# 4-Stroke IDI Turbocharged Diesel Snowmobile Design Clean Snowmobile Challenge 2017 Design Paper

**Charles-Philippe Aubin, Etienne Girard, Pierre-Olivier Langlois, Yoan Lebreux, Guillaume 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 2017 Ski-Doo Tundra chassis with a Kohler KDW1003 diesel engine for our researches. Our modifications include the implementation of a turbocharger, an entirely redesigned exhaust system and exhaust after treatment solutions. These modifications will allow our snowmobile to compete in the diesel utility class and attempt to justify the need for diesel snowmobiles in today's market. The modified snowmobile now has a peak power output of 40hp and 70ft-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 for the DUC. This year, we took on the challenge of designing and building a second snowmobile. Seeing the growing interest for diesel powered UTVs, it seems inevitable that diesel utility snowmobiles will also appear on the market in the near future. With this in mind, we were set on showing the world our team's view of what a diesel snowmobile should be like. We believe that this new platform will open up a plethora of possibilities for future modifications and improvements. Many of the advantages of the diesel engine make it a great powertrain for a utility snowmobile - namely, the high torque output as well as low noise and great fuel economy. We also believe that this year's project is considerably more economically viable than its predecessors, as it relies more on readily available 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 2017.

## SNOWMOBILE BASE CHASSIS SELECTION

### Tundra Sport

As we were starting a new year with a new project, we had the chance to choose the body on which we would build our prototype. Our choice was based on three main criteria. First, it had to be a BRP because they're built in our province and we're proud of that. Second, it had to be a utility snowmobile. Finally, it had to be the most fuel economical design.

We decided to choose the Ski-Doo Tundra Sport as our new platform because it was the best value for us from BRP. If we compare this model to the others from BRP in the utility class, it's the only one to have a 137" track instead of a 154" track. That is a big advantage regarding fuel economy. Also, it has a larger engine bay compared to a normal trail snowmobile. That would help us fit a diesel engine that is normally bigger than a regular snowmobile engine.

***Figure 1, Tundra Sport vs Tundra LT***

**LTS front suspension**

The LTS front suspension is the typical front suspension offered by BRP for their utility snowmobiles. They are easy to adjust and work with compared to conventional trail suspension because the only thing you can adjust is the preload of the springs. This reduces the versatility of the suspension but the dampening is usually acceptable for a utility snowmobile. We've decided to change the springs for stiffer ones because of the extra weight of the diesel engine, turbo and other modifications in the front part of the snowmobile. The compression rate of the new springs is 90lbs/in which is almost 30% stiffer than the stock ones. We also added a *Stability and Turning Enhancement Kit* offered by Qualipieces as shown on *Figure 2*.

***Figure 2, Stability and Turning Enhancement Kit***

This system increases the ski stance by 4" and moves them forward by ¾" to improve the stability of the snowmobile in trail. It should also help at the handling event of the competition. It raises the front of the snowmobile 3" compared to the stock setup. This allow us to have a better weight transfer to the track to have more traction and less resistance from the skis on the snow for a better fuel consumption.

**137'' track**

One of the biggest advantage of a 137" track is its versatility. The track gives you enough traction for a working utilization which is very important for a utility snowmobile, without sacrificing the fuel economy. This track length also offers a wide variety of choices and this is why we were able to replace the stock track by a pre-studded one. So, we've replaced the Cobra 1.6 with an Ice Ripper XT because it's the only model from Camso to have pre-studded lugs with BRP's Silent Drive internal pattern at the moment. Compared to the stock track, the Ice Ripper XT is narrower by 1" going from 16" to 15". We believe this will help us reduce the fuel consumption.


***Figure 3, Ice Ripper XT***

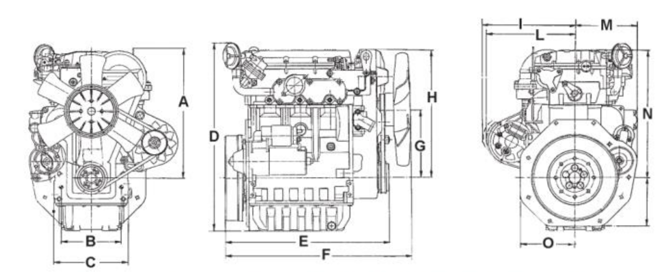
**Pilot DS 2 skis**

The Tundra Sport comes stock with Pilot DS 2 skis. This is an advantage for us with the extra weight. These skis are 6" wide, which is ½" wider than normal trail skis. This offers us better stability in trail conditions and a better "flotation" on snow. Compared to the previous version of the Pilot DS, this model with its new keel design offers lower steering effort, increased agility and predictability according to BRP.

## ENGINE DESIGN AND MODIFICATIONS

### Engine Selection

The diesel engine selection was an important task of this year's project. Our main objectives were to provide great work characteristic to the vehicle in a convenient package for the future potential buyers. This meant having an engine with good torque output, low noise and great fuel economy without sacrificing reliability. Size being the major restriction for power output of a small diesel engine, using a non-turbocharged engine was quickly ruled out, as the displacement of a naturally aspirated diesel would have to be significantly larger to produce the same power as a smaller turbocharged engine. We initially thought about using a Chinese v-twin aluminum block engine, but the unknown reliability and availability of the engine eventually ruled out that option. We finally decided to choose a proven platform with tremendous potential: the Kohler KDW1003 IDI 3 cylinders 1000cc mechanically injected engine. This is the same engine available in the diesel UTV made by Polaris as well as in many light duty applications. It sports unit injectors for precise fuel control and ease of adjustment, a cast iron block, an aluminum cylinder head and glow plugs that allow the engine to start and operate at temperatures as low as -30ºC. It is also capable of operating on Biodiesel up to B20 without any modifications — an important consideration for us. As seen below, the KDW1003 is only slightly larger than the BRP 1200 4-Tec engine which is widely used in this platform. This meant that this engine would require minimal frame modifications to fit.




COPPA OLIO STANDARD IN LAMIERA - CARTER D'HUILE EN TÔLE STANDARD - SHEET METAL STANDARD OIL SUMP - STANDARD BLECHÖLWANNE - CÁRTER DE ACEITE STANDARD EN PLANCHA - CÁRTER DE ÓLEO STANDARD EM CHAPA

| DIMENSIONS mm (in.) - DIMENSIONI mm - MESURES mm - EINBAUMAßE mm - DIMENSIONE mm - DIMENÇÕES mm | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 359 (14.13) | C | 204 (8.03) | E | 450 (17.72) | G | 186 (7.32) | I | 269.2 (10.6) | M | 169.5 (6.67) | O | 150 (5.90) |
| B | 165 (6.5) | D | 515.5 (20.3) | F | 510 (20.08) | H | 351.5 (13.84) | L | 242.5 (9.54) | N | 484.5 (19.07) | | |

*Figure 4. Diesel Engine Dimensions*

The graph below shows the power (NA), torque output (MA) and brake specific fuel consumption (C) of the engine in its stock configuration.

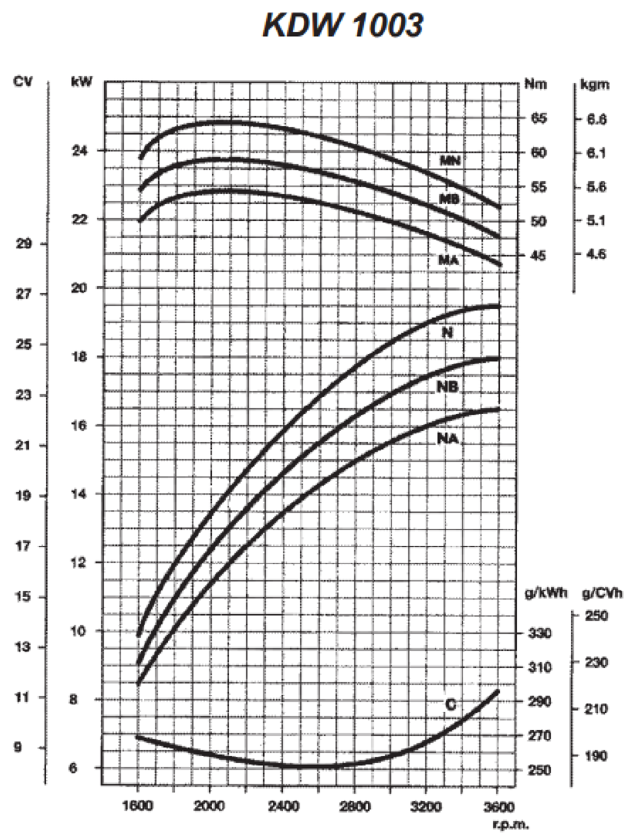



*Figure 5. Power, Torque and BSFC of the Kohler KDW1003*

As seen on the graph above, the best BSFC in the stock configuration is 250 g/kW-hr, an impressive figure for a mechanically injected engine. We hope that by adding a turbocharger, we can achieve even better fuel economy.

*Figure 6. Diesel Engine in the Tundra Chassis*

## Turbocharger Selection

Since a turbocharger is such a complementary addition to a diesel engine, we had no choice but to fit one to our vehicle. This iron block engine made for a great candidate for boost. In order to fully take advantage of the engine, a proper turbo match was necessary. Thankfully, the Garrett MGT1238Z available from Honeywell for SAE competitions fits the bill very well. As seen in the compressor map, the airflow requirements for our current power target of 40hp as well as for our projected target of 50hp both fall within the efficiency map of the turbocharger. Also, the fact that this turbo is internally waste gated and has an integrated recirculation valve makes it a great option for tightly packaged setups like ours.

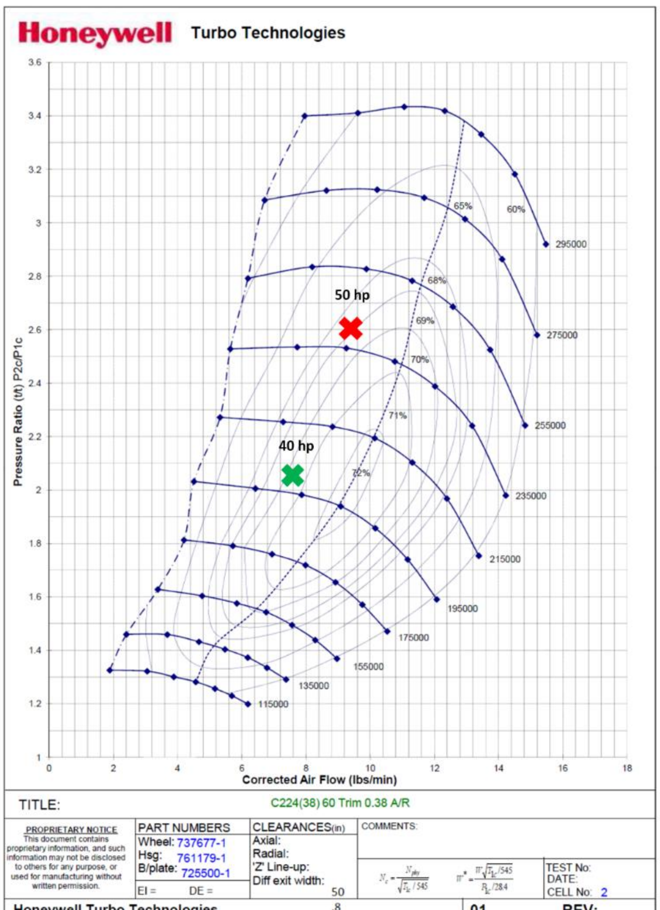



*Figure 7. MGT1238Z Compressor Map*

## Engine Mounts Design

In order to mate the new powertrain to the chassis, we had to design and fabricate new engine mounts. We chose 0.250” A36 water cut steel welded in a box shape to optimize its strength and minimize its deformation under stress. Unfortunately, because space was a constraint, we had no choice but to use solid mounts. We were however able to fit a 0.125” layer of rubber under each engine mount, to try to minimize vibrations transferred to the chassis. To determine the maximum deformation and stress applied to the mounts, a finite element analysis was made. To make this analysis, the worst case scenario was used where 100% of the weight of the engine is on only one mount. The diesel engine weighs 80 kg (784.8 N), which is the force used to make the analysis. Below is a table with the FEA data as well as a picture of the finished product.

***Table 1. Maximum Stress, Deformation and Safety Factor of the Four Engine Mounts***

| | Front left | Front right | Rear left | Rear right |
|---|---|---|---|---|
| Maximum Deformation (mm) | 0.167 | 0.045 | 0.0113 | 0.0025 |
| Maximum Stress (MPa) | 131.77 | 64.5 | 33.76 | 18.561 |
| Safety Factor | 1.9 | 3.87 | 7.4 | 13.47 |

*Figure 8. Diesel Engine Mounts*

### Exhaust After-Treatment

Even though our engine is EPA Tier IV compliant, it is not clean enough to score over 175 E-Score at the lab emissions event. This is mostly due to the fact that it does not come with any emission reduction equipment from the factory. As part of our emissions reduction strategy, we decided to fit two exhaust after-treatment solutions to our engine that work in conjunction with one another. The first one is a diesel oxidation catalyst that effectively converts up to 95% of carbon monoxide (CO) and hydrocarbons (HC) emissions when operated under lean conditions. Since a diesel engine operates lean by definition, this is a very potent emissions reduction device. An additional bonus of running a DOC is the oxidation of several other non-regulated pollutants such as aldehydes and PAHs. A DOC also contributes to reducing the typical diesel odor smell, making our snowmobile a more attractive choice for sensitive consumers.

A significant side effect of the DOC is that the oxidation reaction results in a high production of NO2, which is counted in the infamous NOx. Luckily, there is another after-treatment solution that uses this pollutant to oxidize particulate matter present in the exhaust. The partial flow diesel particulate filter is arranged in a way that diverts part of the exhaust flow into multiple metal fleece layers that store the particles. These particles are continuously oxidized when the exhaust gas temperature is above 200ºC, meaning that this system doesn’t require active regeneration. This also means that the risk of clogging the filter is greatly reduced, making this a safer choice for the competition. The end result is a filtration efficiency that can reach 70% and a reduction of the harmful nanoparticles by almost 90%. Since part of the NO2 found in the exhaust is used for the regeneration of the filter, a noticeable reduction in total NOx is also typical.

***Figure 9. DPF and DOC Used with our Kohler Engine***

Another great advantage of this DPF is its versatility. Because it uses passive regeneration to eliminate particulate matter, it can be retrofitted to almost any application as long as a DOC is fitted upstream. Since the exhaust is only partially routed through the metal fleece layers, the increase in backpressure is minimal compared to a typical wall flow DPF. This results in a minimal efficiency and performance loss compared to an engine running without after-treatment, allowing us to make the most out of our engine.

## CHASSIS MODIFICATIONS

### S-Module Re-Design

Because of its additional height and depth, we had to modify the frame to suit the new engine. The two OEM alloys tubes forming the S-Module are 1.00 inch OD with 0.065 inch wall. These would interfere with the engine so they had to be re-designed. FEA (finite element analysis) was done on Ansys with a force of 3400 N. This force was found by calculating the breaking force of the OEM parts and considering a safety factor of about 2. Results show a safety factor of 2.23 and 112 MPa of stress as shown in figures 10 and 11.

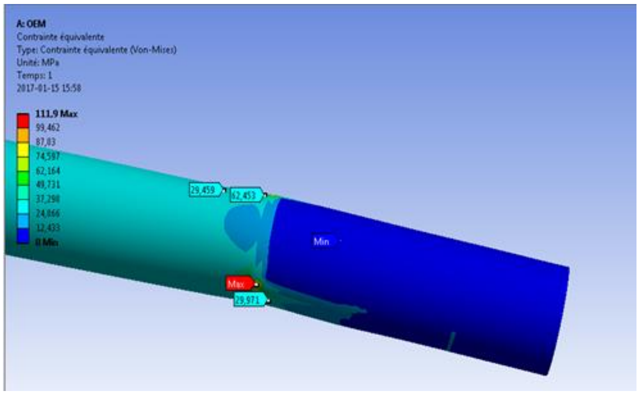



*Figure 10. Maximum Stress of the OEM Part*

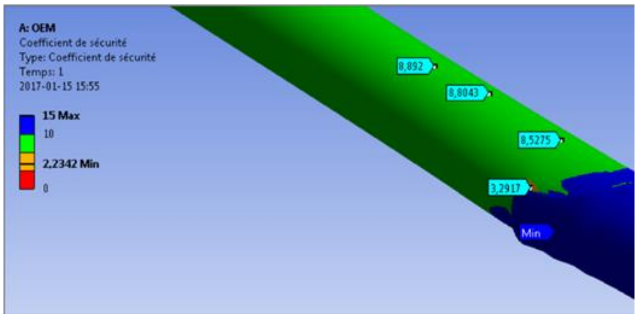



*Figure 11. Safety Factor of the OEM Part*

We used a special design to keep the air box fixed to the frame without changing any parts. The team also aimed for a stronger design because of the additional weight from the diesel engine. After many FEA tests, a 1.00 inch od with 0.250 inch wall gave interesting result as shown in figures 12 and 13. The new tubes have a security factor of 3.34, an increase of 150 % from the OEM part. The stress in the tubes decreased to 75 MPa. The new design is now stronger, more resistant and most importantly, it allows the engine to fit in the chassis.

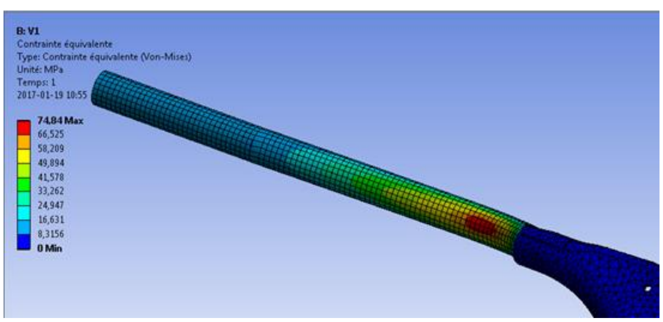



*Figure 12. Maximum Stress of the New Part*

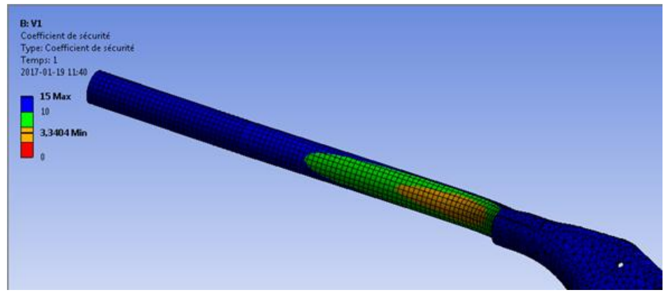



*Figure 13. Safety Factor of the New Part*

We had the parts professionally welded to ensure maximum strength and durability. The result fits the frame perfectly and allows our engine to sit comfortably in place with plenty of room to work around it. It also integrates seamlessly because the body panels fit without modifications.

*Figure 14. New vs OEM S-Module*

### Steering Stem Re-Design

We had to modify the shape of the steering stem to avoid interference with the valve cover of the diesel engine. The new power plant is bigger and larger than the original, so the original shape of the steering stem was hitting the valve cover as soon as we were turning the bars. We had to move the radius earlier and make it bigger to retain as much steering angle as possible.

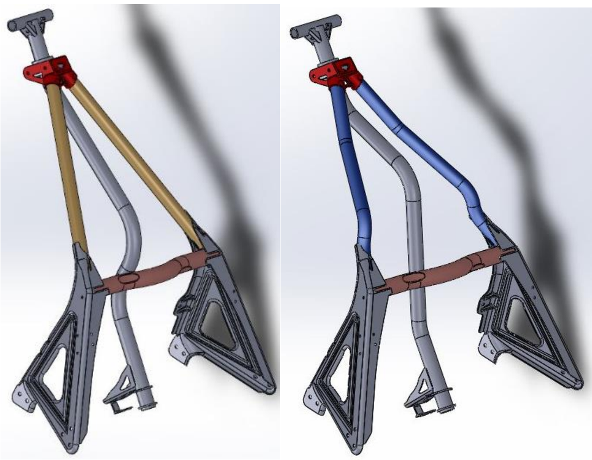


*Figure 15. OEM Steering Shaft and S-Module vs New Parts*

Originally, the Tundra bars could turn to 48 degrees at maximum. With the diesel engine, the modification of the frame and the new steering stem shape, we were able to achieve 45 degrees of turning angle.

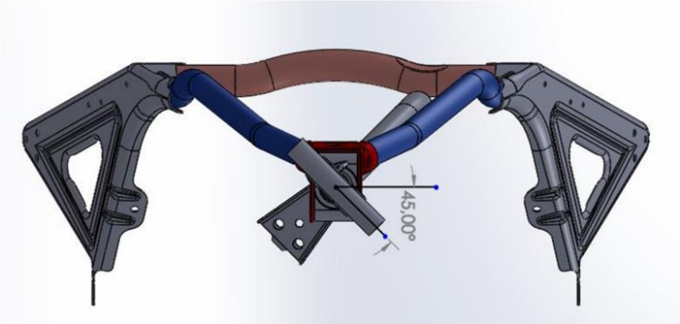



*Figure 16. Steering Angle of the Re-Designed Steering Stem*

We took the original ends of the steering stem and we welded them to the new steering stem with some inserts that we added inside. Below is a picture to compare both of the steering stem shapes. In black is the original one and in silver the new one.

*Figure 17. OEM vs New Steering Tube*

## DRIVETRAIN

### Continuous variable transmission (CVT)

Since diesel engines have a lower maximum RPM than gasoline engines, we had to find a way to make the clutches work properly. We figured that working with a specialized company in this field would be easier for us instead of modifying the clutches by ourselves. This is why we've decided to work with CVtech-IBC, which is a well known company in the CVT industry and that is based in Quebec.

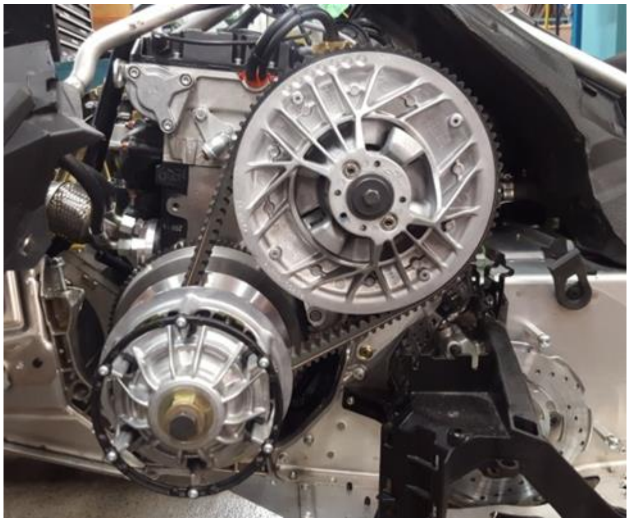


*Figure 18, CVtech-IBC CVT*

Prior to our arrangement, they had already developed a drive clutch specifically for the Kohler KDW1003. This meant that the clutch would work perfectly with the RPM range of our engine, which represents around 900 RPM at idle and 3600 RPM at rated power. We only had to adjust it to match the proper engine RPM at trail speed. Our goal was to maintain 35 mph around 2400 RPM, which is where the engine has the lowest BSFC. At this point, the engine develops most of its torque on its own. With the addition of the turbocharger, this operating condition should shift slightly lower and be close to ideal for trail riding. This will help us to maintain the required trail speed at a lower RPM.

For the driven clutch and the belt, we've decided to complete the package with standard component from CVtech because they have been designed to work together. This meant that we had to position the engine in the chassis to match the correct belt length and to have the proper clutch offset.

### Gear ratio

Even though our clutches were made to work perfectly with our engine, it was impossible to have a sufficient trail speed at a very low RPM. There was no doubt that we had to modify the gear ratio. Before doing anything, we had to keep in mind that we had to have a functional reverse because we think it's a necessity for a snowmobile this heavy. This meant that we could only modify the bottom gear because of the reverse mechanism on the upper one. We based our gear selection on this formula:

$$Gearing = \frac{RPM \times Sprocket\ pitch\ dia.}{Shift\ ratio \times mph \times 336}$$

We found out that the bottom sprocket had to be 20% smaller to reach a minimum speed of 35 mph at a good engine RPM for a good fuel consumption.

## ACOUSTICS AND NOISE REDUCTION

### Track Choice and Silent Drive

As mentioned earlier, we chose the Ice Ripper XT for its Silent Drive internal design. According to BRP, track drivers, interior track design and suspension geometry are designed to noticeably reduce sound to the rider as well as reduce vibration at the rider's feet by up to 70%. We also asked Camso to use a softer rubber for the external lugs. We think that this will help us to reduce the sound and fuel consumption of the snowmobile.

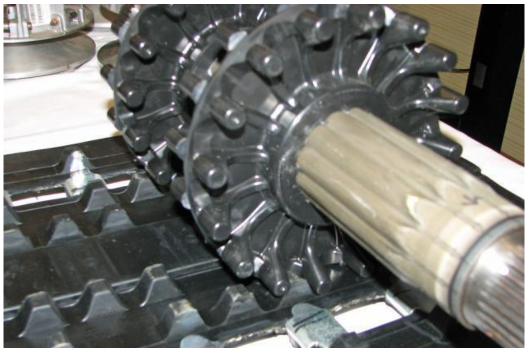


*Figure 19. Silent Drive Drive Sprocket*

### Sound foam

For soundproofing the engine compartment, we choose an egg crate foam of 2-½" thick. Also, this choice was a good option for us because the weight is low and the sound absorption coefficient is good for our application, which is typically around 500 Hz and above. This type of foam is easy to install in all the cab due to its formability.

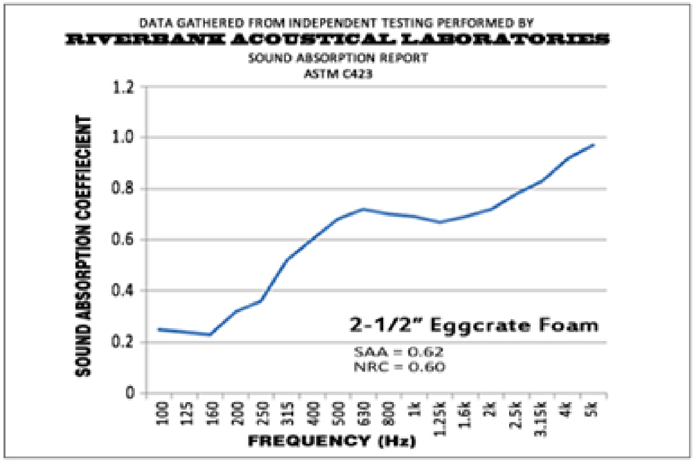



*Figure 20. Sound absorption coefficient*

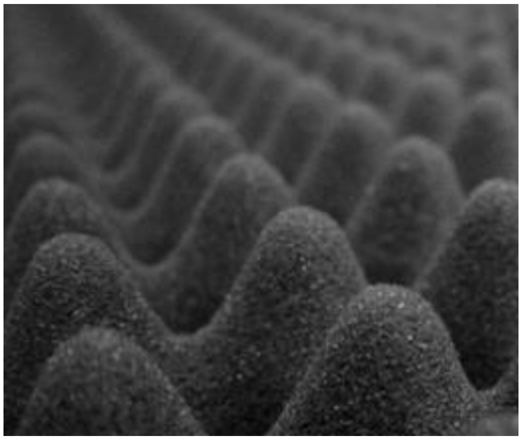


*Figure 21. Egg crate 2-1/2''*

## SUMMARY/CONCLUSIONS

Our new endeavor, the diesel-powered Tundra is a great project that's aimed at proving the need for DUC snowmobiles in today's market. By offering great low-end torque, low fuel consumption and good work characteristics, a snowmobile of this kind makes for a great replacement to a UTV for winter outdoor work. Our team's vehicle is quiet, efficient and reliable, which makes it a robust alternative. The perfect transmission match and upgraded suspension makes it a great trail sled as well, showing the multiple capabilities of this vehicle. We look forward to hearing feedback from the judges and riders this first year, as we strive to improve the upcoming prototypes.

## REFERENCES


1. Çengel, Y.A., Boles, M.A. "Thermodynamics: An Engineering Approach", 8 Edition, McGraw-Hill, Montréal.

2. "Snowmobile track warehouse", consulted on February 15, 2017, http://www.snowmobiletrackwarehouse.com/category/7890/ice-ripper-xt

3. Çengel, Y. A. & Cimbala, J. M. 2014 "Fluid Mechanics: Fundamentals and Applications", 3nd Edition, McGraw-Hill, New-York.

4. Levendis Y A, Pavalatos I, Abrams R F "1994 Control of diesel soot hydrocarbon and NOx emissions with a particular trap." SAE Technical Paper 940460

5. Miller, J. and C. Bowman. "Mechanism and modeling of nitrogen chemistry in combustion: Prog Energy" Combustion. Sci. 15, 287-338, 1989

6. Willard W. Pulkrabek, "Engineering Fundamentals of the Internal Combustion Engine", University of Wisconsin: Prentice Hall

7. AAEN O. “Clutch Tuning Handbook”, 2009 Updated Edition (Original 1986), AAEN Performance, 76 pages.

8. Emitec, “Partial Flow Diesel Particulate Filters (P-DPF) are Easy to Retrofit”, 2009, Press Release. Consulted on Februrary 19th 2017, http://www.emitec.com/fileadmin/user_upload/Presse/Archiv/Presseinformationen/Diesel_particulate_filter_engl.pdf

## DEFINITIONS/ABBREVIATIONS

| | |
|---|---|
| CO | Carbon Monoxide |
| CO2 | Carbon Dioxide |
| CVT | Continuous Variable Transmission |
| DOC | Diesel Oxidation Catalyst |
| DPF | Diesel Particulate Filter |
| EGT | Exhaust Gas Temperature |
| 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) |
| DUC | Diesel Utility Class |