

# Implementation of a Turbo Diesel Engine in a Snowmobile Chassis

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## ABSTRACT

The North Dakota State University chapter of the Society of Automotive Engineers has developed a clean, quiet and efficient turbodiesel snowmobile to compete in the SAE-sponsored Clean Snowmobile Challenge in March, 2012. The snowmobile is based on a 2010 Polaris Turbo LX Chassis and incorporates a Kubota D902 3-cylinder turbo-diesel engine which is mechanically fuel injected and is able to run efficiently on Bio-Diesel B10 through B-39. The emissions from the base engine have been tested to meet Tier-4 standards in the original naturally aspirated configuration and the goal is to reduce the emissions formations to below their original levels through the use of an Oxidation Catalyst and a partial-flow diesel-particulate-filter (DPF). The original equipment chassis and drive train has been modified to be quieter and more efficient. Efficiency modifications include increased diameter low-friction bogie wheels. Modifications for quiet operation include an under-tunnel exhaust outlet routing method, and muffler modifications in conjunction with the DPF and Oxidation Catalyst.

## INTRODUCTION

The Society of Automotive Engineers (SAE) introduced the Clean Snowmobile Challenge (CSC) in 2000 after the U.S. Government banned the use of snowmobiles in many National Parks. The competition is an engineering design competition for student members of SAE and it challenges them to demonstrate clean, quiet and practical alternatives to the traditional type of two-stroke cycle snowmobile which has difficulty achieving an acceptable noise and emissions profile. Competitors build on current original equipment manufacturer (OEM) snowmobiles with the expectation of significantly reducing unburned hydrocarbons, carbon monoxide, nitrous oxide, particulate and noise emissions while maintaining a consumer acceptable level of handling and ride performance at an attainable cost.

This paper details how NDSU student SAE members engineered an entrant to this competition through the use of novel techniques for efficiency and sound improvement with a goal of winning the event. The first section discusses the design problems faced in this competition including engineering, budgetary, environmental, and safety constraints. The second section details the various engineering decisions made in reengineering the snowmobile including the design methodology

## 1. PROJECT CONSTRAINTS

### 1.1 Engineering Constraints

The objective of this project is to be successful in the 2012 CSC and the following constraints are derived from the rules and objectives of the competition. The first set of constraints concerns the chassis the snowmobile is based on. The chassis used must be a production qualified snowmobile that was made in quantities exceeding 500 units from the model years 2006 to 2012. This constraint limits the use of high performance one-off chassis, leveling the playing field for all contestants. The next constraint is that chassis must remain unaltered from its OEM design for structural integrity. This constraint can be bypassed if proper FEA is done to demonstrate that modifications are at least as strong as the original chassis.

The next set of constraints limits the engine and performance requirements of the machine. A maximum output of 130 crankshaft horsepower is enforced. The engine is required to operate using either an E10-E39 Ethanol blend or B10 to B39 Bio-Diesel blend. The engine is also required to start easily after sitting outside overnight. In addition to this, no starting aids such as ether or block

heaters may be used. Constraints dealing with performance dictate that the snowmobile design must be able to reach 45 mph on a smooth trail. Along with reaching that speed the machine must be able to travel at least 500ft in 12 seconds from a standing start.

## **1.2 Budget Constraints**

One of the scored events for the Clean Snowmobile Challenge is the manufacturer's suggested retail price (MSRP) costing event. This event has the teams calculate the estimated MSRP of their reengineered snowmobile based on estimated prices of modifications to the machines. This MSRP needs to be competitive with offerings on the snowmobile market today or the designed snowmobile would be unsuccessful on the market. As this is what the budget controls are for the competition they are also this project's budget constraints. Due to this scoring event, every decision made will have the projected MSRP in mind in addition to the constraints set by the funds available.

## **1.3 Environmental Constraints**

The clean snowmobile competition is based on making snowmobiles that can run cleaner, quieter and more efficiently therefore this is a large component of the environmental constraints. 20% of the possible points are awarded from objective and subjective noise performance thus making this a primary constraint of the project. Since a standard stock snowmobile's noise output is around 78 decibels therefore the constraint will be set to 78 dB or less. Another constraint is the emissions of the engine due to the in-service and lab emissions tests which are weighted at 21% of the overall points. These events measure the output of NO<sub>x</sub>, CO, HC's, and particulate matter; therefore these emissions components must be minimized in addition to minimizing brake specific fuel consumption.

## **1.4 Safety Constraints**

The Competition is sponsored by the Society of Automotive Engineers and one of SAE's main concerns is the safety of all participants of the competition. Besides putting every entered snowmobile through a rigorous technical inspection, they require many safety features on the snowmobile. First, every snowmobile must be equipped to completely de-power in case of an emergency. To accomplish this, a kill switch is required on the handles bars of every machine. A tether that attaches the rider to a secondary kill switch is also required at all times when the sled is in operation. Along with emergency stopping of the sled, another focus is protecting riders and bystanders from failing parts. This is why the requirement of a clutch cover and snow flap are included in the rules [3]. These safety features are not only required but are also important for the safety of the team, therefore they are the projects safety constraints.

# **2. DESIGN DECISIONS**

## **2.1 Engine Selection**

Recently, OEM's have been successful producing relatively low emissions snowmobiles with the introduction of four-stroke turbocharged gasoline engines. Adding emissions and sound attenuation to these vehicles has historically been the most popular solution at the CSC. It was decided, however, that the benefits of modern diesel engine efficiency and quiet operation was an excellent design choice. The ability of a diesel engine to efficiently use many fuel types equally well without internal modification was also a significant consideration as the ability to run on various Bio-Fuel blends is a requirement.

A four-stroke diesel engine operates on the Diesel cycle which has the highest thermal efficiency of any volume-production heat engine. This efficiency owes to the high compression ratios possible in a diesel engine. It also has the advantage of being throttle-less; the engine speed is controlled strictly by the amount of fuel injected. This eliminates the large pumping losses inherent to gasoline engines at partial throttle leading to modern turbo-diesels reaching thermal efficiencies close to 50%.

The decision was to find a suitable small diesel engine that would fit into the space requirements of our donated chassis as major chassis modifications are not allowed by the CSC rules. The engine needed to be capable of producing enough power to achieve a minimum of 45 mph and propelling the sled 500 ft. in 12 seconds or less. It would also need to emit low amounts of particulate and other emissions as-produced as major engine design modifications are outside the scope of this project.

The decision was made to utilize a Kubota D902 898cm<sup>3</sup> three-cylinder engine (Figure 2.1) that had been donated for research to NDSU by Bobcat Co. This engine was a good choice as it fits between major chassis components easily and is rated for the most

recent off-highway Federal emissions standards (Tier-4). It is also capable of producing adequate power and torque for the speeds required without major internal modification, producing 24.8h.p. and 40 lbf\*ft in stock form.

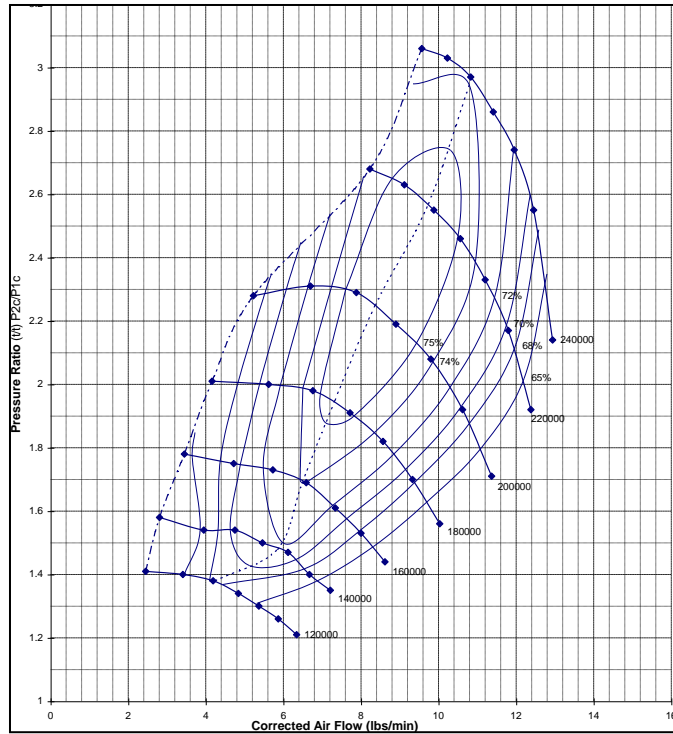


**Figure 2.1 - Kubota D902 Diesel Engine**

## **2.2 FORCED INDUCTION**

Meeting the competition's minimum speed and acceleration requirements was an area of concern judging by the power produced by other OEM snowmobiles and past competitors of the CSC. An increase in power and torque were needed. The decisions to add a turbocharger to increase the rate of fuel-air charge delivered was made after the factory engine had been tested on a water brake dynamometer with and without the addition of a turbocharger (See Appendix 1).

The turbocharger that was selected was a Garrett GT1241 turbo that is traditionally employed on compact European diesel automobiles. It has a turbine side A/R ratio of 0.43 that closely matches the expected corrected exhaust flow rate of 5.13lb/min for the D902 and is also recommended by Garrett for engine displacements from 0.5L to 1.2L. A compressor/turbo efficiency map provided by Garrett is shown in Figure 1.2 and it can be seen that our expected exhaust flow rate falls within a reasonable zone of this map (Pressure Ratio=1.36).



**Figure 2.2 - Turbo Ratio Map for Garrett GT12**

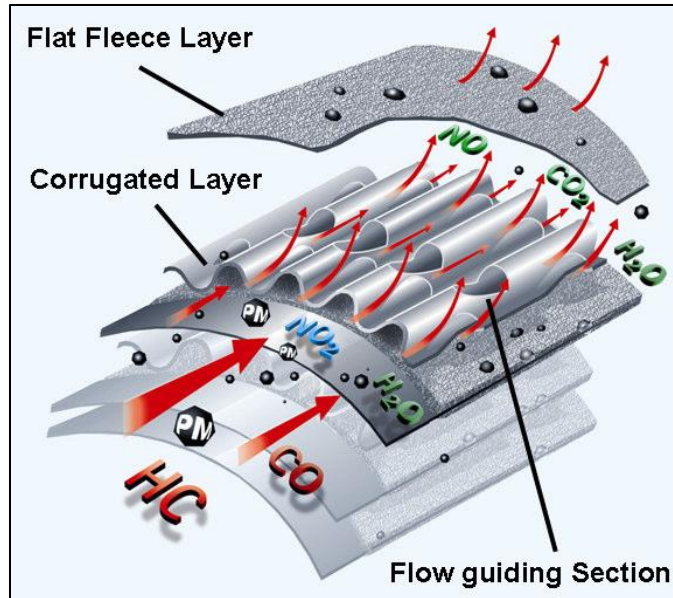
## 2.3 EMISSIONS

The engine in its naturally aspirated form is exempt from emissions regulations due to the low power output. With the addition of a turbo charger and increased fuel delivery we expect to see a change in our emissions spectrum toward more oxides of nitrogen ( $\text{NO}_x$ ), HC's, and diesel particulate matter (PM) due in part to the increased cylinder temperatures and the non-ideal fuel regulation scheme of the mechanical fuel injection system. To mitigate these effects and perform well in the emissions tests at CSC '12 we chose to implement an exhaust after-treatment system.

The design of reliable diesel after-treatment systems on road-going vehicles is an area of much research in industry due to regulation pressures. The method of treating the exhaust to reduce HC's,  $\text{NO}_x$  and PM has many variables, but the strategy that has been adopted by the automotive and trucking industries for its high  $\text{NO}_x$  and PM conversion efficiency is the Selective Catalyst Reduction (SCR) system which incorporates a urea dosing system that includes a standalone computer controlled doser-nozzle fed by a refillable urea tank. Particulate conversion efficiencies for this type of system typically achieve 65-75% reduction of  $\text{NO}_x$  while soot reduction can achieve 80% [2]. In practice the SCR is combined with an active DPF (Diesel Particulate Filter) which collects particulate and periodically burns it off with either an increased fuel load which burns in the filter or an auxiliary electric heater system.

An alternative to this system, presented by Emitec, is the Partial Flow DPF in combination with an upstream DOC (Diesel Oxidation Catalyst). This method maintains most of the particulate conversion efficiency (40-60%, [2]) of the active DPF but is maintenance free and doesn't require development of complex urea dosing equipment and control algorithms. It is also therefore much less expensive than an active DPF and was chosen based on this and the aforementioned simplicity.

The final design of the partial flow DPF will be based on Emitec's PM-METALIT® technology seen in Figure 2.3. The Oxidation Catalyst (not shown) will be platinum and palladium coated by Aristo and serves to generate  $\text{NO}_2$  which is used downstream for the reduction reaction of the captured particulate matter. It also serves to reduce the HC's and CO emissions of the engine by reducing them to  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ , and NO respectively.



**Figure 2.3 - Emitec PM-Metalit Filtration Technology**

The diameters and lengths of each component are finalized by Emitec based upon the measured exhaust gas temperature post-turbo as well as mass flow rate at the rated condition and the measured values of  $\text{NO}_x$ , CO, HC's, and PM.

## 2.4 EXHAUST MANIFOLD

The OEM supplied engine is equipped with a restrictive log-style exhaust manifold. The internal geometry of this type of manifold is fine for the factory naturally-aspirated engine; however, it is not conducive to good performance for a turbocharged recreational vehicle. A new exhaust manifold was required that improves exhaust flow by supplying the turbo with equally timed pulses of exhaust gas to improve the transient response of the turbo.

The design of a three-into-one exhaust manifold was chosen to be the most effective based on decreased loss in turbocharger delivered enthalpy compared to a constant pressure log style (Figure 2.4). It is planned that the header will be wrapped in insulation to decrease this enthalpy loss further. It's constructed from laser cut 304 Stainless Steel flanges and 1.000" OD by 0.068" wall thickness tubing for longevity and to support the cantilevered turbocharger. A merge collector was constructed such that the exhaust pressure pulses would arrive at the turbine inlet directly to promote fast spool time.



**Figure 2.4 - 3-Into-1 Stainless Steel Exhaust Header**

## 2.5 FUEL INJECTION SYSTEM MODIFICATIONS

The injection pump on the Kubota D902 is an inline cam and plunger style pump. The pump is mounted to the side the block, the camshaft is gear driven by the crankshaft. The camshaft drives a set of plungers, which compress fuel to a pressure above 1800 PSI. These high pressure pulses flow through steel lines to injector which then injects fuel into a pre-chamber where ignition is initiated. Finally the combustion process continues into the cylinders.

The engine was tested with the stock settings and produced horsepower and torque numbers that correlated closely with the rated power given by Kubota. After running a baseline test a turbocharger was installed on the engine. With the added air from the turbocharger more fuel was added for a more powerful power stroke. To add more fuel the delivery plates on the injection pump were set to the fully open position (Figure 2.5).

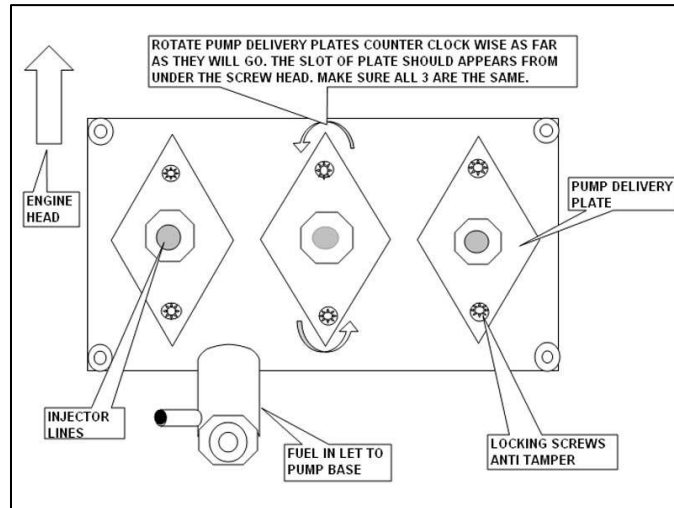


Figure 2.5 - Delivery Plate Adjustment [4]

After these changes to the fueling system were made along with the addition to the turbocharger the motor was dynamometer tested again. The engine showed gains in both horsepower and torque. The engine appeared to be running out of fuel. This conclusion was reached by evaluating several factors. The boost pressure was low; maximum boost pressure was about 5 PSI, the engine is capable of handling boost pressure in excess of 20 PSI with no natural limit to the final pressure. The exhaust gas temperatures were also low. The maximum exhaust gas temperature was measured at less than 700° F post turbocharger. Typical exhaust gas temperatures will run in the 900°-1200° F on a modified diesel engine under full load.

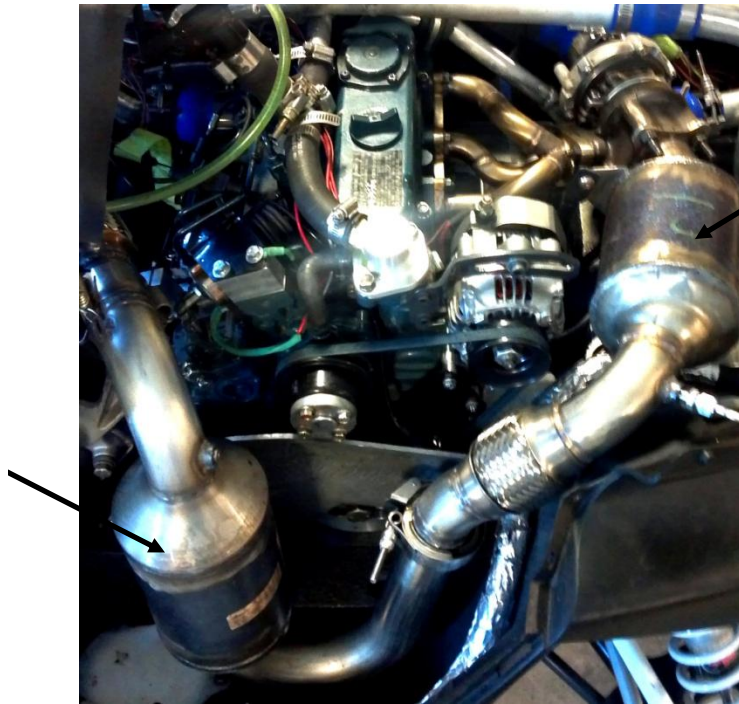
To solve the fueling issues the injection pump will be modified. The injection pump currently has 5mm plungers that flow 13 mm<sup>3</sup> per 1000 strokes. The pump will be modified with parts from a Kubota D1105 injection pump that is built on the similar architecture, just with larger parts and higher volume flow rate. The pump should have a maximum output of 21 cubic millimeters per 1000 strokes once the modifications are complete. This represents a 61% increase in fuel provided to the motor. With this added fuel it has been estimated that horsepower would be increased to 44HP. (Appendix1). Testing of the new injection pump modification showed better than expected results. The engine produced 55hp at 3900 rpm and peak torque 78.4ft-lbs at 3200. Boost was in the 15-17 psi range and EGT was approximately 800° F. which is more in line with a modified diesel engine.

## 2.6 EXHAUST ROUTING

Based on the success of NDSU's 2010 CSC design team, this year it is planned to have the exhaust exit pointing at the track under the rear of the tunnel as shown in Figure 2.7. It was found previously that this location of exhaust exit dramatically decreased the sound emitted during the SAE specified J192 test for snowmobile sound measurement. NDSU's measured decibel level for this test was registered at 87 dB which was a significant improvement over stock but still did not meet the J192 drive-by noise recommendation. A dB level of 78 or less is required to pass this test and it is expected that the use of a low frequency diesel engine will allow us to pass this test and score well on both the J192 and subjective-noise portions of the competition.



Diesel  
Particulate Filter  
(DPF)



Diesel Oxidation  
Catalyst  
(DOC)

**Figure 2.6**



**Figure 2.7: Exhaust Exit Strategy**

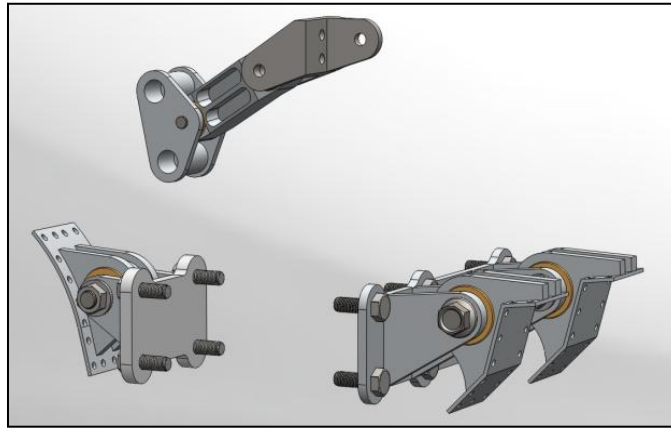
Having the exhaust pulses enter this area of the snowmobile maximizes the chance that the sound energy exiting the exhaust is absorbed by the flying snow that is present there. It is thought that there will be a need to develop a system to keep snow from packing the exhaust outlet and this will be investigated further during the testing phase of the snowmobile.

## 2.7 ENGINE MOUNTING

The design of a mounting solution of the engine into a Polaris LX Turbo chassis is of primary focus. One key factor regarding the noise output from snowmobile chassis is that they are constructed mainly from aluminum plate which acts to amplify any vibration coming from the engine. An engine mounting strategy needs to allow freedom of movement of the engine around its crankshaft axis to eliminate drive belt alignment issues and thus premature belt wear. A good solution also needs to provide damping properties to attenuate engine vibrations that are transferred to the chassis.

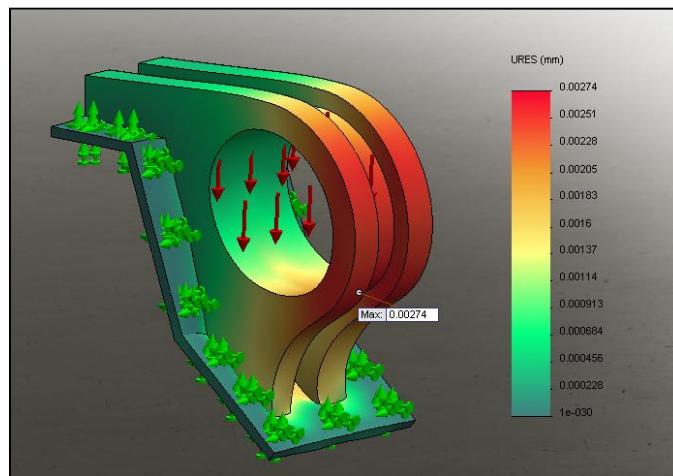
The engine mounts are designed such that the entire engine is isolated from the chassis via polyurethane bushings. Two variations in shore hardness (45A and 60A) bushings will be made and tested in the chassis for sound emissions. The sound tests will be made in accordance with SAE standard J192 which is used in the CSC competition. The hardness which attenuates the most noise will be chosen.

Due to the need for precise drive clutch alignment during high torque loading, the engine mounts have been designed around keeping the engine's crankshaft axis parallel to the secondary clutch and they can be seen in Figure 2.8. The engine was shimmed to allow proper alignment of the primary and secondary clutches.



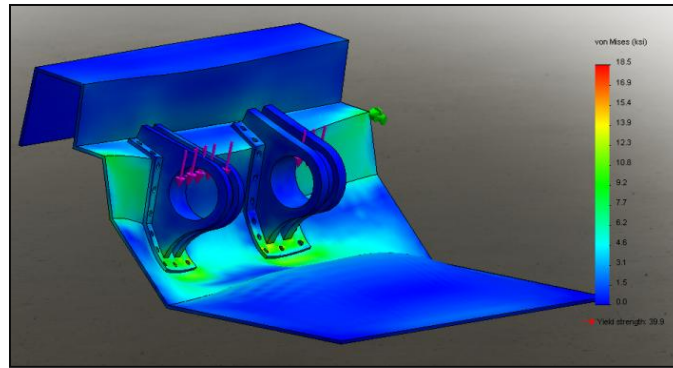
**Figure 2.8 - Engine Mounts with Engine Not shown for Clarity**

Another important factor is the strength to support the engine under a maximal loading scenario. A landing impact of 5G was chosen based on recommendations from Bobcat. As shown in the finite element analysis of Figure 2.9 and Figure 2.10, with a design factor of 2 chosen for simulated loads on the mounts, we confirmed that the chassis and mounts would survive the impact and that the chassis would fail before the mounts themselves.



**Figure 2.9 - Deflection at 5G Max loading Scenario (max = .001")**



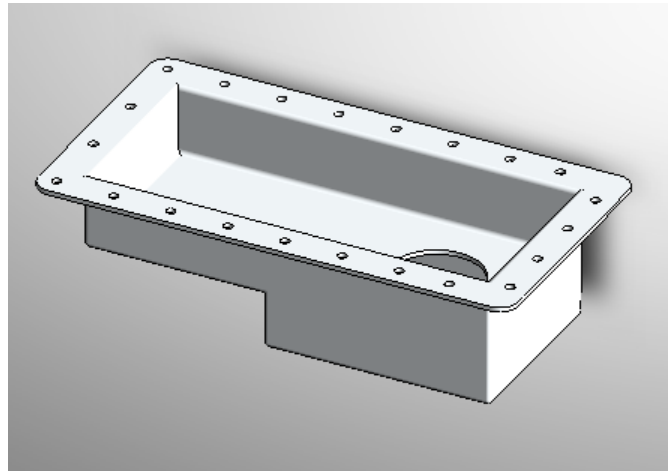


**Figure 2.10 - Von Mises Stresses and Exaggerated Deformation Simulation of Front Engine Mounts**

## 2.8 OIL PAN DESIGN

The design of a replacement oil pan is required to lower the placement of the engine in the snowmobile. This will in turn lower the center of gravity to help retain the original handling characteristics of the snowmobile considering the heavier engine.

The stock oil pan has a capacity of four quarts; this is due to the fact that this engine is used in industrial applications where a long maintenance interval is required in order to reduce downtime. It was decided that an oil capacity of two quarts was acceptable for this application. The service interval will be reduced but this is more than enough oil to lubricate then engine internals effectively. A well was added to the bottom of the oil pan for the placement of the oil pickup as seen in Figure 2.11 this was designed to keep oil around the pickup at all times, even while the snowmobile is undergoing extreme tilt angles. This will help prevent oil starvation of the engine.



**Figure 2.11 - Oil Pan with Recessed Well**

Another consideration for the design of the oil pan was the location of the steering components. The stock steering of the snowmobile was redesigned so that the steering components pass underneath the engine. The oil pan design has been modified to accommodate this.

## 2.9 EFFICIENCY IMPROVEMENTS

One of the main issues that plague modern snowmobiles is the relative inefficiency of the track system driving the vehicle compared to the pure rotation of a wheel. The rubber in the track is constantly being deformed as it bends around the skid on which it rides leading to significant power losses in the drive train [1]. This can be reduced through the use of a larger diameter idler wheel on the rear of the skid. It was decided that using Avid Products' 9" idler wheels (Figure 2.12) to replace the stock 7.25" wheels would provide the snowmobile with increased acceleration and top speed performance at a minimal cost.



**Figure 2.12 - Avid Products 9" Idler Wheel Kit and Relocation Bracket**

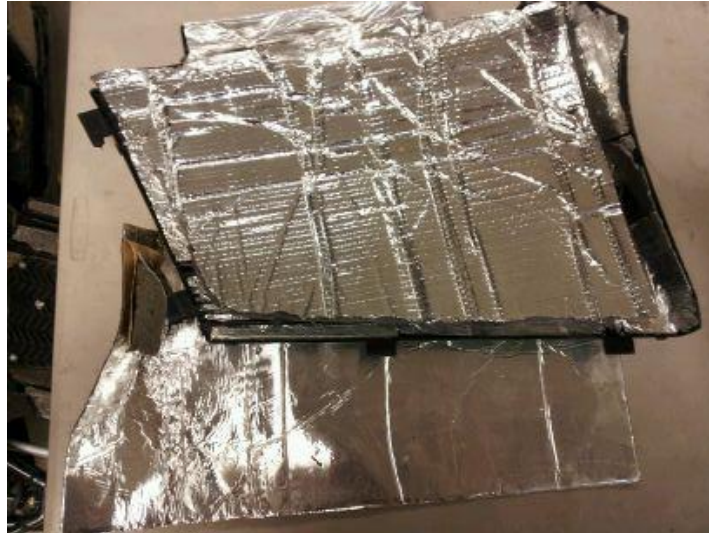
Another area to reduce the drag of the track that was investigated has to do with the HDPE skid runners called the Hyfax. These runners are in constant sliding contact with the track and contribute to the drivetrain losses present. One method that was proposed to mitigate this loss was to replace the Hyfax with low friction PTFE material. It was decided that the inclusion of this method would be prohibitively expensive for a consumer sled.

## **2.10 CLUTCH SYSTEM DESIGN**

The clutch system used for the Clean Snowmobile Challenge is specified in the competition rules [3] to be a factory designed continuously variable-ratio transmission (CVT). This type of transmission uses a belt and two pulleys that expand and contract constantly in response to the load and rpm of the engine changing the gear ratio of the CVT. Due to the fact that most snowmobile engines spin at a rate of up to 8000 rpm, there will be a significant amount of clutch tuning required for the diesel engine to function in this application. It will be very important for the engagement of the clutch to begin at around 1200 to 1300 rpm and the clutch to be fully engaged around 3500 to 3600 rpm. The clutches are a pair of custom pieces made by Team Clutches. The Primary clutch is a Rapid Response that uses 193.5 gram weights. The Secondary clutch is a Team Industries Rapid Reaction Twin Trax unit set on the 48 helix. The clutch engages at 1300 rpm and is full open at 4000 rpm. To determine the top speed, calculations were performed (Appendix 6.A and 6.B) to find the speed of the snowmobile at many speeds if the clutch were fully engaged. It was found that with the current gear ratio the snowmobile should be able to reach 72 mph at the highest rated rpm using a rough estimate of the drive ratio of the clutches. Upon testing the snowmobile was only able to obtain a top speed of 52 mph at 4000 rpm. To have better fuel efficiency and gain top end speed the chain case was changed out for unit with more available gear ratios. The stock gear ratio was 1.66:1 versus the replacement gear ratio of 1.48:1. This change should allow the snowmobile to reach a calculated top speed of 68 mph. This will also allow the sled to run at a more efficient RPM range while riding on the trail.

## **2.11 NOISE ATTENUATION**

With the goal of the sound attenuation to lower the audible bystander noise down below factory levels (78 Db) every designed part of the sled must be taken into consideration. When approaching the project there were key components designated as sound attenuation problem areas. These were designated as the CVT, the engine bay, the chain case, the tunnel, emissions and the power plant. The CVT, engine bay and chain case were all approached the same way. It was decided that a two layer system is to be used. On the side panels and hood a combination of Quiet Ride, an adhesive substrate used on the interior of cars to keep road noise out, and a heat resistant sound absorbing foam as seen in figure 2.13. With the foam having a sound absorbing rating of 60% followed by the quiet ride to absorb the remaining sound. In the engine bay, center and side panels, a sound absorbing compound called lizard skin was sprayed onto these areas. This compound is used in automotive applications and is specified to reduce noise by at least 12 decibels.



**Figure 2.13**

Along with the sound damping it also dampens propagation of vibrations through the tunnel. Another consideration that was made was sound escaping through the air vents in the hood and around the seals of the hood, to combat this baffles and foam were placed to seal in the sound into a contained area to be properly absorbed while still allowing proper airflow to the intake and for cooling. The tunnel on the snowmobile is a very large concern, a large metal object which is designed to flex propagates vibrations easily. With this vibration a pinging noise is easily audible when the correct frequency is reached causing the tunnel to vibrate against itself. To keep this vibration from propagating the lizard skin as seen in figure 2.14 was applied underneath the tunnel, except on the heat exchangers, this keeps the vibration down while keeping 12 decibels of sound inside the tunnel.



**Figure 2.14**

To keep sound inside the tunnel, track noise and reverberations, a large rubber flap was applied to the back. This flap will redirect the sound back into the tunnel and into the snow where it can be absorbed. The next concern was emissions; to keep the second hand sound down the exhaust is directed to the tunnel where the sound will be directed into the snow damping most of the sound. Along with the direction the application of a catalyst and two diesel particular filters along with the low rpm creates enough baffling to lower the Db of the engine. Finally while deciding on the propulsion method for the snowmobile; standard Weber vs. a diesel replacement,

diesel method had more advantages when it came to sound attenuation. The RPM range being half that as the Weber engine leads to lower frequency which when transfers to tunnel leads to less vibration of parts. After completing the exhaust system, the lizard skin coating and only partial engine bay coverage testing to J192 was completed. The test yielded a result of 77.8 Db and 76.2 Db on the left and right sides respectively. Yielding results lower than the required standard before sound attenuation is completed shows the snowmobile should yield the same or lower numbers at competition which in turn will allow it to pass the sound emissions section of the Clean Snowmobile Challenge.

## CONCLUSIONS

The 2012 North Dakota State University entry has proven that the implantation of a small turbo diesel power plant is a viable solution for a clean quiet and efficient snowmobile. By utilizing this power plant immediate gains were noticed in both noise and efficiency. This snowmobile would be an excellent choice for a utility application where large amounts of torque are required, which in most cases would be diesel. The diesel power plant also does not require any internal modifications to run at maximum efficiency for any mix of bio-fuel. It is a simple solution to this problem. With the correct clutching and drive gears the torque of the engine makes up for the reduced horsepower when compared to a gasoline powered snowmobile.

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FASS Fuel Systems: U.S.A

Custar Hot Rods: Deshler, OH

United Lease and Finance: Fargo, ND

Castle Sales: USA

Crary Industries: West Fargo, ND

## DEFINITIONS/ABBREVIATIONS

CO	CARBON MONOXIDE		Nitric Oxides
CSC	Clean Snowmobile Challenge	OD	Outside Diameter
CVT	Constant Velocity Transmission	OEM	Original Equipment Manufacture
DOC	Diesel Oxidation Catalyst	PM	Particulate Matter
DPF	Diesel Particulate Filter	PSI	Pounds per Square Inch
EGT	Exhaust Gas Temperature	PTFE	Polytetrafluoroethylene
HC	Hydrocarbon	RPM	Revolutions per Minute
HDPE	High-density polyethylene	SAE	Society of Automotive Engineers
HP	Horsepower	SCR	Selective Catalyst Reduction
MPH	Miles per Hour	TQ	Torque
NDSU	North Dakota State University		

# APPENDIX 1

