SAE Clean Snowmobile Challenge 2013

Proving Diesel Viability in the Snowmobile Industry

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ABSTRACT

For the 2013 SAE Clean Snowmobile Challenge, the University at Buffalo (UB) Clean Snowmobile Team has made significant strides to reduce the environmental impact of snowmobiles while retaining the performance, cost, and durability that riders and manufacturers require. To achieve this, the UB team has reverse-engineered the snowmobile in its entirety. Systems such as the engine, drive train, suspension, cooling, and chassis were studied to determine the best medium between the environment, the operator, and the manufacturer. Our team has implemented a three-cylinder turbo diesel engine in a 2011 Polaris Turbo IQ chassis. The engine of choice is a Daihatsu made, Briggs and Stratton marketed, DM950DTH indirect injected engine. The engine was then tested, analyzed and calibrated to meet the specific needs of our application. A belt drive was chosen due to its numerous benefits over the traditional chain drive, and was manufactured to easily replace the stock unit. The stock front and rear suspension has been replaced with air shocks to aid with performance and adjustability. An intercooled intake design was also researched and implemented to achieve a more efficient performing engine. Significant weight reduction has been performed where possible in order to offset the addition of necessary heavier components. System design validation was achieved by both experimental testing on a dynamometer and theoretical modeling with Ricardo WAVE software. The Ricardo engine model was validated using data correlation between measured engine outputs and simulated software outputs. With these modifications to the stock snowmobile, our team has closed the performance gap between a diesel-powered snowmobile to those available today, while meeting the strict emissions standards of the EPA.

INTRODUCTION

Due to increasing regulations on exhaust and noise emissions on modern snowmobiles, there is an ever-growing need for further development of new technologies that make snowmobiles cleaner, quieter, and more efficient. The Clean Snowmobile Challenge (CSC) is a collegiate design completion for student members of the Society of Automotive Engineers (SAE). “The intent of the competition is to develop a snowmobile that is acceptable for use in environmentally sensitive areas. The modified snowmobiles are expected to be quiet, emit significantly less unburned hydrocarbons, carbon monoxide and particulate matter than conventional snowmobiles, without significantly increasing oxides of nitrogen emissions [1].” The snowmobiles are to pass current industry noise tests and emission standards. The snowmobile needs to be designed to ride primarily on groomed trails at speeds up to 45 mph and is expected to remain cost effective, as well. With all of these constraints considered, the UB Snowmobile Team has chosen to continue to pioneer the diesel engine as the engine of choice for this competition. Diesel technology has great potential that has yet to be exploited within the snowmobile industry. The diesel engine is vastly superior to gasoline two and four stroke engines with respect to efficiency, emissions, and torque output, all of which are desired in the modern age of snowmobiling.

DESIGN INTENT

For the past seven years, the UB snowmobile team has steadily improved the viability of a diesel engine in a snowmobile chassis. This year our team is continuing this progress. Our team chooses a diesel platform over a flex fuel ethanol platform for multiple reasons. One reason is due to the “compromise” in the engine design for a flex fuel vehicle. As reported by the Department of Energy, a flex fuel vehicle operating on gasoline alone compared to diesel has a fuel economy of approximately 20% to 40% less. When E85 is run, the fuel economy drops from 40% to as much as 65% [2]. Because of this, The UB team still believes that a diesel-powered snowmobile adds to the excitement of the ever-growing snowmobile industry, while remaining beneficial to all of its customers. Every design decision made for this sled considers the snowmobile’s main three customers: the environment, the operator, and the manufacturer.

DESIGN CONSIDERATIONS

The Environment

The environment is the most important factor that the UB Team designed around. It directly relates to the main goal of the Clean Snowmobile Challenge (CSC), which is to design innovative ways to make a snowmobile clean, quiet, and efficient. Some of the many ways that our team chose to deal with this goal included using a diesel power plant, reducing unnecessary weight, and utilizing sound dampening material in noise output areas.

The Operator

The operator is an important customer that the UB team considered. This customer directly relates to the performance aspect of the snowmobile. An operator expects adequate power output to make the machine enjoyable, while also maintaining acceptable fuel economy. If both of these requirements remain unmet, the snowmobile will not be successful in today's market. To address this, our team researched and designed in the areas of the engine, belt drive system, intake system, exhaust set up, and suspension characteristics.

The Manufacturer

The manufacturer also needs to benefit from the design choices made. The manufacturer needs the cost of the snowmobile to be reasonable, while still being able to make profit. The manufacturer also needs the snowmobile to be durable and to retain its resale value. To satisfy these requirements the UB team looked into areas that would increase the time between maintenance periods of the snowmobile at a reasonable cost. These areas included the engine choice, belt drive system, and suspension choice.

ENGINE SELECTION

For the 2013 Clean Snowmobile Challenge, the University at Buffalo Snowmobile Team chose to run an indirect-injected Daihatsu DM950DTH turbocharged diesel marketed by Briggs & Stratton. This engine was chosen because it meets all specifications by the stated design considerations.

Model	58A447 (0305)
Engine Type	Four Stroke Turbo Diesel
Displacement	952cc
Bore	72 mm
Stroke	78 mm
Number of Cylinders	3 in-line
Dry Weight	196 lb
Intake Valve Open	10° BTDC
Intake Valve Close	45° ABDC
Exhaust Valve Open	45° BBDC
Exhaust Valve Close	10° ATDC

Table 1. Daihatsu DM950DTH Engine Specifications

The University at Buffalo Clean Snowmobile Team chose a diesel platform over a flex fuel ethanol platform, 2 or 4 stroke, for multiple reasons. One such reason is due to the "compromise" in the engine design for a flex fuel vehicle. As reported by the Department of Energy, a flex fuel vehicle operating on gasoline alone compared to diesel has a fuel economy of approximately 20 to 40% less. When E85 is run, the fuel economy drops from 40% to as much as 65%. Another reason for our choice of a diesel is due to the lower total energy and carbon footprint of a biodiesel blend, as compared to an ethanol blend. Fuel flexibility is another factor that played into our decision. Bio-fuel and regular pump diesel are nearly identical reducing much, if not all concerns when switching between the two. With regards to the amount of fuel, no change is needed. Unlike a gasoline-fueled vehicle that needs to stay near to its stoichiometric ratio for operation and control its power output with a throttle body, a diesel changes its power output via the amount of fuel it injects every power cycle. Therefore even if the energy content of the fuel changed, it would only hinder the full power operation and have no effect at partial throttle.

Although many new diesel engines are utilizing homogeneous charge compression ignition (HCCI) direct injection systems, there are certain benefits to an indirectly injected, stratified charge compression ignition (SCCI), which justifies the Daihatsu. With SCCI, combustion is initiated at the fuel rich spot in the pre-combustion chamber, propagating into the main combustion chamber into the cavities of the piston. The fuel rich point is important to having a full combustion, but also causes unburned fuel to puddle on cylinder walls before the rich point is ignited, leading to exhaust soot. However, due to the fuel rich ignition point, NOx formation is minimized. Conversely with HCCI, there is no fuel rich ignition point because it has a homogenous fuel concentration in the combustion chamber, resulting in minimal soot formation. While soot output is low due to a lean cylinder composition and raised cylinder temperature, NOx formation is very high [10]. When considering the emissions of an engine for our application, the required catalyst technologies were taken into account. While particulate filters can easily trap soot formed from combustion, reducing the NOx formed in HCCI engines to acceptable levels requires expensive catalysts, external exhaust injection systems, and exhaust gas recirculation technologies.

The ability of the DMT950DTH to produce excellent horsepower while producing low emissions output was the main factor for choosing the engine. Operator enjoyment is improved by the good low-speed torque of the engine, while still producing adequate overall power to achieve needed snowmobile speeds. Great engine-out emissions are achieved by engine design, calibration and added low-cost catalysts. Prices remain low due to the simplicity of the design, along with easily manufactured components. When evaluating the three major design considerations of the snowmobile, the operator, manufacturer and the environment, we have concluded that the Daihatsu is the optimal choice.

ENGINE MOUNTS

With durability being a major priority this year, the engine mounts were redesigned in order to achieve increased reliability, riding enjoyment, and decreased vibration. Due to the inherent imbalance of a 3-cylinder engine, past teams have been plagued with engine mount issues. These issues have consisted of excessive fatigue, unwanted vibrations, and ultimately failure. This year the mounts were designed to isolate vibration, while still providing excellent support to the engine. This was accomplished with using 4130 steel that provided a high strength to weight ratio, allowing an increase in strength and decrease in weight of the engine mounts.

High density polyurethane bushings were utilized to allow a reduction in mechanical vibrations transmitted to the chassis from the engine. Shown in Figures 1 and 2 are the factor of safety plots for both left and right side engine mounts, having a minimum factor of safety of 3.5 with a 300 lbf applied to each mount. This force corresponds with a 1 foot vertical drop of the front suspension, representing a slight bump or drop located on a trail during slightly aggressive riding.

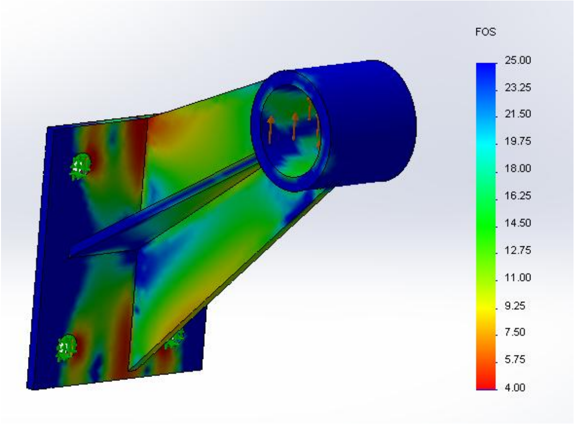

Figure 1. Right Side Engine Mount FOS Plot

The axis of rotation for both mounts (the axis of the through bolts for the mounts), is offset between the different side mounts. Offset axes of rotation provide different primary functions for both mounts; the right mount provides acceleration torque resistance, while the left mount provides the braking torque resistance of the engine. Varying major tasks of the mounts decrease stress concentrations during operation, which contribute to the overall durability of the engine mounts, increasing the operator enjoyment.

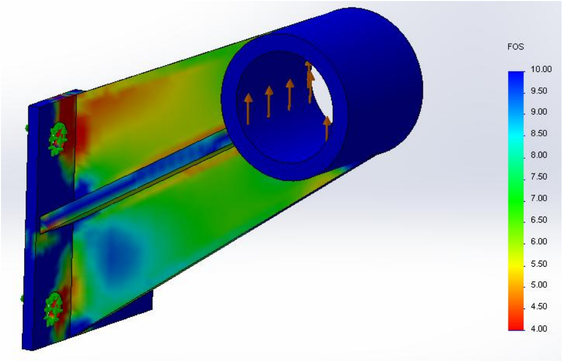

Figure 2. Left Side Engine Mount FOS Plot

Manufacturablility remains simple and inexpensive by designing the mounts from plate steel, which can then be cut using any number of processes, and welded together for final assembly. This illustrates the postitive manufacturer considerations of the engine mount assembly by limiting costs, but still maintaining product life through durability.

FUEL SYSTEM

With the introduction of a new engine into the snowmobile this year, many aspects of performance, emissions and economy were changed. In previous years power output was increased dramatically due to the changes in the fuel injection pump of the engine. Previously, a modified Bosch VE-9A4 was run with modified plunger depth, for increased fuel delivery capabilities. The current engine’s injection pump, a Bosch VE-9UH, was feared incapable of delivering the needed fuel mass for the desired power level.

Further investigation into the fuel pump found that while the plunger volume was decreased, it was equipped with a varying injection pulse width timing device. This allows the increase in duration of the fuel injection, providing an equal amount of fuel to be delivered as the previous modified injection pump. This variable pulse width is also a key contributor to the exceptional fuel economy of the engine. Due to the fact that the engine utilizes a mechanical indirect injection fuel system, it operates without any computer control. Therefore fuel quantity injected is conventionally calculated off of a simple linear relationship from engine speed and load, varying injection advance to achieve the correct quantity of fuel. However when injection pulse width is able to vary, the fuel advance does not need to be so large, being able to also retard the injection deeper into the combustion stage.

As shown in Figure 3 this allows for a more controlled fuel quantity, lowering soot emissions and maintaining power output.

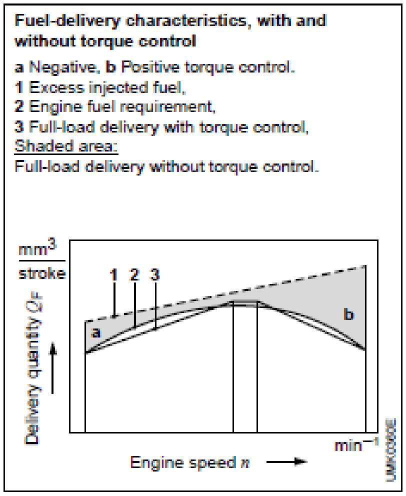

Figure 3. Bosch VE-9UH Torque Control Diagram

Varying injection pulse width, also called torque control, allows for a longer injection period, which corresponds to increased ignition lag. The ignition lag, or time from the injection event to the time of the ignition, allows for the proper in cylinder air fuel mixture distribution to achieve efficient combustion. The more homogeneous fuel mixture reduces the unburned fuel content of the exhaust gases, improving HC and soot emissions of the engine. This phenomenon was experimented in the Ricardo Wave software, and fuel injection timing with the engine's specific valve events was optimized to be within ±3 crank degrees of the injection pump's actual timing. This choice of injection pump demonstrates the snowmobiles attentiveness to user function in terms of both power output and fuel economy, while also decreasing tailpipe emissions to improve the snowmobile impact on the operational environment.

COOLING SYSTEM

A consistent difficulty with implementing a diesel engine into a snowmobile is the cooling capacity needed by a diesel engine for operation. In order to achieve optimal operating temperatures for the engine, highly innovative designs were considered outside of simply upgrading the radiator. In addition to using a thicker, 1.5" core radiator, extensive airflow analysis across the engine and radiator was considered in the design of the system as a whole.

To achieve the maximum efficiency possible by the radiator, the path of the air flowing through was considered, with the attempt of maximizing velocity. The radiator was placed at a 60° angle with respect to the horizontal to keep air velocity high, instead of previous designs with sheet aluminum chassis pieces directly behind the radiator, which decreases the air velocity post radiator. This decrease in velocity from the chassis creates a high-pressure zone behind the core of the radiator, which in turn disallows any air from traveling across the fins. By angling the radiator air has a direct path into and over the top of the engine bay, a known low-pressure zone. This low-pressure zone, which is caused by the engine taking in air, increases air velocity flowing across the fins of the radiator and therefore increases the cooling efficiency of the radiator. Control of the airflow was accomplished by using neoprene linings to block openings in the hood and body panels. Neoprene is a prime choice for this function as it is very lightweight, is resistant to heat, and acts as a sound damper for the engine noise. Due to the ducting within the engine bay, air is forced to continue over the engine and out the rear under the seat. This aids in exhaust surface cooling, which is very important in aggressive riding situations with elevated exhaust gas temperatures. Due to the airflow across the exhaust system, the heat from the exhaust is kept out of the engine bay and therefore also contributes to decreased engine temperatures.

Along with increased airflow, the radiator itself was also considered for an overall improved cooling system. A Mishimoto ATV radiator was utilized, with a thicker core than previous years; it can provide improved cooling of the engine's water while also having smaller overall dimensions to fit better within the chassis of the snowmobile. The radiator is a standard tube and fin radiator with a tube thickness of 0.125" and fin height of 0.25" inches. The unit is made of 5052 aluminum, with sheet end tanks and therefore produced for a relatively inexpensive cost.

The design of the cooling system illustrates all of the intended considerations of the snowmobile in general. The overall high efficiency of the cooling system improves the operator interaction by preventing any overheating and subsequent poor operation of the engine. The improved cooling also decreases the convective temperatures that the rider would experience during operation of the snowmobile, increasing the overall rider experience. With the engine staying within the desired operating temperature, engine life is prolonged enormously and reliability is improved, positively affecting both the manufacturer and the operator.

INTAKE SYSTEM

Due to a diesel engine's low horsepower output the need for increased horsepower is necessary. Although diesel engines produce a large amount of torque, horsepower is necessary to keep a snowmobile moving and accelerating at high speeds. The UB Clean Snowmobile team's 34hp turbo-diesel engine has a very low power output in comparison to other snowmobiles seen at the competition. Raising the power output of a diesel engine is achieved by increasing the volume of fuel and air entering the combustion chamber. Increasing the amount of fuel can be accomplished relatively easily, while increasing air volume requires a redesign to the intake manifold geometry. Due to the engine's use in industrial applications, the stock intake is not optimal for performance requirements, thus needs to be optimized.

Intake Manifold

In order to obtain a higher power output, our team decided to increase the volume flow rate of air into the cylinder head by redesigning the intake manifold. For optimal flow rate of air into and out of the cylinder during each combustion cycle, the volume flow rate of each manifold must be greater than or equal to the volume flow rate within the cylinder head.

In measuring the success of our modified intake manifold design, the horsepower output of the engine was examined. Using the stock manifold, power levels would not be high enough to be a strong competitor in the Clean Snowmobile Competition. In its stock form the engine produces 32 horsepower and 52 ft-lbs of torque.

Due to the snowmobile's space constraint and the turbocharger's orientation, our team narrowed down our numerous designs to one. The design chosen was a tapered conical shape with the inlet on the right hand side. Once the design was chosen, it was modeled in SolidWorks and analyzed using SolidWorks Flow Simulation software. The stock intake manifold was modeled and analyzed as well, for comparison of flow. The results are shown in below in Figures 4 and 5.

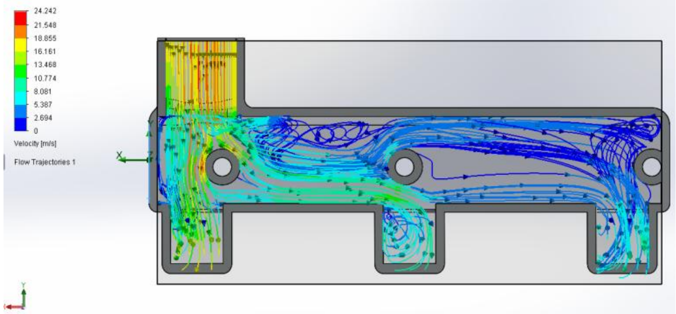

Figure 4. Cross Sectional View of Stock Intake Manifold Flow Trajectories Showing Velocity Changes and Vortices

With the elimination of the bolt holes, which creates numerous vortices and slows the airflow as shown in Figure 4, the flow in the optimized manifold (Figure 5) is laminar and is distributed to all three runners equally, which is desired in high engine efficiency. The tapered design also allows the third runner (furthest away from the inlet) to receive the same amount of air as the first runner. This occurs because as the cross sectional area decreases the velocity of the fluid increases to satisfy the principle of continuity.

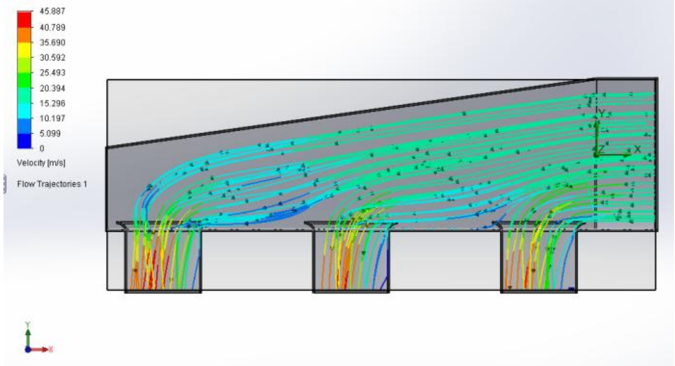

Figure 5. Cross Sectional View of Optimized Intake Manifold Flow Trajectories Showing Velocity Changes and Vortices

Velocity stacks were implemented inside the plenum to further increase the efficiency of the plenum. According to fluid dynamic's boundary layer no-slip condition at the wall, the velocity of air is zero. Therefore, having the runners raised up off of the floor of the plenum and into the high velocity air stream, prevents the velocity from slowing down before it enters the runners, as it would if the runners were flush with the wall of the plenum.

Through these modifications and observing the flow characteristics, a non-restrictive equal air distributing plenum was designed and manufactured. A comparison of the stock and optimized intake manifold is shown in Table 2 below. Through dynamometer testing, it was observed that the power of the engine was increased to 48 horsepower, including other modifications.

	Stock	**Optimized**
Air Capacity	21.01in^3	37.48 in^3
Mass of Manifold	0.85 lb	0.28 lb
Min Outlet Velocity	5.39 m/s	45.89 m/s
# of Vortices	4	0

Table 2. Comparison of Stock vs. Optimized Intake Manifold (Results Calculated From SolidWorks Software)

Intercooler

An intercooler provides the necessary charge air-cooling needed to keep combustion temperatures down while maintaining acceptable air flow through the intake tract. Low in-cylinder air temperatures lead to decreased oxides of nitrogen output, decreased thermal load on the engine, and an increase in overall combustion efficiency. A liquid to air intercooler system was again utilized this year, eliminating the need for large air charge pipes throughout the engine bay and allowing for a high capacity of charge cooling, dissipating heat through the snowmobiles rear mounted heat exchanger.

This year extensive testing was completed in regards to the intercooler, and how effective it actually is. This was done by calibrating the engine to different power outputs, and measuring intake manifold air temperatures during WOT full load situations. These tests were carried out with both a non-intercooled intake tract, and an intercooled intake tract. The

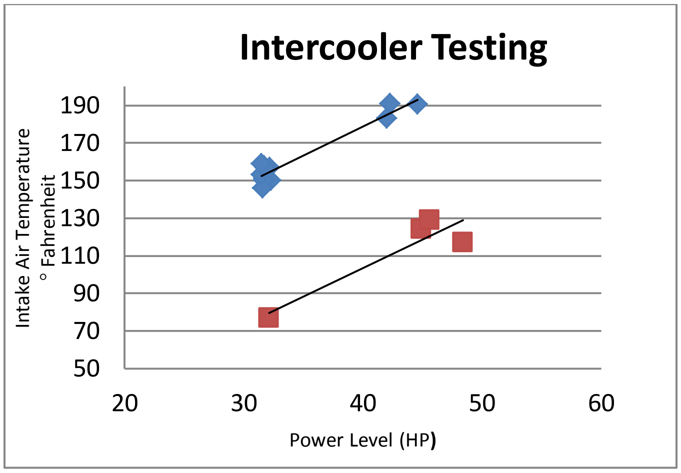

Figure 6. Intercooler Testing, Red Data Points Intercooled and Blue Data Points Non-Intercooled

Data shown in Figure 6 illustrates the outcome of the tests, showing how the non-intercooled air temperatures were approximately 80 Fahrenheit degrees higher than the intercooled temperatures. A reduction is very impressive, allowing for both improved combustion, reduced oxides of nitrogen and lowered engine operating temperatures. However due to diesel being a compression ignition fuel, it needs high pressure and high temperature to ignite completely. This becomes a problem when a diesel must undergo a cold-start, when temperatures are very cold, allowing for a complete burn of the fuel-air mixture nearly impossible, leading to high unburned hydrocarbon emissions on startup. To aid in both starting and the emissions of starting, the water pump for the liquid-air intercooler is set on a relay to delay flow of the water for the first minute of engine operation. Without the water pump for the intercooler system running, air intake temperatures raise much quicker to normal operating temperatures, which decreases the duration of time in which the engine is producing elevated amounts of unburned hydrocarbons due to low cylinder temperatures. The increase in overall performance of the engine provided by the intercooler demonstrates the added operator enjoyment, while significantly improving the engine-out emissions both during normal operation and cold-start conditions.

Turbo Selection

This year the turbocharger was an important design decision for the engine's operational emissions and power output. From the manufacturer the engine is equipped with an IHI RHF3 turbocharger. The RHF3 has a 22mm compressor inducer, can flow up to 9 lb/min of air, and the ability to maintain a maximum pressure ratio of 2.7. The previous year's turbocharger was a Garret GT-15 VNT turbocharger, a 32mm compressor which could flow approximately 15 lb/min of air and maintain a pressure ratio of 2.5. Comparatively the Garrett is much larger, designed for a much larger engine than the IHI, and is commonly used on engines 1800 cc or larger. This larger size, while preferable for total air mass flow, does have considerable disadvantages for use in our engine. Due to the Garrett's larger size, it is capable of higher efficiencies at higher flow rates, as indicated by the turbocharger's compressor map. Utilizing a higher efficiency compressor is important to reducing intake air temperatures, as a lower efficiency compressor increases air temperatures during the compression of the air [11].

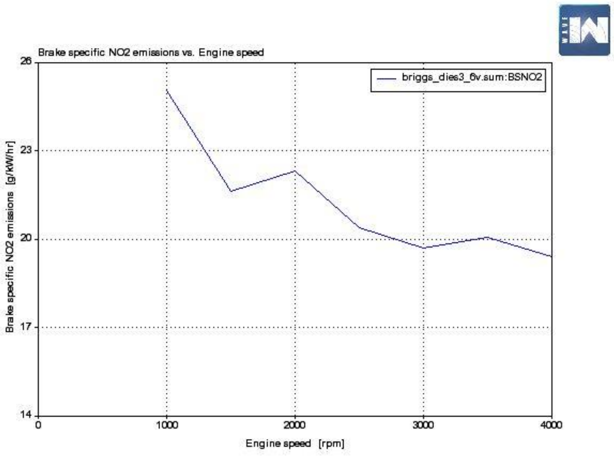

Figure 7. Brake Specific Oxides of Nitrogen Output for the Garrett GT15 Turbocharger

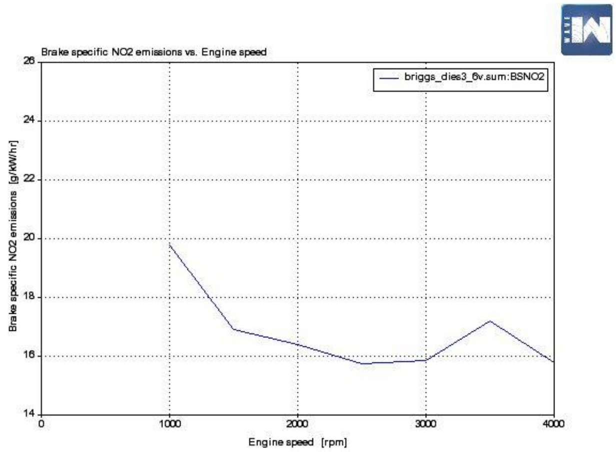

Figure 8. Brake Specific Oxides of Nitrogen Output for the IHI RHF 3 Turbocharger

In our team's turbocharger selection, our developed Ricardo Wave engine model was employed to estimate the air flow rates of the engine dependent on all possible engine calibrations. With our current engine configuration our engine's airflow was calculated to be 7lb/min. Looking into the compressor maps of both Garrett and IHI turbochargers, it was determined that the IHI would be operating at an efficiency level of 72% while the Garrett would be operating at approximately 65%. This difference in compressor efficiency would increase the air temperatures, negatively effecting both combustion efficiency and oxides of nitrogen output. The brake specific oxides of nitrogen output from our engine were calculated from the Ricardo engine model and shown in Figures 7 and 8. The brake specific NOx output from the engine using the Garrett turbocharger was 10% or greater more than that of the IHI turbocharger throughout the entire engine operating range.

These plots are accounting for the different efficiencies of the compressors, and different efficiencies of the turbines between the two turbochargers. Although it may seem miniscule, a 10% reduction in NOx emissions correlates to a realized NOx reduction post-catalyst of approximately 30%, a very significant amount.

When considering manufacturing costs, the IHI turbocharger exceeds the Garrett due to the simplicity of the design being a submerged journal bearing center cartridge. This decreases costs for both the manufacturer and the operator, as well as increases turbocharger life improving the reliability of the engine. Due to the lowered oxides of nitrogen output, the turbocharger choice also reflects the environmental considerations, thus proving the IHI RHF3 to be the superior turbocharger for use in this application.

ENGINE CALIBRATION

With the implementation of a new engine for this year's competition, extensive testing of the various parameters was needed to establish the most beneficial state of the engine. All engine testing was performed on a Land and Sea Water Brake Dyno-Mite Dynamometer. Initial engine break in and testing was first completed by slowly introducing the engine to different load vs. speed cells, gradually increasing the maximum load given to the engine via the water brake. This let the engine heat cycle through various working periods, slowly increasing the in cylinder pressures realized by the engine over multiple testing sessions, with the intent of properly seating the piston compression rings. Engine lubrication oil was changed periodically during testing, observing the metal content to ensure proper break-in of vital engine mating surfaces within the crankcase.

Once the appropriate engine break in period was attained, extensive testing of the engine's power output, emissions levels, and overall operation was initiated. Figure 9 illustrates the engines initial power level, 32 SAE horsepower and 52 ft-lbs of torque. While torque is known to be very high in diesel engines, the power output of the engine was deemed to be not acceptable in this application. To increase the enjoyment of the operator, power was sought to be increased to improve acceleration and outright top speed of the snowmobile.

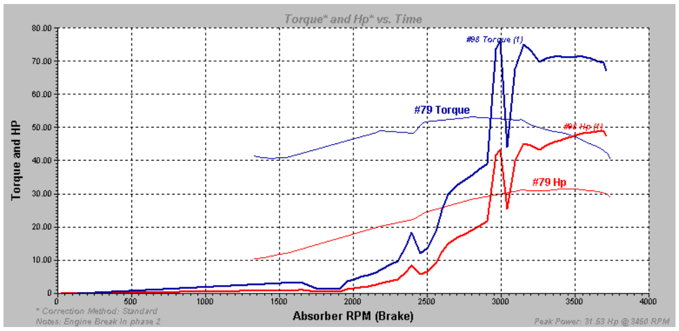

Figure 9. Stock Power Output Sweep with Maximum Power Output in Bold

Some of the first engine testing on the dynamometer included testing of the intake, and more specifically the intercooler system, shown in Figure 9. Further testing of the engine included fuel system development, varying fuel injection quantities to improve engine power while maintain safe exhaust gas temperatures. Experimenting with various fuel injection pumps, with modified injection timing, to understand the engine's reaction to advancement and retardation of the injection timing. While all engine testing was conducted, oxides of nitrogen output of the engine was measured via NTK NOx Sensors both pre and post catalyst, and used to refine the Ricardo Wave model of the engine. Diesel oxidation catalyst efficiency was measured and recorded to monitor the realized tailpipe emissions, much like those measured at competition.

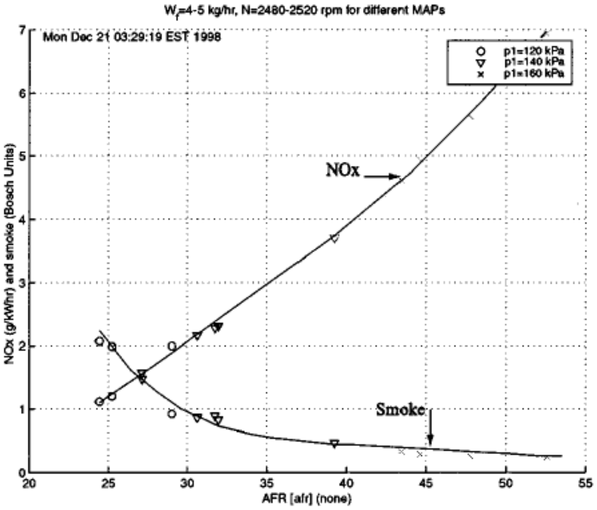

Figure 10. Relative Relationship between Oxides of Nitrogen and Soot Output vs. Air-Fuel Ratio

For final calibration of the engine, a number of variables were identified as the important, direct relationship variables for the model of power and emissions output of the engine. These characteristic variables were found to be the boost pressure of the turbocharger, also known as the pressure ratio, the fuel injection quantity, measurable by the equivalence ratio of the engine, intake air temperatures, and the load acting upon the engine. Engine output measurements were done by holding full load upon the engine, and varying speed throughout its upper speed range to acquire precise measurements of maximum horsepower. Through intensive testing of multiple variable analyses, important relationships were developed and further explored. Figure 10 demonstrates a common relationship between equivalence ratio and oxides of nitrogen and soot output [12]. Although it is a qualitative relationship for our engine, there is an equilibrium point where the NOx output and soot output have a shared low value on the equivalence ratio scale.

Due to the relationship shown in Figure 10, it was decided that NOx concentrations while varying turbocharger pressure ratio and fuel delivery to the engine from the injection pump needed to be tested. It was found that as an equivalence level of 0.04 (AFR of 25:1) that the brake specific NOx output was optimal with the BSFC and brake specific soot output still within allowable limits. This was established with the maximum pressure ratio for our engine's flow rate and turbochargers capacity, a pressure ratio of 1.8, corresponding to a boost pressure of 12 psig. This higher pressure ratio was used in order to achieve optimum in cylinder combustion dynamics by supplying high amounts of air to aid complete combustion of the fuel air mixture.

The engine's calibration is an important feature of the engine, and the snowmobile in general, that must be designed around the intent of the snowmobile. In our application, that is to achieve outstanding fuel economy, emissions, and reliability while maintaining the enjoyment of any common snowmobile. Developing a sound engine calibration demonstrates the benefits experienced by the operator in terms of engine performance, while continuing to produce exceptional levels of both brake specific soot and NOx output.

EXHAUST SYSTEM

The engine is used in off-road applications that currently do not have strict emissions regulations. Due to this, the stock motor is not equipped with a system to control oxides of nitrogen (NO_x), hydrocarbons (HC's), or particulate matter (PM). In addition, more fuel is being used by the motor in order in increase power to a useable level. This will bring to emissions to an unacceptable point. To control this, a diesel oxidation catalyst and a diesel particulate filter are being used collectively to achieve this goal.

The oxidation catalyst is used to reduce the hydrocarbon, carbon monoxide, and NO_x levels by converting each one to H_2O, CO_2, and NO_2, respectively. The water and carbon dioxide will exit the tail pipe as harmless compounds, while the nitrogen dioxide will be used downstream in the particulate filter. The oxidation catalyst used is optimized for NO_2 production and is coated with Platinum to interact with the HC's and CO. This unit is supplied by Emitec and is placed post turbine in the exhaust system.

The particulate filter will reduce the amount of particulate matter, or soot, exiting the tail pipe. In the past, a ceramic "wall flow" system was used to achieve this. It collected the soot, which then required excess fuel to burn off the accumulation. This is an inefficient system, therefore a "Partial Flow Filter" made by Emitec will be used. It is used in combination with the oxidation catalyst to control soot levels while not obstructing the exhaust flow. The NO_2 created by the oxidation catalyst is used to actively burn the soot off as it passes through the filter. Since it does not affect exhaust flow, it can be added to any system, after the catalyst, to reduce soot output up to 70 percent.

BELT DRIVE SYSTEM

Poly Chain belt driven power transmission systems are one of the most durable and efficient power transmission systems on the market today. They are built for high horsepower and torque applications, which is ideal for the power transmission from a turbo diesel engine. They can achieve efficiency ratings of 96 to 98%. Due to the nylon coated teeth on the belt, noise is reduced drastically compared to that of the steel to steal contact on a chain driven system. The belts themselves outlast chains 3 to 1[4]. Belt drive systems also do not need to be contained in a concealed case subjected to a constant oil bath. This decreases the weight of system, produces less drag force, as well as totally eliminates the use of toxic petroleum products (i.e. oil). Because no concealed case is needed, the ease of maintenance and part changeability of the belt drive system increases drastically. Draining the oil and disassembling the case is no longer needed when changing and upgrading parts, which is a very attractive trait when maintenance is needed. Belt drive systems also consist of less moving parts, which increases durability and decreases time between maintenance periods. Because of all of these benefits, our team decided to continue to pursue the concept of the belt drive system.

In doing extensive research on belt drive systems for snowmobiles, our team realized that purchasing an aftermarket belt drive system was not practical and would go against the CSC goals of keeping solutions cost effective, seeing a how the aftermarket systems ranged from $1900-$2500. Thus our team decided to design and manufacture our own cost effective belt drive system.

When designing this system, four main objectives were considered. These included efficiency, manufacturability, ease of maintenance, and cost. As a result a complete redesign of last year's belt drive system was done, shown in Figure 11. An adjustable belt tension was added to this year's model which allows for quick belt adjustability as well as the ability to swap out different pulley sizes and belt lengths to optimize snowmobile performance. The industry leading Gate's Poly Chain GT Carbon Belt was chosen due to its durability, low noise characteristics, and high efficiency. The SolidWorks package was utilized for the design. FEA analysis was done on every component of the belt drive in order to optimize weight and material usage. In doing so, the weight was reduced by 37% compared to that of last year's manufactured belt drive system.

Figure 11. Belt Drive Assembly Designed in SolidWorks

Pulley Design

The pulley design is one of the most significant changes that we made to the belt drive this year. Last year's pulleys consisted of 1.58" thick round steel billets with splined center bores. These pulleys were designed for industrial use to which longevity of the pulley is more of a desired characteristic than that of weight savings. To save weight, make the pulley manufacturing more efficient, and make the belt drive ratio easily interchangeable, a studded hub mounting design was implemented, similar to how a wheel attaches to a vehicle.

By implementing this design, the pulleys, which are the most expensive part of the belt drive, will be much cheaper to produce and weigh a significant amount less. This is due to the fact that no splined bore is needed in the pulley itself, which results in the pulley's wall thickness to be able to decrease significantly. A comparison of weight savings of the old belt drive to the new belt drive is shown in Table 2 below.

Table 3 shows that the optimized pulleys weigh a significant amount less and results in a total belt drive system weight reduction of 37%, which greatly reduces the rotating mass of the system, improving efficiency.

Due to extensive calculations and testing results from last year, it was determined that the pulley ratio of 1.656 was enough to propel the snowmobile to a theoretical top speed of 72 mph, thus this ratio was used for this year as well. Once sold modeled, FEA was done on both driver and driven pulleys using AISI 1020 steel as the material. The results are shown in Figures 5 and 6.

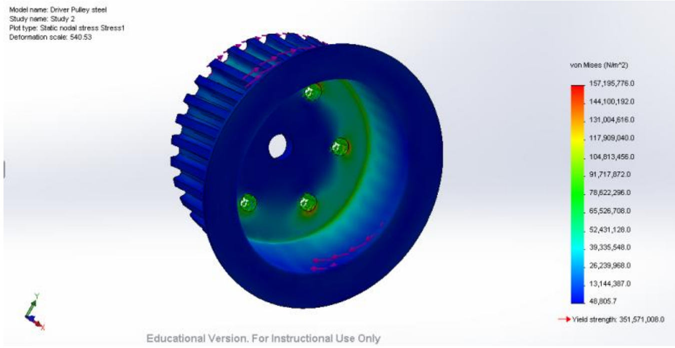

Figure 12. Von Mises Stresses and Exaggerated Deformation of Driver Pulley

From Dyno testing, it was determined that the max torque that our engine can produce was 70 lb-ft. Using the worst case scenario, the following calculation was conducted:

Input Torque (M_i): 70 lb-ft = 840 lb-in

Output Torque (M_o): ?

Max CVT Ratio (r): 5.5:1

Gear Reduction Formula:

$$M_o = M_i * r \qquad (1)$$

	2012 Design	Optimized
Top Pulley	3.95 lb	1.73 lb
Bottom Pulley	7.00 lb	3.89 lb
Total System	17.31 lb	10.90 lb

Table 3. Weight Comparisons of 2012 Belt Drive Design vs. Optimized Belt Drive Design

Using equation 1, the torque that is applied to the driver pulley, from the CVT, was calculated to be 4620 lb-in. Through angle of wrap calculations and solid model simulation, it was determined that 20 teeth will be in contact with the belt at once. Therefore, the torque was then divided up onto each of the 20 teeth. The FEA of the pulley's stress distribution is shown in Figure 12. The figure shows that the highest concentration of stress occurs only around the boltholes and results in a factor of safety of 2.2, which is an acceptable safety rating for trail riding purposes.

The same process was executed for the driven pulley as well. A torque of 7715.4 lb-in was calculated and applied to the pulley and distributed to 35 teeth. The FEA simulation, shown in Figure 6, shows a concentration of forces around the mounting holes as expected. The factor of safety for the driven pulley is 3.6.

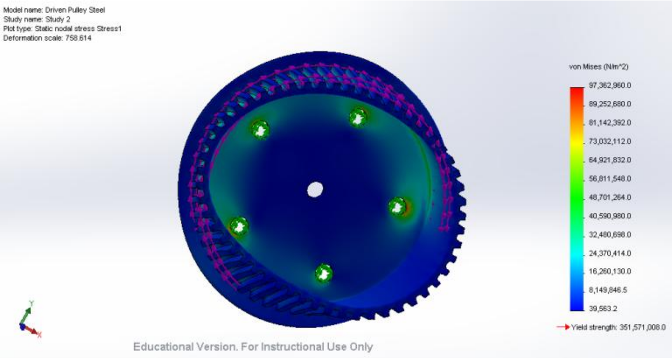

Figure 13. Von Mises Stresses and Exaggerated Deformation of Driven Pulley

SUSPENSION

Due to the increase in weight onset by a bulky chassis and heavy motor, several suspension-tuning aspects were considered for this year's snowmobile. The M-10 rear air suspension was chosen once again, adding nearly infinite adjustability of stiffness and ride height, as well as increasing rider comfort. The stock front suspension was replaced with Fox Float air shocks. This year, a 2" statically longer air shock was chosen over previous years. Due to our inherent weight increase on the front of the snowmobile, air pressure was run at nearly max psi in previous years. Since the pressure in the air shock shares a nearly linear relationship with stiffness, damping, and ride height, the ride in previous years was harsh and slow to respond to terrain changes, being generally unpleasant to the rider. This year it was found that increasing the static length of the air shock slightly allows us to run 50% less pressure in the shock while maintaining the same ride height of previous years. Since the shock is now able to dampen more in its linear region, its "sweet spot", the ride has become much softer and responsive than previous years.

The use of air suspension both front and rear was also found to significantly decrease weight over the stock units. Each front shock is roughly 6 lbs lighter than the stock coil spring struts. This weight decrease improves rider enjoyment leading to a lighter, more efficient snowmobile.

BULKHEAD SOUND DAMPING

Due to the numerous mechanical components incased in the bulkhead, such as the engine, CVT, radiator fan, and the belt drive, sound deadening in this area is essential towards designing a quiet snowmobile. To achieve this, our team decided that an economical solution would be to line the inside of the bulkhead and hood with 1.5" egg crate acoustical foam. This choice was made because of the 1.5" thick eggcrate foam having a 0.45 NRC (noise reduction coefficient) rating, which is the highest rating while still being thin enough to fit in between the cowling and the engine components. The total NRC rating was calculated by Foam Factory tests by averaging the ratings at 250Hz, 500Hz, 1000Hz, and 2000Hz [5]. The foam also has a flame retardant classification of CA TB #117 ASTM E84 – Class A which means that if exposed to a flame it will self-extinguish once the flame is removed, which is a great characteristic to have in high temperature applications.

To achieve maximum sound deadening characteristics, foam was strategically placed to seal every crack in the bulkhead while still allowing an air stream to flow across the engine, which is essential for cooling the components under the hood and prevent overheating.

SNOW FLAP DESIGN

Realizing that the snow flap could have a significant impact on dampening track noise, our team decided to look into innovative solutions in this design area. The design that was chosen was that of using last year's polyethylene rear snow flap with added side skirts along the full length of the track. The idea originated from noticing how tractor trailers use side skirts on their trailers to increase its aerodynamic characteristics. A solid model of the design is shown below in Figure 14.

Figure 14. SolidWorks Solid Model of Snow Flap Design

Numerous material choices were considered, and the material that was chosen was closed cell neoprene. This choice was made due to its low cost, low weight, water resistance, ozone resistance, and great sound deadening characteristics. Its service temperature ranges from -40°F to 200°F, which is well within the temperature range that snowmobiles commonly encounter. One downfall of the neoprene is its flexibility. To compensate for this and to keep the neoprene from getting caught up into the track, aluminum bracing was fastened to the side skirts for added support. Through this design, our team is confident that track noise will be reduced considerably.

MSRP

Every component that has replaced a stock part on our 2013 competition sled was designed with manufacturability, cost, and our customer groups in mind. Many of the parts that have replaced underperforming stock units actually cost less than the OEM parts. While this does add a perceived value to the snowmobile, it would actually decrease the cost of the snowmobile to the customer. These reductions in price cannot be accounted for in the MSRP due to competition rules stating that any part replaced must add a 50% premium to the cost if it increases the customers perceived value of the sled.

The MSRP of the 2013 competition sled is $13,125, an increase of roughly 10% over similarly equipped snowmobiles. A significant amount of this increased cost stems from the vast majority of our power plant systems not being mainstream in the snowmobile or power sport industry. Due to this, some of the added cost comes from the development of our technologies. Should diesel technology become mainstream in the snowmobile industry, special purpose diesel engines could be mass produced, significantly reducing the cost of diesel implementation. The increase in price over a standard sled is also justified by the significant increase in fuel economy as well as the significant decrease in service intervals and cost compared to a flex fuel 2 or 4 stroke engine, lowering the maintenance cost to the owner.

Conclusion

Implementing a diesel fueled engine into a snowmobile application has its apparent difficulties, but when properly executed can provide excellent fuel economy, very low HC, CO, NOx and Soot emissions, good reliability and maintain performance levels of an average snowmobile. The UB Motorsports Clean Snowmobile team accomplished this through the design considerations of the operator, environment, and the manufacturer applied to various systems of the snowmobile as follows.

(1) The engine was selected for being efficient, powerful, and cost effective by utilizing indirect injection, turbocharged diesel.
(2) The engine was calibrated to optimize emissions and power output through extensive theoretical and experimental research, producing 48 horsepower and 70 ft-lbs of torque.
(3) Engine mounts were fabricated having a high strength to weight ratio for increased reliability with a minimum factor of safety of 3.5.
(4) The cooling system was developed to efficiently maintain desired engine temperatures in all situations, and decreased overall engine under-hood temperatures for increased rider comfort and reliability.
(5) Intake tract was refined to properly cool the charge air, reducing brake specific NOx to 16 g/kW-hr, and deliver the charge via the intake manifold effectively increasing power output.
(6) A belt drive was engineered to increase driveline efficiency, improving fuel economy and reducing maintenance required.
(7) Tailpipe emissions were reduced by the use of an Emitec Diesel Particulate Filter and Diesel Oxidation Catalyst, maintaining high catalyst efficiencies with a specially designed exhaust system.

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SolidWorks	Custom Laser
Ricardo	Student Association
NYSSA	Autometer
DEI	Moty Design
UB Engineering Machine Shop	Klispie Motorsports
Misimoto	Trail Tech

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-UB Engineering Machine Shop Personnel

DEFINITIONS/ABBREVIATIONS

SAE	Society of Automotive Engineers
CSC	Clean Snowmobile Challenge
UB	University at Buffalo
FEA	Finite Element Analysis
SCCI	Stratified Charge Compression Ignition
HCCI	Homogeneous Charge Compression Ignition
CVT	Continuously Variable Transmission
WOT	Wide Open Throttle
NOx	Oxides of Nitrogen
BSFC	Brake Specific Fuel Consumption

APPENDIX

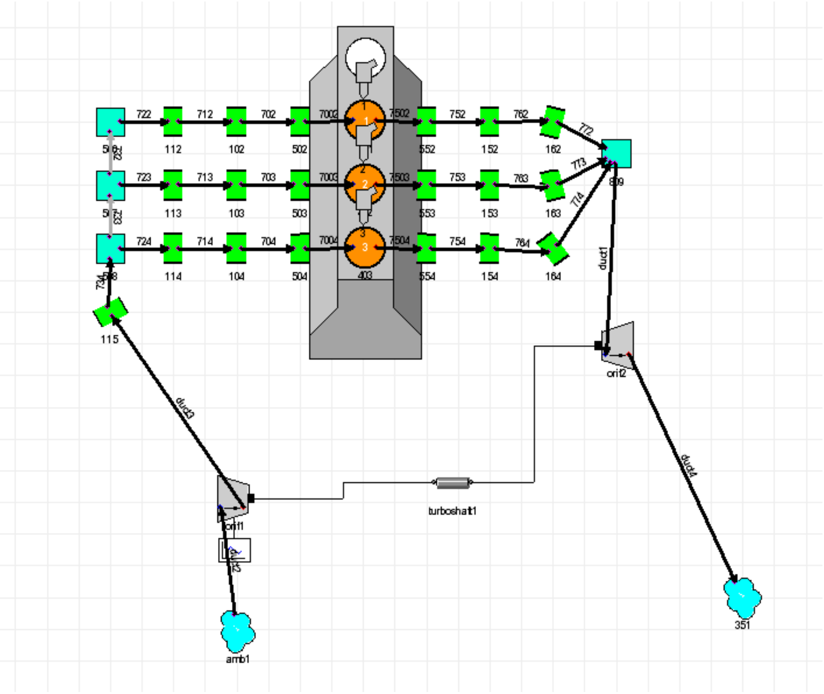

Figure 15: Ricardo WAVE Engine Model