4-Stroke Turbocharged Direct Injection Snowmobile Design Paper
Clean Snowmobile Challenge 2018

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Introduction

Team QUIETS is proud to present it's 2018 Clean Snowmobile Challenge submission. This year, we are pushing further the 4 stroke Otto cycle engine design. By converting the port injection BRP Ski-Doo 600 ACE engine to a high compression turbocharged direct injection engine, we were able to considerably increase efficiency, while also increasing power output and reducing emissions. We've addressed most of the issues we've faced last year and we look forward to showing our improvement at the CSC 2018.

Innovations

Cylinder Head Revision

In response to the cylinder head failure our engine suffered just days before CSC 2017, the team has decided to completely rethink and reengineer this part of the engine. The design showcased last year relied heavily on the performance of the high strength adhesive used to assemble the injector holder to the modified BRP OEM cylinder head, which resulted in a catastrophic engine failure after approximately 25 hours of run time.

Figure 1. Previous version of the failed injector holder and cylinder head

The new cylinder head design eliminates the need for an adhesive and relies mostly on a dual interference fit to ensure proper strength and sealing. The injector holder has been modified from the previous tapered design to straight edges sporting two different outer diameters to properly suit the shape of the injector and to allow for an interference fit on two separate surfaces. We've also decided to manage fabrication ourselves instead of outsourcing the job to one of our sponsors like we did last year. Therefore, we also designed a machining jig, that allowed us to precisely mill the cylinder head features using a 4 axis CNC.

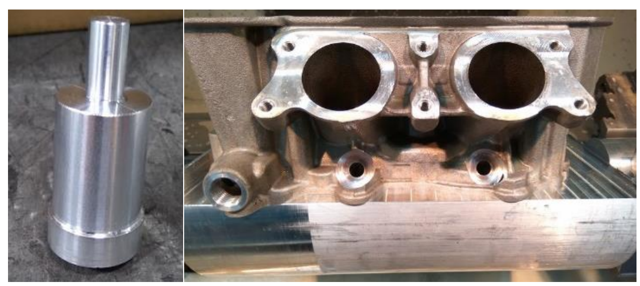

Figure 2. New version of the injector holder and cylinder head

We've also welded the tip of the injector holder before milling the face of the head, to ensure a leak free seal inside the combustion chamber. The head was then mounted once more on the jig to drill and ream the holes in the injector holders.

Figure 3. Welded injector holder tips and final head assembly

The finished part also sports a threaded flange that allows the injector cap to secure the injector in place and connect it to the high-pressure fuel system.

Figure 4. Milled cylinder head face and complete head assembly

This new concept solved the weak points in the previous design and should resist the test of time. The engine will undergo hours of dyno and vehicle testing to ensure it can resist the intended abuse.

Pistons Revision

Our better understanding of the physics principles of combustion has lead us to redesign the pistons used in our direct injection 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. However, the team ultimately decided against running a turbo last year for simplicity reasons; the new GDI engine being complex enough on its own. We've decided to run a turbo this year, to fully utilize the potential of the direct injection technology. 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 mitigation offered by the direct injection system 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 should the team decide to develop the required software. 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 5. 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 6. 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.

Figure 7. Engine Assembly

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.

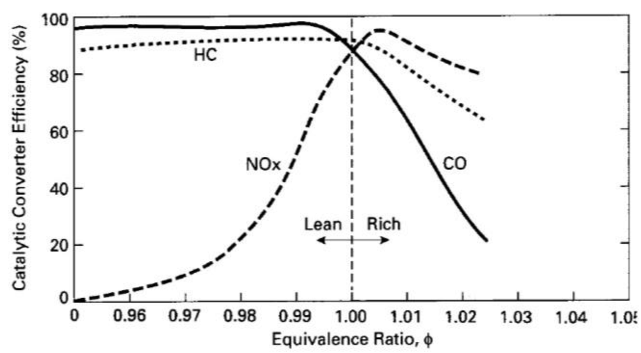

Figure 8. Catalytic Converter Efficiency vs Equivalence Ratio

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.

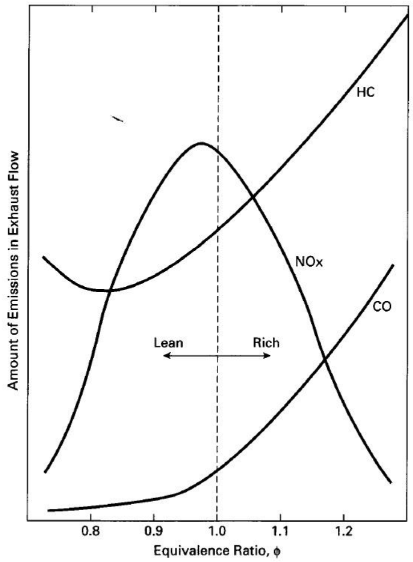

Figure 9. Amount of Emissions in Exhaust Gases vs Equivalence Ratio

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.

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.

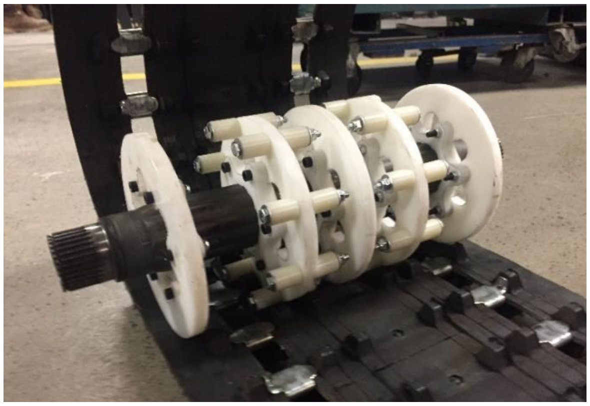

Figure 10. Custom track drive sprocket

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 bellow.

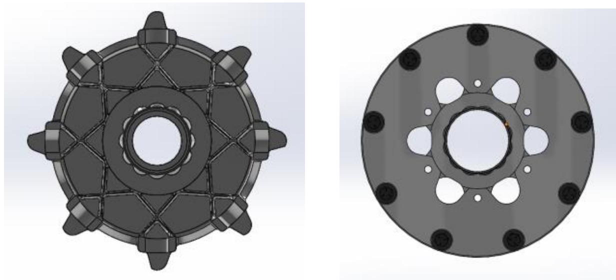

Figure 11. Drive Sprocket Comparison OEM vs Custom

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 12. 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.

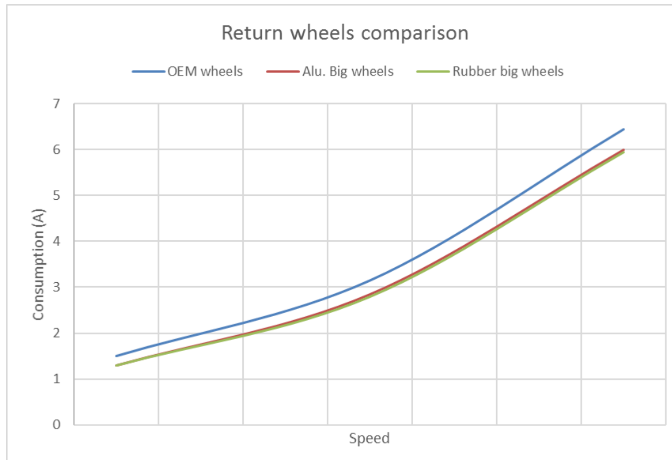

Figure 13. Big wheels' test

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 14. 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, 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. This has helped quiet down the induction noise significantly. However, the team doesn't have any data to show the difference.

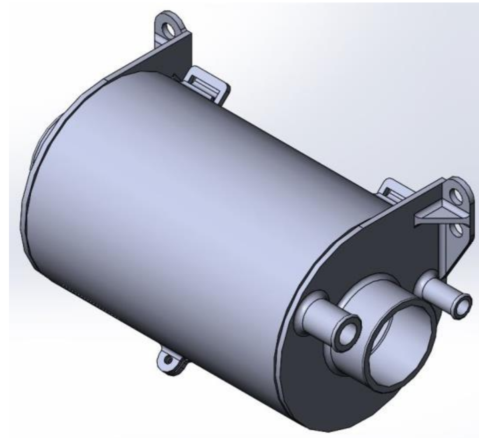

Figure 15. Air Intake Expansion Chamber

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
Guillaume Verner	Team Captain
Edouard Levesque	Interim Captain
Dominic Mathieu	DUC everyday operations oversight
Pierre-Olivier Langlois	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.

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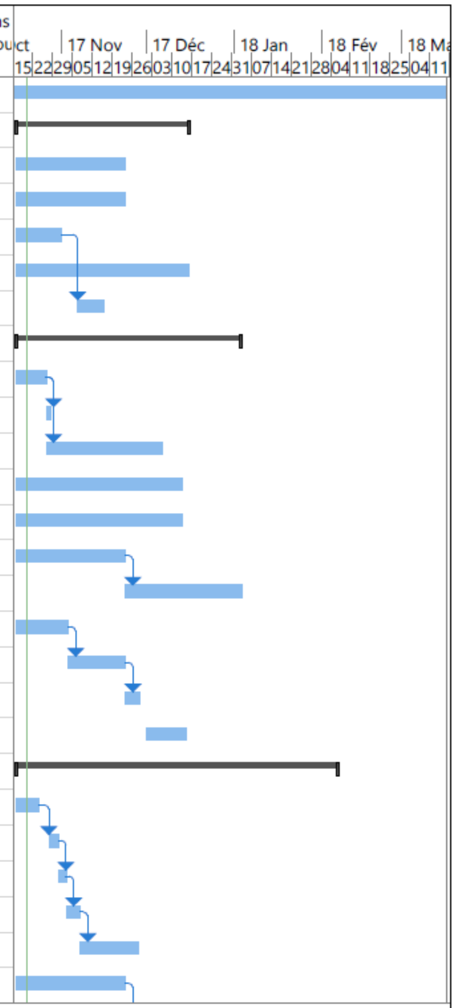
Definitions/Abbreviations

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°		Mod Tâch	Nom de la tâche	Durée	Début	Fin	Préd	Noms ressou
1			Début session H-17	98,7 jours	Ven 17-09-01	Ven 18-03-16		
2			**Moteur HPDI**	**31,5 jours**	**Lun 17-10-16**	**Ven 17-12-15**		
3			Fabrication support pompe V2	1 mois	Lun 17-10-16	Jeu 17-11-23		
4			Fabrication tête V2 (commandite)	1 mois	Lun 17-10-16	Jeu 17-11-23		
5			Achat pièces backup	8,4 jours	Lun 17-10-16	Mar 17-10-31		
6			Fabrication Cam V2	31,5 jours	Lun 17-10-16	Ven 17-12-15		
7			Remonter Base 600ACE	5 jours	Lun 17-11-06	Mer 17-11-15	5	
8			**Moteur diesel**	**40 jours?**	**Lun 17-10-16**	**Mer 18-01-03**		
9			Démonter injecteur	6 jours	Lun 17-10-16	Jeu 17-10-26		
10			Contacter fournisseur	1 jour?	Jeu 17-10-26	Ven 17-10-27	9	
11			Trouver solution injecteur	20 jours	Jeu 17-10-26	Mer 17-12-06	9	
12			Commander servomoteur	30 jours	Lun 17-10-16	Mer 17-12-13		
13			Commande turbo	30 jours	Lun 17-10-16	Mer 17-12-13		
14			Layout couette motec m400	20 jours	Lun 17-10-16	Jeu 17-11-23		
15			Fabrication couette motec	20 jours	Jeu 17-11-23	Mer 18-01-03	14	
16			Dessin support moteur V2	10 jours	Lun 17-10-16	Ven 17-11-03		
17			Découpe support moteur V2	10 jours	Ven 17-11-03	Jeu 17-11-23	16	
18			Test support moteur dans XU	2 jours	Jeu 17-11-23	Mar 17-11-28	17	
19			Remontage moteur diesel	7 jours	Ven 17-12-01	Jeu 17-12-14		
20			**Dyno 2.0**	**57 jours?**	**Lun 17-10-16**	**Mar 18-02-06**		
21			Découpe plaque support moteur	4,2 jours	Lun 17-10-16	Lun 17-10-23		
22			Soudage des supports	1 jour	Ven 17-10-27	Lun 17-10-30	21	
23			Montage sur banc de test	2 jours	Mar 17-10-31	Jeu 17-11-02	22	
24			Montage réservoir d'essence/fuel	2 jours	Jeu 17-11-02	Mar 17-11-07	23	
25			Fabrication ligne à essence	10 jours	Mar 17-11-07	Lun 17-11-27	24	
26			Assemblage panneau 2.0	20 jours	Lun 17-10-16	Jeu 17-11-23		



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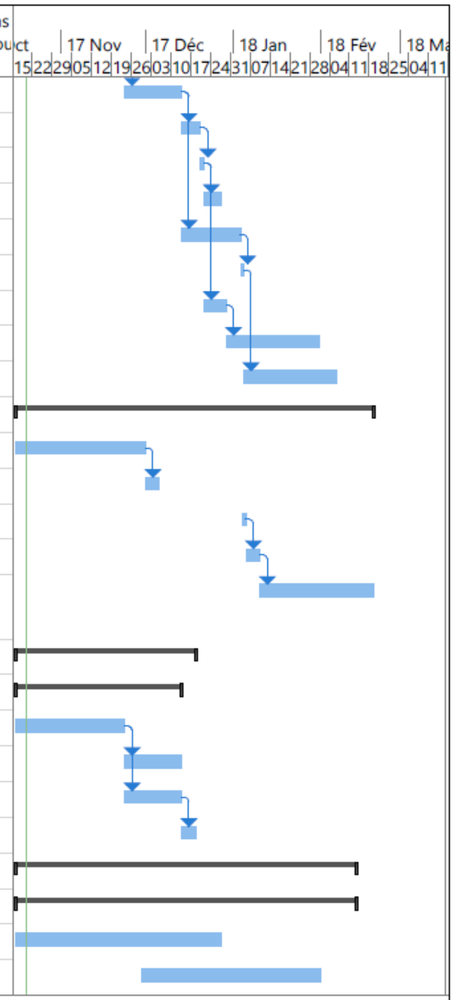
Gantt Chart (continued)

N°		Mod Tâch	Nom de la tâche	Durée	Début	Fin	Préd	Noms ressou
27			Pose du panneau sur banc de test	10 jours	Jeu 17-11-23	Mer 17-12-13	26	
28			Installation moteur 600 stock	3 jours	Mer 17-12-13	Mer 17-12-20	27	
29			Départ dyno 600 ace stock	1 jour?	Mer 17-12-20	Jeu 17-12-21	28	
30			Dyno 600 ACE stock	3 jours	Jeu 17-12-21	Mer 17-12-27	29	
31			Montage moteur diesel sur dyno	10 jours	Mer 17-12-13	Mer 18-01-03	27	
32			Début du dyno diesel	1 jour?	Mer 18-01-03	Jeu 18-01-04	31	
33			Montage 600 HPDI sur dyno	4 jours	Jeu 17-12-21	Ven 17-12-29	29	
34			Dyno 600 HPDI	16 jours	Ven 17-12-29	Mer 18-01-31	33	
35			Dyno diesel	16 jours	Jeu 18-01-04	Mar 18-02-06	32	
36			**Remontage banc de test acoustique**	**63,6 jours**	**Lun 17-10-16**	**Lun 18-02-19**		
37			Fabrication nouveau garde poulie	23,8 jours	Lun 17-10-16	Jeu 17-11-30		
38			Instalation garde poulie	2 jours	Ven 17-12-01	Mar 17-12-05	37	
39			Mise en marche banc de test	1 jour	Jeu 18-01-04	Ven 18-01-05		
40			Test de son Barbottin/Chaincase	2 jours	Ven 18-01-05	Mer 18-01-10	39	
41			Test son des nouvelles composantes	1 mois	Mer 18-01-10	Lun 18-02-19	40	
42			**Suspension arrière**	**32 jours**	**Lun 17-10-16**	**Lun 17-12-18**		
43			**Anti stab variable**	**30 jours**	**Lun 17-10-16**	**Mer 17-12-13**		
44			Fin de conception	20 jours	Lun 17-10-16	Jeu 17-11-23		
45			Envoi à la découpe des pièces	10 jours	Jeu 17-11-23	Mer 17-12-13	44	
46			Tournage des pièces	10 jours	Jeu 17-11-23	Mer 17-12-13	44	
47			Instalation sur banc de test	2 jours	Mer 17-12-13	Lun 17-12-18	46	
48			**Électronique**	**60,5 jours**	**Lun 17-10-16**	**Mar 18-02-13**		
49			**Nouveau cadran de bord HPDI**	**60,5 jours**	**Lun 17-10-16**	**Mar 18-02-13**		
50			Création interface motoneige	37 jours	Lun 17-10-16	Mer 17-12-27		
51			Modification interface	32 jours	Mer 17-11-29	Mer 18-01-31		



Page 2

Gantt Chart (continued)

N°	Mod Tâch	Nom de la tâche	Durée	Début	Fin	Préd	Noms ressou
52		Connection avec couette file HPDI	15 jours	Lun 18-01-15	Mar 18-02-13		
53		Connection GPS	24 jours	Jeu 17-11-30	Mer 18-01-17		
54		**Kit graphique**	**24 jours**	**Lun 18-01-15**	**Ven 18-03-02**		
55		Achat nouveaux plastiques	20 jours	Lun 18-01-15	Jeu 18-02-22		
56		Kit graphique	4 jours	Jeu 18-02-22	Ven 18-03-02	55	
57		**Banc d'essai injecteur**	**51,9 jours**	**Jeu 17-10-19**	**Mer 18-01-31**		
58		Conception Mécanique	22,4 jours	Jeu 17-10-19	Ven 17-12-01		
59		Fabrication mécanique	14 jours?	Lun 17-12-11	Ven 18-01-05	58	
60		Achat des composants standards	1 jour?	Lun 17-12-04	Mar 17-12-05	58	
61		Assemblage banc de test	3 jours	Lun 18-01-08	Ven 18-01-12	59	
62		Mise en marche banc de test	4 jours	Ven 18-01-12	Ven 18-01-19	61	
63		Aquisition de données	5 jours	Lun 18-01-22	Mer 18-01-31	62	
64		**Embrayage EVT**	**64,9 jours**	**Jeu 17-10-19**	**Lun 18-02-26**		
65		Conception Mécanique	25,9 jours	Jeu 17-10-19	Ven 17-12-08		
66		Achat des composants standards	4 jours	Mar 18-01-02	Mar 18-01-09	65	
67		Fabrication des pièces sur mesure	20 jours	Mar 18-01-09	Lun 18-02-19	66	
68		Programmation	35 jours	Lun 17-12-11	Ven 18-02-16	65	
69		Essai sur banc de test acoustique	4 jours	Lun 18-02-19	Lun 18-02-26	68	
70		**Assemblage prototype**	**6 jours**	**Ven 18-02-16**	**Mer 18-02-28**		
71		Diesel	3 jours	Ven 18-02-16	Jeu 18-02-22		
72		Essence	3 jours	Ven 18-02-16	Jeu 18-02-22		
73		essai sur neige	3 jours	Jeu 18-02-22	Mer 18-02-28	71	
74		**Compétition**	**5,2 jours?**	**Ven 18-03-02**	**Mar 18-03-13**		
75		Départ	1 jour?	Ven 18-03-02	Lun 18-03-05		
76		Retour	1 jour?	Lun 18-03-12	Mar 18-03-13