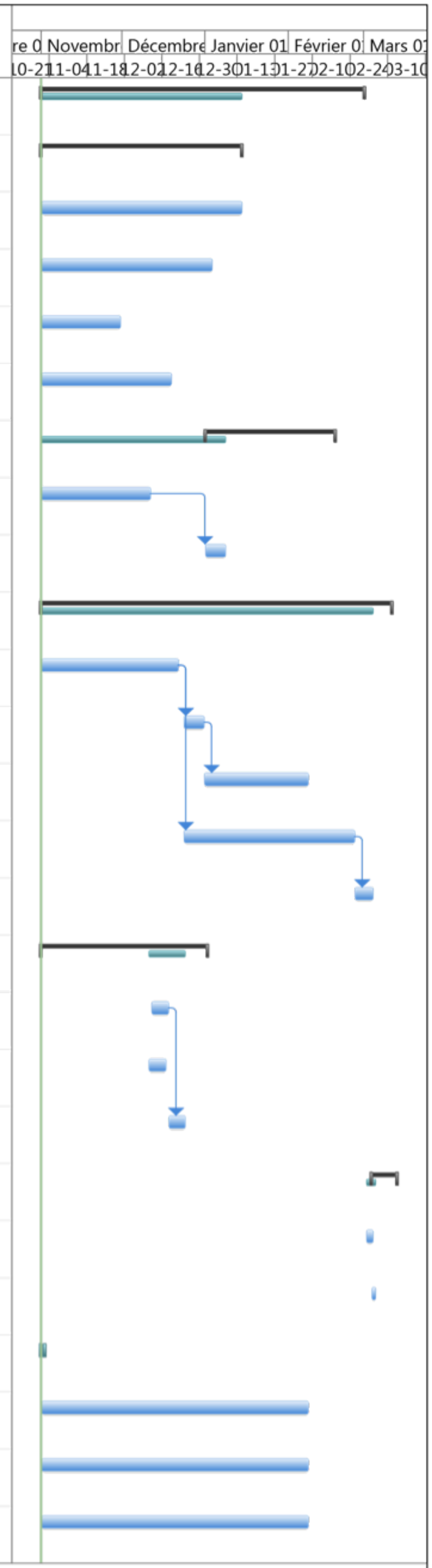
Gantt Chart

N°		Mode Tâche	Nom de la tâche	Durée	Début
1			Début session H-18	128,1 jours	Mar 18-09-04
2			**Moteur HPDI**	**221,6 jours**	**Mar 18-09-04**
3			Fabrication support pompe V2	1 mois	Mer 18-11-21
4			Fabrication tête V3 (commandite)	1 mois	Mar 18-11-20
5			Achat pièces backup	8,4 jours	Mer 18-11-21
6			Fabrication Cam V2	9 jours	Jeu 18-12-06
7			Remonter Base 600ACE	5 jours	Ven 18-12-07
8			**Moteur diesel**	**98,7 jours**	**Sam 18-09-01**
9			Commande turbo 2019	30 jours	Lun 18-11-12
10			Layout couette motec m400	20 jours	Lun 18-11-19
11			Fabrication couette motec	20 jours	Jeu 18-12-27
12			Dessin support moteur V3	10 jours	Mer 18-12-19
13			Découpe support moteur V3	10 jours	Mar 19-01-08
14			Test support moteur dans XU	2 jours	Lun 19-01-28
15			**Dyno 2.0**	**38,9 jours?**	**Jeu 18-11-01**
16			Assemblage panneau 2.0	20 jours	Jeu 18-11-01
17			Installation moteur 600 stock	3 jours	Jeu 18-11-01
18			Départ dyno 600 ace stock	1 jour?	Mer 18-11-21
19			Dyno 600 ACE stock	3 jours	Lun 18-11-19
20			Montage moteur diesel sur dyno	10 jours	Lun 18-11-26
21			Début du dyno diesel	1 jour?	Ven 18-12-14
22			Montage 600 HPDI sur dyno	4 jours	Jeu 18-11-22
23			Dyno 600 HPDI	16 jours	Ven 18-11-30
24			Dyno diesel	16 jours	Lun 18-12-17
25			**Suspension arrière**	**32 jours**	**Jeu 18-11-01**
26			**Anti stab variable**	**30 jours**	**Jeu 18-11-01**
27			Fin de conception	20 jours	Jeu 18-11-01
28			Envoi à la découpe des pièces	10 jours	Mar 18-12-11
29			Tournage des pièces	10 jours	Mar 18-12-11
30			Instalation sur banc de test	2 jours	Lun 18-12-31



Page 1

N°		Mode Tâche	Nom de la tâche	Durée	Début
31			**Électronique**	**60,5 jours**	**Jeu 18-11-01**
32			**Nouveau cadran de bord HPDI**	**37 jours**	**Jeu 18-11-01**
33			debug écran E-Controls	37 jours	Jeu 18-11-01
34			Modification interface	32 jours	Jeu 18-11-01
35			Lecture du signal CAN du Motec	15 jours	Jeu 18-11-01
36			Connection GPS	24 jours	Jeu 18-11-01
37			**Kit graphique**	**24 jours**	**Mar 19-01-01**
38			Achat nouveaux plastiques	20 jours	Jeu 18-11-01
39			Kit graphique	4 jours	Mar 19-01-01
40			**Embrayage EVT**	**65,6 jours?**	**Jeu 18-11-01**
41			Révision conception Mécanique	25,9 jours?	Jeu 18-11-01
42			Achat des composants standards	4 jours	Lun 18-12-24
43			Fabrication des pièces sur mesure	20 jours	Lun 18-12-31
44			Programmation	32 jours	Lun 18-12-24
45			Essai sur banc de test acoustique	4 jours	Lun 19-02-25
46			**Assemblage prototype**	**30,8 jours**	**Jeu 18-11-01**
47			Diesel	3 jours	Mer 18-12-12
48			Essence	3 jours	Mar 18-12-11
49			essai sur neige	3 jours	Mar 18-12-18
50			**Compétition**	**5,2 jours?**	**Lun 19-03-04**
51			Départ	1 jour?	Sam 19-03-02
52			Retour	1 jour?	Lun 19-03-04
53			**Nouveau prototype (pour comp. 2020)**	**1 jour?**	Jeu 18-11-01
54			Choix du moteur 2020	50 jours	Jeu 18-11-01
55			Choix du ECU 2020	50 jours	Jeu 18-11-01
56			Choix de la plateforme 2020 (Essence)	50 jours	Jeu 18-11-01



Appendix B

Intercooler calculations

Calcul Grosseur intercooler			
Hp	in^2		
60	7		
125	15		
Ratio			
65	8		
8,125	1		Power to area ratio (HP\ in2)
Spec Hp intercooler Audi couper			
Core lenght	8,50	in	Mesurement of our intercooler
Bar height	0,38	in	Mesurement of our intercooler
# of bar	5,00		Mesurement of our intercooler
core flow	16,15	in^2	Core lenght * Bar height * # bar of bar
charge area	35,89	in^2	core flow \
core thickness	2,60	in	Mesurement of our intercooler
internal flow	13,80	in^2	
WHP rating	112		The formulas are made for car so they put it in WHP instead of BHP so we need to transfer the result in BHP
WHP to BHP	20% lost in whp for rwd car as they use in their formulas		
BHP	135		

Reference link for intercooler calculations:
https://www.mishimoto.com/engineering/2015/04/drop-intake-temperatures-drop-track-times-drop-mouths-the-ultimate-guide-for-intercooler-selection/#Bigger%20is%20Not%20Always%20Better