The Design of Formula SAE Fuel and Lubrication Systems

Leonardus Simonis

A thesis submitted in partial fulfillment
of the requirements for the degree of

BACHELOR OF APPLIED SCIENCE

Supervisor: Prof. M. Bussmann

Department of Mechanical and Industrial Engineering
University of Toronto

March 2008

Abstract

The purpose of this thesis is to design and produce a fuel system and a lubrication system for the 2008 University of Toronto Formula SAE race car. The main goal of the project is to design and manufacture upgraded and reliable fuel and lubrication systems. The 2008 systems, based on previous fabrications will seek to accomplish four new key design implementations:

1. Location and Size of the Fuel Tank
2. Oil Pan with Integrated Pickups
3. Rapid Prototyped Intake Runners
4. Engine Mapping for Fuel Economy

Included in this report is a literature overview which provides the motivation and the necessary background for the understanding of how a fuel and lubrication system works. Also, a background of Formula SAE and the competition is covered. The key design features will be discussed in greater detail. The design and manufacturing, results, evaluation, and recommendations will be covered for each design feature.

This thesis is not primarily based on theory. The designs and concepts are derived through experience, inference, and need as well. However, each design objective has a clear benefit that can be characterized qualitatively or quantitatively. This thesis should be of significant use for future Formula SAE members in stimulating design concepts.

Acknowledgements

I have several people I would like to thank for helping me and guiding me with my thesis. First, I would like to thank my parents, sister, and Jessica for all their support and encouragement throughout my university career. I would also like to thank the University of Toronto and the Department of Mechanical Engineering for allowing me to learn and mature as a student at this great institution. As well, I would like to thank them for their support of the Formula SAE Race team, which allowed me to gain valuable design, manufacturing, hands-on, and testing skills. I would like to thank Professor Markus Bussmann for his supervision during my thesis. I would like to thank Axis Prototype for their generous sponsorship of the rapid prototyped intake system. Finally, I would like to thank all my Formula SAE teammates over the years for their support and teamwork. The project could not have been done without them.

Table of Contents

List of Symbols

D_h	Hydraulic Diameter
A	Area
p	Wetted Perimeter
r	Radius
l	Length
w	Width
P	Pressure
E	Young's Modulus
t	Thickness
δ	Deflection
ϕ	Equivalence Ratio
m_{fuel}	Mass of Fuel
m_{ox}	Mass of Oxidizer
$_{st}$	Denotes stoichiometric ratio

List of Figures

List of Tables

1 Introduction

The Formula SAE competition is a student based design project. This series of racing allows for a great deal of innovation and invention as the rules are targeted toward safety rather than design restriction. Participation within the design and production of a Formula SAE car exposes one to a great deal of opportunity and experience. The project not only includes design and fabrication, but also business, marketing, team work and interaction with sponsors. The competition integrates all these factors into one.

Both the fuel and lubrication systems are fundamental elements of any automobile. The main focuses of this thesis is to optimize certain facets within each system by studying the systems earlier in the design phase and making them more reliable, lighter, etc . The location and size of the fuel tank will be addressed. An oil pan with incorporated oil pickups will be implemented. Third, the intake runners will be rapid prototyped. Finally, when all the subsystems are completed, the engine will be mapped for greater fuel economy.

Within the report a number of topics will be discussed. First, the literature review will provide pertinent background and terminology that will be needed for this project. The design and manufacturing of the 4 key design features will be the focus of the thesis. The problems with previous designs will be mentioned and the resolution to these problems will be noted. Necessary calculations, models, and analysis will be included to support the arguments. The results and findings will follow, with a final evaluation and conclusion.

2 Literature Review

2.1 Motivation

The motivation behind the design of the 2008 University of Toronto Formula SAE fuel and lubrication systems is to improve upon and optimize the designs. The goal is to progress the design of the car and rectify previous faults by looking at four different features within the fuel and lubrication systems. More thought was put into the design and packaging of the fuel tank, which will improve the handling of the car by lowering the center of gravity and evening out the weight distribution. An oil pan with integrated pick ups will allow for a more reliable system. Rapid prototyped intake runners allow for a more versatile design. The runners can be a more complex shape and allow the injector bosses to be incorporated into the design. Lastly, the engine will be mapped to achieve better fuel economy. Fuel economy scores have hindered the team in the past.

2.2 Background

2.2.1 Formula SAE and Competition

Formula SAE is now in its 29^{th} year as of 2008. There are eight competitions around the world in Michigan, California, England, Germany, Australia, Italy, Japan, and Brazil. The competition in Detroit, Michigan is the world's largest hosting 140 teams. A comment made at the competition last year stated that there are close to 300 university teams in over 45 different countries around the world. The objectives of the Formula SAE competition are best described within its rules document:

"The Formula SAE Series competitions challenge teams of university undergraduate and graduate students to conceive, design, fabricate and compete with small, formula style, autocross racing cars. To give teams the maximum design flexibility and the freedom to express their creativity and imaginations there are very few restrictions on the overall vehicle design. Teams typically spend eight to twelve months designing, building, testing and preparing their vehicles before a competition. The competitions themselves give teams the chance to demonstrate and prove both their creativity and their engineering skills in comparison to teams from other universities around the world" [1].

The vehicle design objectives can also be characterized through the rules as well:

"For the purpose of this competition, the students are to assume that a manufacturing firm has engaged them to design, fabricate and demonstrate a prototype car for evaluation as a production item. The intended sales market is the nonprofessional weekend autocross racer. Therefore, the car must have very high performance in terms of its acceleration, braking, and handling qualities. The car must be low in cost, easy to maintain, and reliable. It should accommodate drivers whose stature varies from a 5th percentile female to a 95th percentile male. In addition, the car's marketability is enhanced by other factors such as aesthetics, comfort and use of common parts. The manufacturing firm is planning to produce four (4) cars per day for a limited production run and the prototype vehicle should actually cost below $25,000. The challenge to the design team is to develop a prototype car that best meets these goals and intents. Each design will be compared and judged with other competing designs to determine the best overall car" [1].

Each competition is held over four days. The first two days are allocated for registration, technical inspection, and presentations. A thorough inspection of the car is done to see if all safety and design requirement are met.

The car must also pass a break test for which all four wheels must lock. A noise test is also performed. The loudness of the car must not exceed 110 dB. The final test is a tilt test. The car must not role when it is placed on a platform and tilted to 60 degrees which corresponds to 1.7 G's [1]. One presentation to be completed is a cost presentation. A cost report is sent to the judging committee prior to the competition costing out all the components of the car. Other presentations include marketing, manufacturing, and design. The marketing presentation deals with the fabrication of a nonprofessional weekend autocross vehicle intended for market sales. The manufacturing presentation is about automotive parts that usually bought by a Formula SAE team. Finally, the design presentation is an in depth scrutinizing of the vehicle by automotive professionals. This concludes the static portion of the competition.

The dynamic part of the competition consists of skid pad, acceleration, autocross, and endurance. Skid pad is a figure eight course. The driver enters the course in the center then completes two turns to the left and two turns to the right before exiting. The second turn for each direction is timed and the two are averaged. The acceleration is a stand still start of 75 meters which is timed. The autocross is a timed course lap. Two drivers are allowed two runs at the circuit. The main event is held on the final day, which is the endurance race. For the endurance race, two drivers each complete 11 km of the 22 km race. After 11 km (11 laps) the first drive must pit and shut off the car. The drivers switch and the second driver must be able to restart the car. The entire race is timed and in conjunction with fuel economy scores are totaled.

2.2.2 Rules

There are several rules that pertain to the fuel and lubrication systems. However, there are a not significant amount of rules that pertain to these sections when compared to others. Here are a few rules that are pertinent to the design of the fuel and lubrication systems:

Rule 3.5.2 – Fuels: The basic fuel available at competitions in the Formula SAE Series is unleaded gasoline with an octane rating of 93 (R+M)/2 (approximately 98 RON). Other fuels may be available at the discretion of the organizing body.
Rule 3.5.2.2 - Fuel Additives – Prohibited: No agents other than fuel (gasoline or E85), and air may be induced into the combustion chamber. Non-adherence to this rule will be reason for disqualification. Officials have the right to inspect the oil.
Rule 3.5.3.1 - Fuel Tank Size Limit: Any size fuel tank may be used. The fuel system must have a provision for emptying the fuel tank if required.
Rule 3.5.3.2 - Filler Neck & Sight Tube: All fuel tanks must have a filler neck: (a) at least 38 mm (1.5 inches) diameter, (b) at least 125 mm (4.9 inches) vertical height and (c) angled at no more than 45 degrees (45°) from the vertical. The 125 mm of vertical height must be above the top level of the tank, and must be accompanied by a clear fuel resistant sight tube for reading fuel level (figure 7). The sight tube must have at least 75 mm (3 inches) of vertical height and a minimum inside diameter of 6 mm (0.25

inches). The sight tube must not run below the top surface of the fuel tank. A clear filler tube may be used, subject to approval by the Rules Committee or technical inspectors at the event.

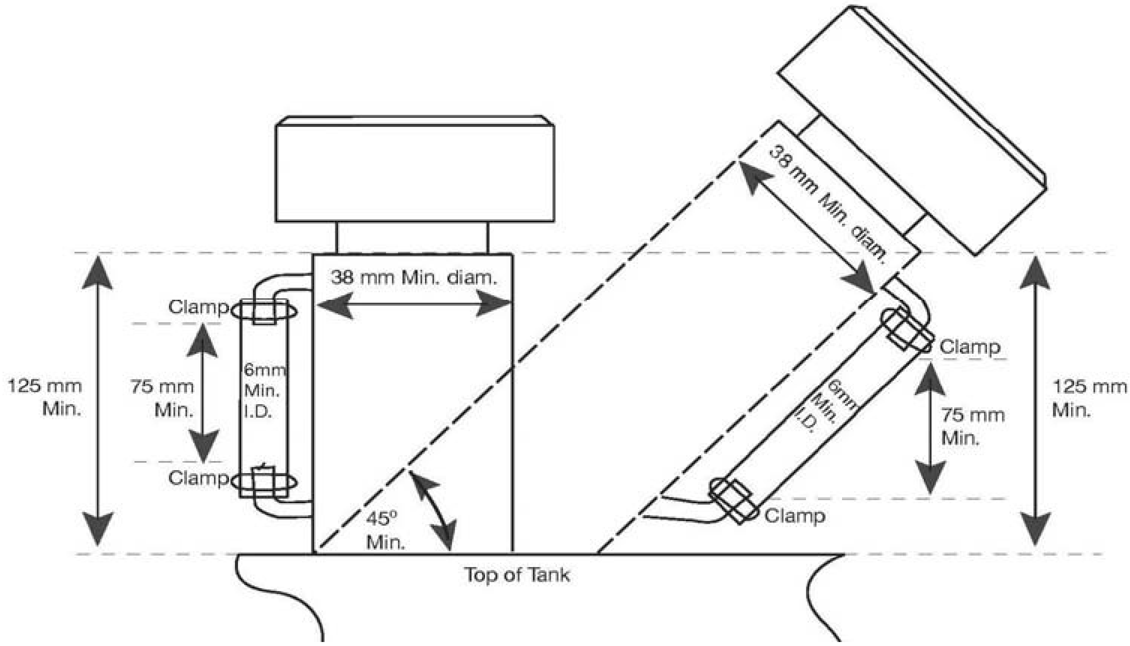


Figure 1 - Filler Neck & Sight Tube Rule [1]

Rule 3.5.3.9 - Air Intake and Fuel System Location Requirements: All parts of the fuel storage and supply system, and all parts of the engine air and fuel control systems (including the throttle or carburetor, and the complete air intake system, including the air cleaner and any air boxes) must lie within the surface defined by the top of the roll bar and the outside edge of the four tires (see figure 8). All fuel tanks must be shielded from side impact collisions. Any fuel tank which is located outside the Side Impact Structure required by 3.3.8 must be shielded by structure built to 3.3.8. A firewall must also be incorporated, per section 3.4.10.1. Any portion of the air intake system that is less than 350 mm (13.8 inches) above the ground must be shielded by structure built to 3.3.8.

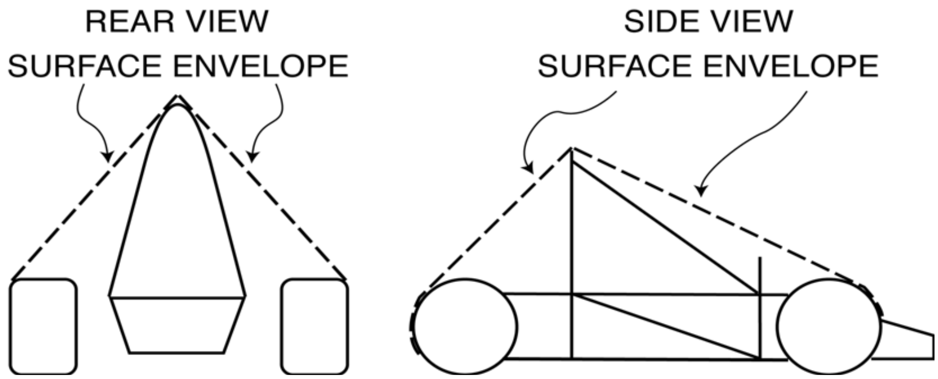


Figure 2 - Envelope of fuel system location requirements [1]

Rule 5.7.3 - Fuel Economy (50 points): The car's fuel economy will be measured in conjunction with the endurance event. The fuel economy under racing conditions is important in most forms of racing and also shows how well the car has been tuned for the competition. This is a compromise event because the fuel economy score and endurance score will be calculated from the same heat. No refueling will be allowed during an endurance heat.

Rule 5.7.4 - Endurance Course Specifications & Speeds: Course speeds can be estimated by the following course specifications. Average speed should be 48 km/hr (29.8 mph) to 57 km/hr (35.4 mph) with top speeds of approximately 105 km/hr (65.2 mph) [1].

2.2.3 Automotive Fuel and Lubrication Systems

2.2.3.1 Fuel System

The fuel system and its components will be discussed as they occur along the path of fuel flow. We begin with where the fuel is stored; the fuel tank. Fuel tanks vary in size and shape according to their application. Fuel tanks are generally made of steel or plastic and usually have baffles inside. A baffle is a partition which reduces the sloshing of fuel in the tank.

The fuel pump is generally electric and located inside the fuel tank. It is used to pump fuel from the tank to the engine under high pressure for a fuel injected engine.

Next is the fuel filter. This device is used to remove dirt and other particles from the fuel. Without a fuel filter, particles can cause damage to the fuel pump and fuel injectors.

Fuel is metered using the injectors. The injectors are mounted using a fuel rail. The fuel rail delivers the high pressure fuel to the injectors. An injector is an electronically controlled valve. When the injector is initiated, an electromagnet moves a plunger which in turn opens a valve. This allows the pressurized fuel to be released through a tiny nozzle. The nozzle is designed to atomize the fuel; to create a fine mist so that it can burn easily [2].

The amount of fuel delivered to the engine is controlled by the ECU (Electronic Control Unit). The ECU uses a number of sensors to control the amount of fuel it releases to the engine. These sensors include the mass airflow sensor, which tells the ECU the mass of air entering the engine. The oxygen sensor measures the amount of oxygen in the exhaust gas to determine if the fuel mixture is rich or lean and makes adjustments. A rich mixture is one that has excess fuel. Conversely, a lean mixture is one that has excess air. The throttle position sensor monitors the throttle valve position, which determines the amount of air released into the engine. Therefore, the ECU can make changes to the amount of fuel that is injected. A manifold absolute pressure sensor is used to monitor the pressure of the air in the intake plenum. Finally, the engine speed sensor measures engine speed, which is a factor in calculating pulse width (the amount of time the injector is open). Fuel injectors can all open at the same time or just before the intake valve for its respective cylinder opens. The latter is called sequential multi-port fuel injection and it is the most commonly used in automobiles today [3].

The fuel is usually delivered at a pressure of 25 to 45 psi to the fuel rail from the pump. The fuel pressure regulator is used to keep the pressure constant. A spring loaded diaphragm controls a valve that opens when there is an excessive pressure in the fuel rail [4]. The fuel is then returned to the fuel tank.

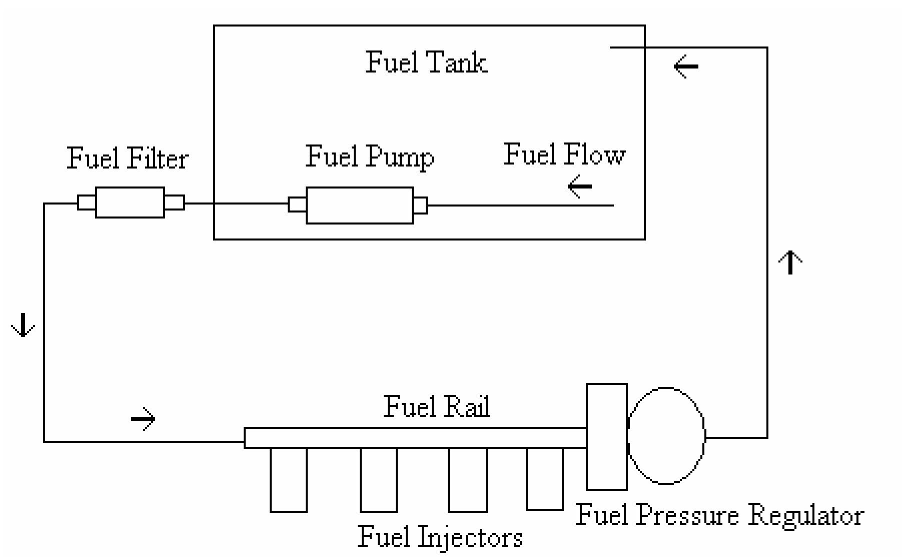


Figure 3 - Fuel System

Most automobiles run on fuels of octane rating 87 to 94. When an engine is on its compression stroke, a cylinder full of air and fuel is compressed into a small volume before being ignited by a spark plug [5]. The amount of compression is called the compression ratio. The compression ratio is the volume in the cylinder when the piston is at bottom dead center (the bottom of the stroke) to the volume in the cylinder when the piston is at top dead center (the top of the stoke). Typical values for an automobile compression ratio range from 8:1 to 10:1. The octane rating indicates how much fuel can be compressed before it spontaneously combusts. If the fuel ignites prematurely, this causes the engine to "knock", causing damage to the engine. Lower octane ratings can handle lower compression before igniting [5]. Using a higher octane rated fuel in a car that requires a lower octane rated fuel causes the car to be less efficient. Not all of the energy in the fuel is being used. This causes excess fuel to be wasted, resulting in increased emissions [3].

The stoichiometric ratio is the calculated ideal ratio of air-to-fuel (AFR). At this ratio theoretically all of the fuel will be burned using all of the oxygen. For pure octane, the stoichiometric ratio is about 14.7:1. This means that for each pound of gasoline, 14.7 pounds of air will be burned. For naturally aspirated (fuel injected) engines powered by octane, maximum power occurs when the AFR is about 12.5 [3].

Engine mapping is the process of modeling engine outputs as a function of inputs. Outputs are torque, emissions, and fuel economy, whereas the inputs are fuel flow rate, stoichiometric ratio, and the measure of oxygen in the exhaust gas, etc [3]. When mapping a naturally aspirated engine the stoichiometric ratio is set to 12.5:1 for maximum power. The stoichiometric ratio can be increased to achieve better fuel economy, which will be explored within the thesis; however the engine will run hotter. The amount of oxygen in the exhaust determines whether the mixture is lean or rich as mentioned earlier. Exhaust gas temperature (EGT) sensors are also used to determine which cylinders of the engine are hot. This will give an indication as to which cylinders need more fuel. The interface used when mapping an engine is a large resolution matrix. The horizontal axis is RPM and the vertical axis is throttle position in percent or manifold absolute pressure. Each cell of the matrix is filled in with the length of time the injector stays open. All these parameters must be taken into consideration when mapping.

2.2.3.2 Oil System

There are two types of oil systems; wet sump and dry sump. Most production cars have a wet sump oil system. The sump is located beneath the crankshaft. Oil is stored in a deep pan at the bottom of the engine. In a wet sump, the oil pump sucks oil from the bottom of the pan and pumps it through the engine [6].

In a dry sump system (Figure 4), the oil is stored in an external oil tank rather than in the oil pan. Two pumps are needed, one to pump oil to lubricate the engine and the other to return oil to the tank from the sump. Therefore, a very small amount of oil remains in the engine. A few advantages of a dry sump system include: the oil pan can be shallower to allow for the main mass of the engine to be placed lower in the car; therefore, lowering the center of gravity and the oil tank can be any size and placed anywhere on the car [6].

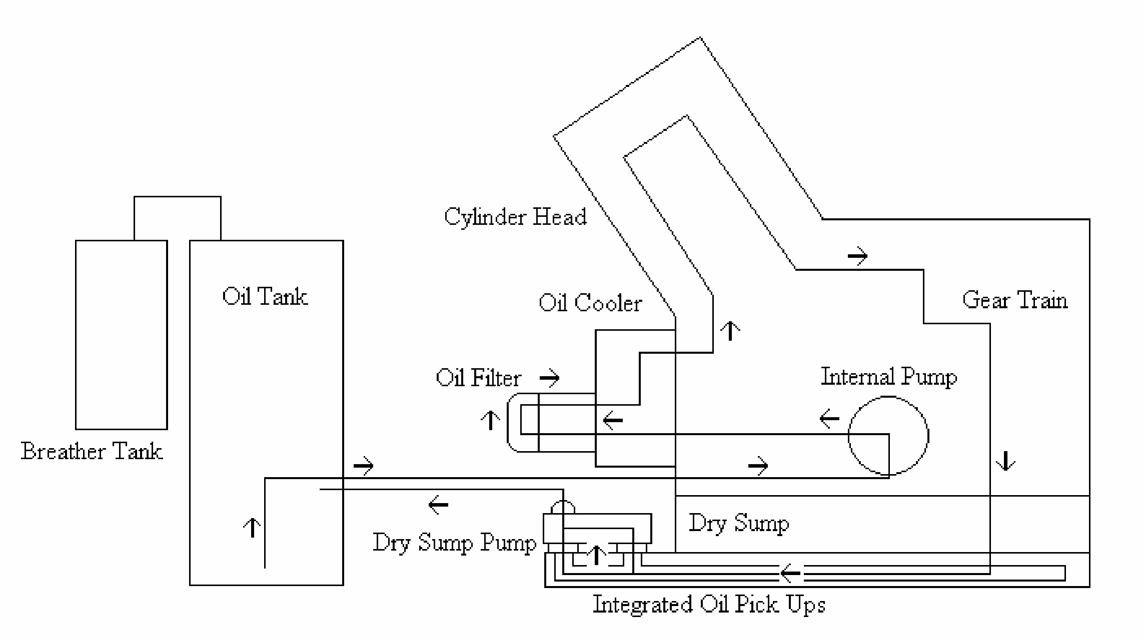


Figure 4 - Dry Sump Oil System and Oil Path

The components of a wet sump oil system will now be explained in more detail following the path of oil flow (Figure 5). The oil pan holds the oil in the bottom of the engine. The pan is usually large and deep, to hold the required four to six quarts of oil.

The internal oil pump sucks oil from the pan; the oil then travels through a filter and an oil cooler before being distributed to certain components inside the engine for lubrication.

The oil pressure created by the oil pump is retained at around 30 to 35 psi allowing the oil to circulate thorough the engine. Low oil pressure or pressure loss in the engine can cause great damage. If there is not enough oil in the pan, the oil is too low a viscosity, there is a plugged oil filter, or the oil pump is worn this can lead to low oil pressures.

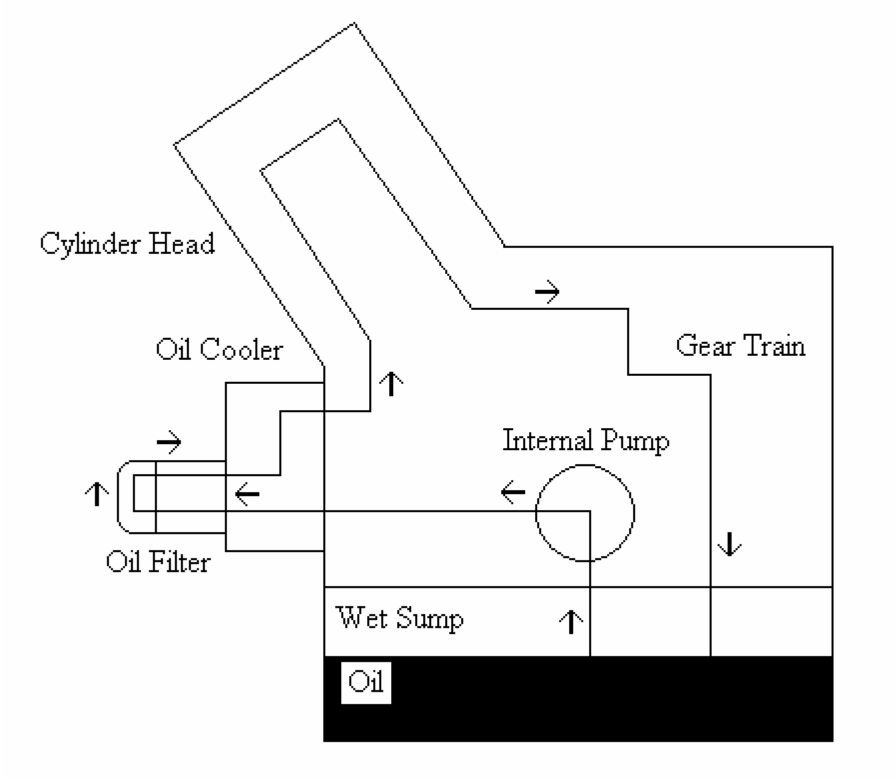


Figure 5 - Wet Sump Oil System and Oil Path

Engine motor oil is not only used for lubricating the components in an engine such as the camshaft, piston, and gear train, but it also cleans, inhibits corrosion, reduces friction and cools the engine by removing heat from moving parts. Most motor oils are produced from petroleum. Over time the oil breaks down becoming impure and requires replacing. However, synthetic motor oils are the most popular today. They consist of artificially-synthesized compounds and offer greater performance (higher tolerance to heat), but at an increased cost [7].

3 Fuel and Lubrication Systems Key Design Features

The main design objectives for the fuel and lubrication systems for the 2008 University of Toronto Formula SAE race car will be to produce reliable, well packaged, and improved systems. An overview of past designs will be discussed with the improvements and new concepts revealed. The results of the new designs will be evaluated and quantified. A recommendation section and conclusions will follow.

3.1 Location and Size of Fuel Tank

3.1.1 Design and Manufacturing

In an effort to improve on previous fuel tank packaging and design, more thought was put into the process. Previously, the fuel tank has been located on one side of the car and was usually a tall, oversized structure (Figure 6).

Figure 6 - Oversized and Poorly Packaged Fuel Tank

This year, the goal was to locate the fuel tank low and central in the car directly behind the driver (Figure 7). This allows for a lower center of gravity. As well, with the tank located in the middle of the car it will not have as great of an affect on the weight distribution causing one side to be heavier than the other. With the fuel tank placed lower in the car there will be a decreased C of G. By placing the fuel tank in the center of the car, it is also expected that the weight distribution will be more even.

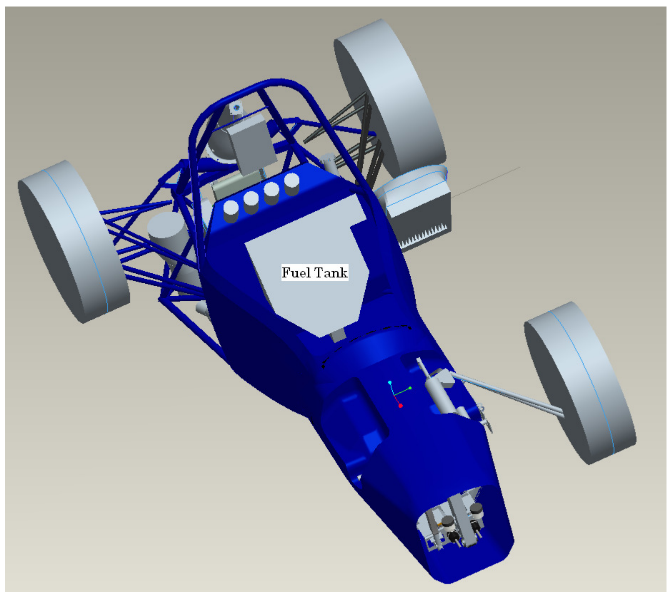


Figure 7 - 2008 Fuel Tank Packaging

The tank volume was determined to be about 6 L, 2 L less from last year. This will in turn reduce the weight of the tank. The amount of fuel consumed during the 2007 Formula SAE endurance event was measured to be 4.5 L; therefore a 6 L tank size is sufficient. The fuel tank was modeled in CAD and the design was tailored to the prearranged area for the tank.

The volume achieved was 385 in^3 or 6.3 L as shown in Figure 8.

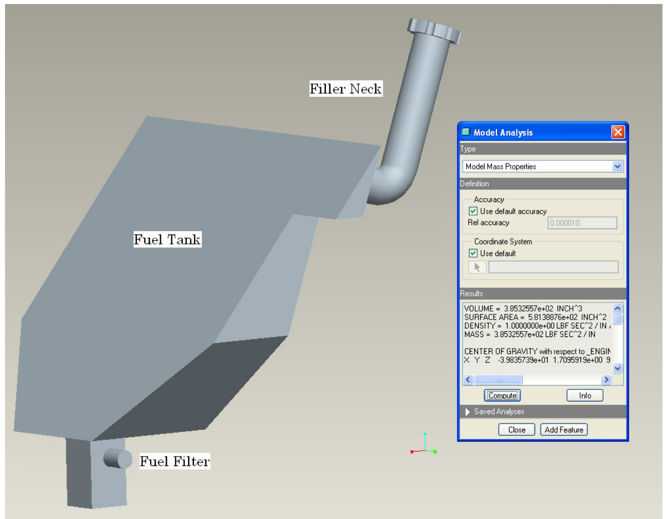


Figure 8 - 2008 Fuel Tank (CAD)

The fuel tank is a simple shape that was easy to manufacture. Using the CAD model, templates were created. Aluminum sheet of 0.050" thickness was used to construct the tank. The tank consists of multiple bends and welds. The fuel filter was modified and welded directly into the tank. The filler neck is removable and satisfies Rule 3.5.3.2 (Figure 1 in Section 2.2.2). The top of the filler neck is higher than the required 4.92" from the horizontal plane.

The manufactured fuel tank can be seen in Figure 9.

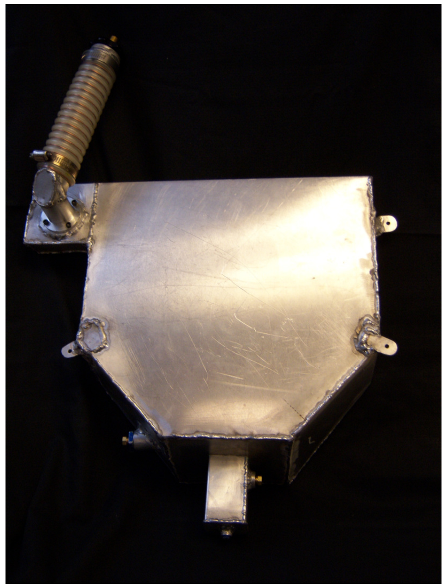


Figure 9 - 2008 Manufactured Fuel Tank

By allocating a space for the fuel tank in the early stages of packaging design, the tank was able to be placed lower and central in the car and the geometry was simpler, which reduced the manufacturing time by a significant amount (Figure 10).

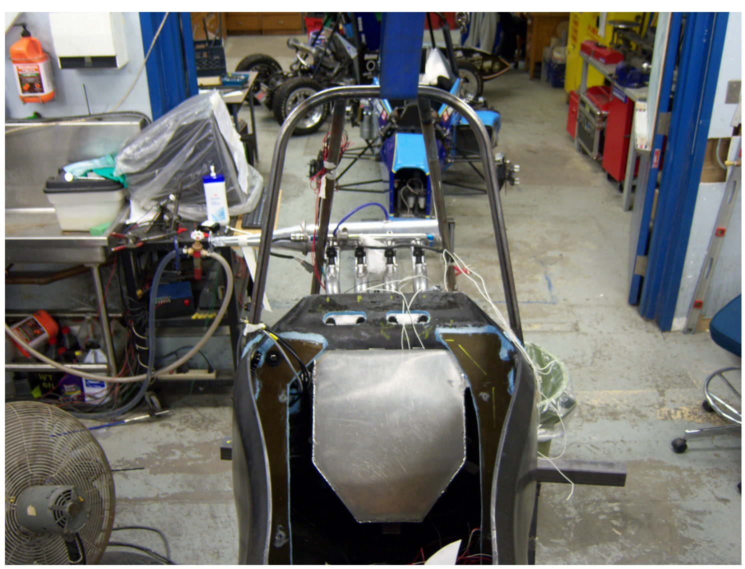


Figure 10 - 2008 Fuel Tank in Car

3.1.2 Evaluation

The results of locating the fuel tank low and central in the car were evaluated to see if the assumptions were correct. First, the weight of the 2007 and 2008 fuel tanks including filler neck were compared. The 2007 tank weighs 1.7 kg and is 7.75 L in volume. The 2008 tank weighs 1.4 kg and is 6.3 L in volume. Therefore, a lighter tank was achieved. However, the difference in weight is not as significant as was originally thought due to the fact that a heavier removable filler neck was need for the 2008 tank in order to be packaged properly.

The recorded center of gravity for the 2007 car with a full tank of fuel is 10.5”. The left to right weight distribution of the 2007 car is 55% to 45%. The 2008 car was not completed in time to conduct a center of gravity or left to right weight distribution test. However, with the positioning of the fuel tank, it should theoretically lower the C of G and create a more even weight distribution of the car.

3.2 Oil Pan with Integrated Pickups

3.2.1 Design and Manufacturing

The oil system for the 2008 car will continue to be a dry sump. In past years, the oil pan had external pickups and lines that were welded (Figure 11).

Figure 11 - External Pickup and Lines

This year's oil pan was designed with integrated pickups. The dry sump pump will also mount directly to the oil pan. The pan will be made of two parts: the block which will include the pickups and the plate which will cover the block (Figures 12, 13, and 14).

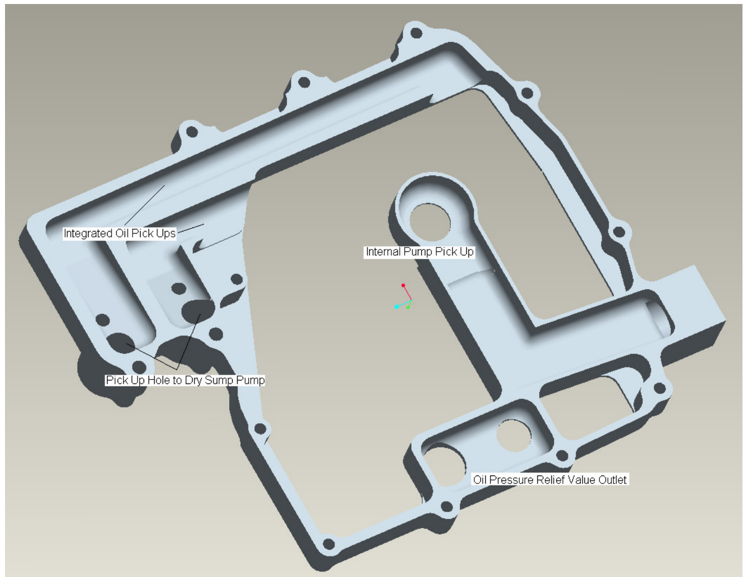


Figure 12 - 2008 Oil Pan Block (Bottom)

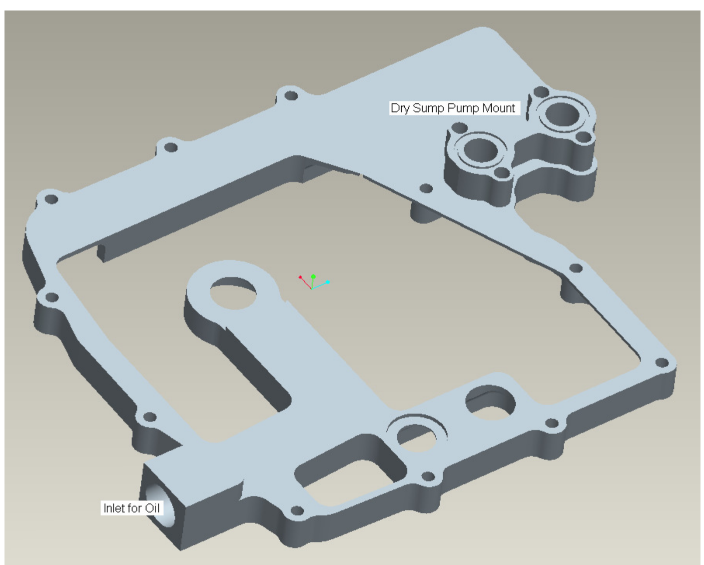


Figure 13 - 2008 Oil Pan Block (Top)

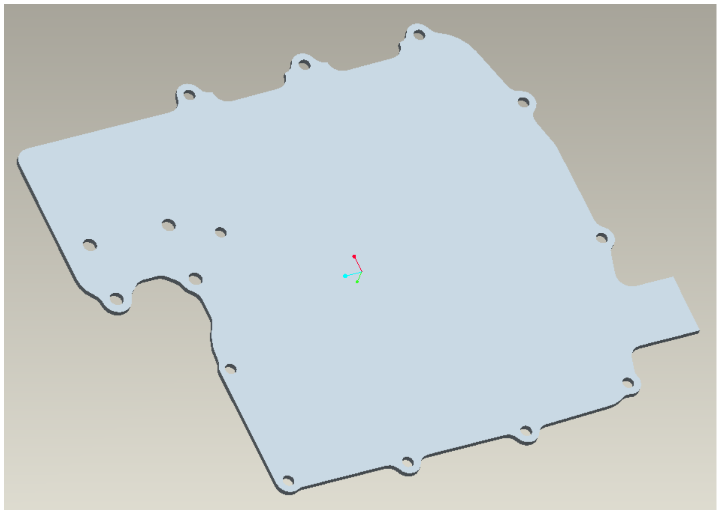


Figure 14 - 2008 Oil Pan Plate

The new oil pan design will insure a greater reliability, as external features on previous pans were prone to leaking. This qualitative improvement cannot directly be quantified. However, a car that leaks during dynamic events at competition will be pulled from the track. This year's pan will also help to lower the C of G, as it will be thinner due to the integrated pickups. However, the weight of the pan will increase. When designing a race car there are always compromises. In our case, a small increase in weight, but lower center of gravity and greater reliability is the compromise.

The oil pan was designed with all the necessary features situated internally. There is the inlet, the internal oil pump pickup, oil pressure relief outlets, internal pickups, and pickup holes for the dry sump pump (Figure 12).

The dry sump pump mounts to the surface of the pan. It will be fastened using bolts. O-rings must be used to seal the pump face to the surface of the pump mount (Figure 13). The O-ring groove design is based on a standard O-ring of thickness 0.070" and inner diameter of 0.876". According to the 'O' Series O-ring groove design table (Table 1), the required dimensions for the groove width and depth are 0.094" ("D") and 0.052 ("C") (Figure 15) respectively.

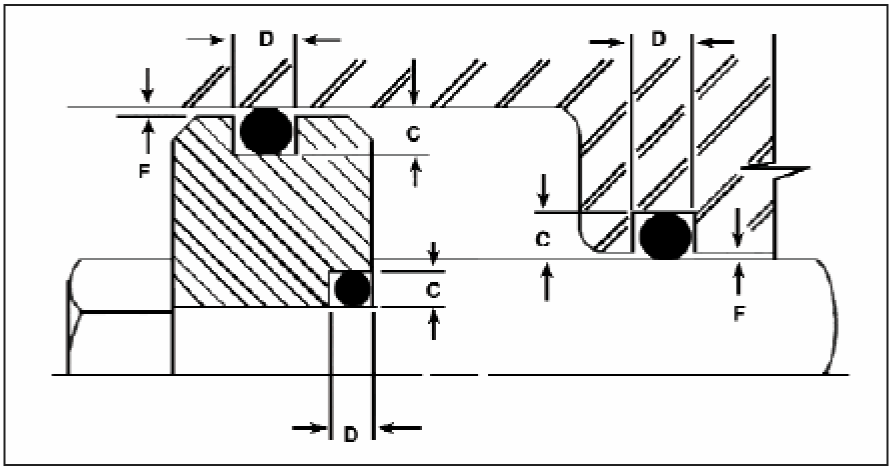


Figure 15 - O-ring Groove Design Diagram [10]

O-Ring Size No.	Actual Cross Section	Minimum c/s Squeeze		"C" Maximum for minimum c/s Squeeze		"D" Groove axial dim. -.000 + .005	"D" Groove axial dim. -.000 + .005	"D" Groove axial dim. -.000 + .005	"F" Diametrical Clearance Max.	Eccentricity Max.
		Dynamic	Static	Dynamic	Static	No Back-Up	One Back-Up	Two Back-Up	(See note 1)	(See note 2)
'O' Series	.070 ± .003	.010	.015	.057	.052	.094	.149	.207	.005	.002
100 Series	.103 ± .003	.010	.017	.090	.083	.141	.183	.245	.005	.002
200 Series	.139 ± .004	.012	.022	.123	.113	.188	.235	.304	.006	.003
300 Series	.210 ± .005	.017	.032	.188	.173	.281	.334	.424	.007	.004
400 Series	.275 ± .006	.029	.049	.240	.220	.375	.475	.579	.008	.005

Table 1 - O-ring Groove Design Table [10]

The height of the dry sump pump mount was determined by locating the internal pump shaft that is used to run the dry sump pump. Using dimensions of the dry sump pump from the manufacture (Appendix B) the pump was aligned with the internal pump shaft. The height of the dry sump pump mount was found to be 0.732".

The external pickups on previous cars were connected to the dry sump pump using round 0.625" diameter tubing. For the internal pickup troughs (Figure 12) which are rectangular, a hydraulic diameter equivalency calculation was needed to achieve the trough dimensions. The circular duct hydraulic diameter and the rectangular duct hydraulic diameter are set equal to each other to insure that the flow rate within the rectangular duct remains the same as the previous tubing.

The hydraulic diameter is defined as:

$$D_h = \frac{4A}{p} = \frac{4 \times Area}{perimeter(wetted)} = 4R_h \text{ [11]}$$

For a circular duct the hydraulic diameter is:

$$D_h = \frac{4A}{p} = \frac{4\pi r^2}{2\pi r} = 2r \text{ [11]}$$

For a rectangular duct the hydraulic diameter is:

$$D_h = \frac{4A}{p} = \frac{4(lw)}{2l + 2w} = \frac{2lw}{l + w} \text{ [11]}$$

Therefore, the equivalency calculation using the length of the trough to be 0.625" is as follows:

$$\begin{aligned}
&D_{h\,circular} = D_{h\,rectangular} \\
&2r = \frac{2lw}{l + w} \\
&2(0.3125) = \frac{2(0.625)w}{0.625 + w} \\
&0.625 = \frac{1.25w}{0.625 + w} \\
&1.25w = 0.390625 + 0.625w \\
&0.625w = 0.390625 \\
&\therefore w = 0.625
\end{aligned}$$

Therefore, the internal rectangular troughs can be 0.625" by 0.625". A similar calculation was done to find the dimensions of the internal pump pickup trough. In 2007 the steel braided line connecting the tank to the oil pan was -12AN, which has a bore diameter of 0.75”. If the duct length is to be constant at 0.625”, the width of the internal pump pickup trough will be 1.06”. Since the pickup troughs are 0.625” in width it was decided that the overall thickness of the oil pan would be 0.75”.

When the design of the pan was completed a finite element analysis was conducted on the oil pan to assess the contact pressure between the surfaces of the block and the plate. This was done to ensure that the pressure between the two was great enough to cause a closed seal. The finite element analysis showed that only bolting the plate to the oil pan block would not create a force great enough for a closed seal. Therefore, the plate was welded to the block creating a closed seal.

Another FEA was run to detect the stresses in the pan due to the static pressure forces created by the pressure relief valve. The pan was cut in half to run the analysis more quickly. The half of the pan used is subjected to the pressure load. For the analysis, the pan was held fixed at each bolt hole in the Y direction and in rotation. At one hole the pan was fixed in the X and Z directions as well. This simulated the oil pan being fixed to the bottom of the engine and in the x-direction which is parallel to the length of the car. Typical oil pressures reach 40 psi. A 2.5 safety factor was used in the FEA, therefore a 100 psi pressure force was used (Figure 16).

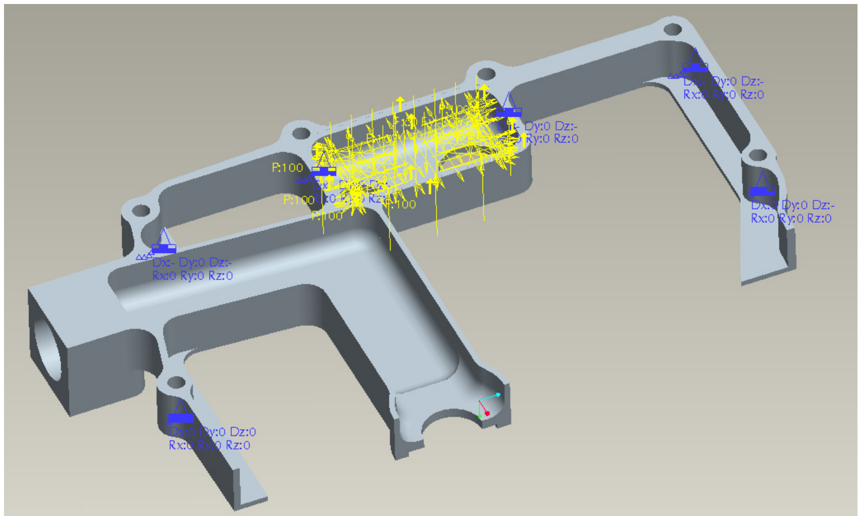


Figure 16 - Oil Pan FEA Constraints and 100 psi Pressure Load

Several design and FEA iterations were needed. The oil pan's wall thicknesses were varied in order to keep the von Mises stresses under the safety factor of 100 psi. The final design FEA results can be seen in Figure 17.

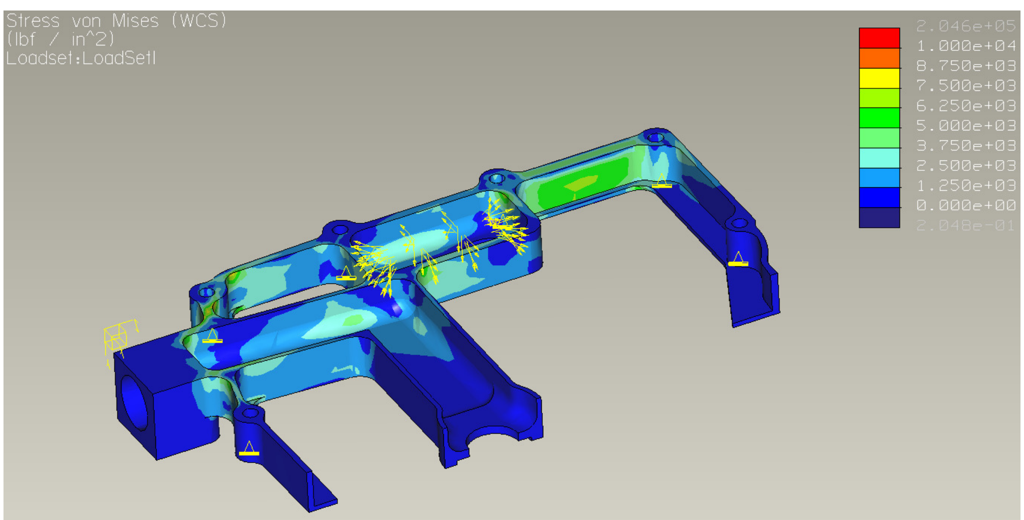


Figure 17 - Oil Pan FEA Results

An engineering drawing of the oil pan block (Appendix A) was sent out for CNC machining upon design completion. The final product can be seen in Figures 18 and 19.

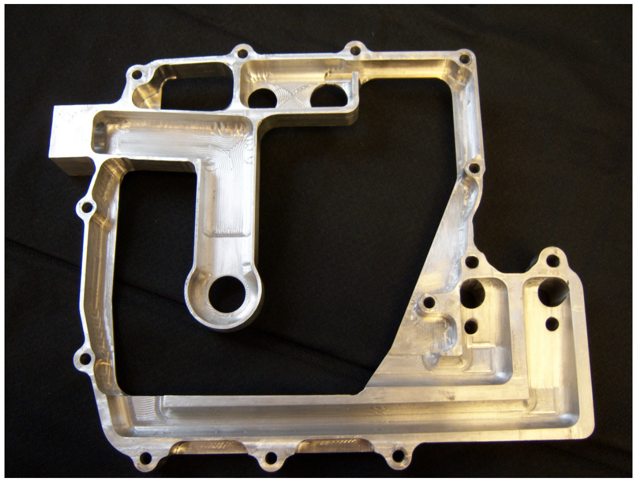


Figure 18 - 2008 Oil Pan Block (Bottom)

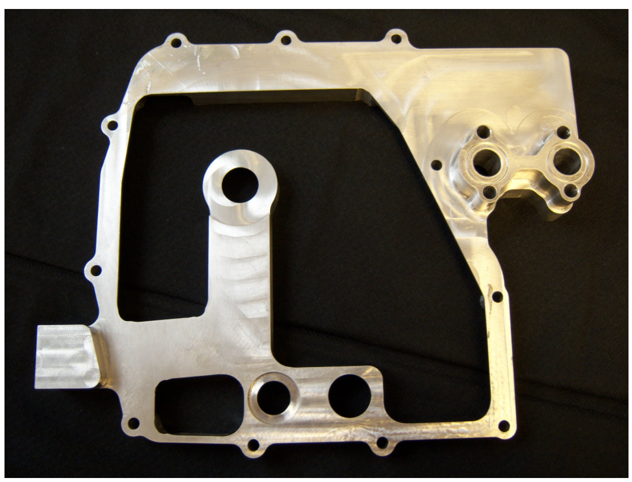


Figure 19 - 2008 Oil Pan Block (Top)

The oil pan plate was created using a template of the block bottom. It was traced on 0.125” thick aluminum plate, cut, and filed. The inlet boss (centre of Figure 20), two pressure relief bosses (centre bottom of Figure 20), and oil pan plate were welded to the oil pan block. The inlet was tapped and the fitting (left of Figure 20) was inserted. Finally, the O-rings were inserted and the dry sump pump (right of figure 20) was mounted to the oil pan.

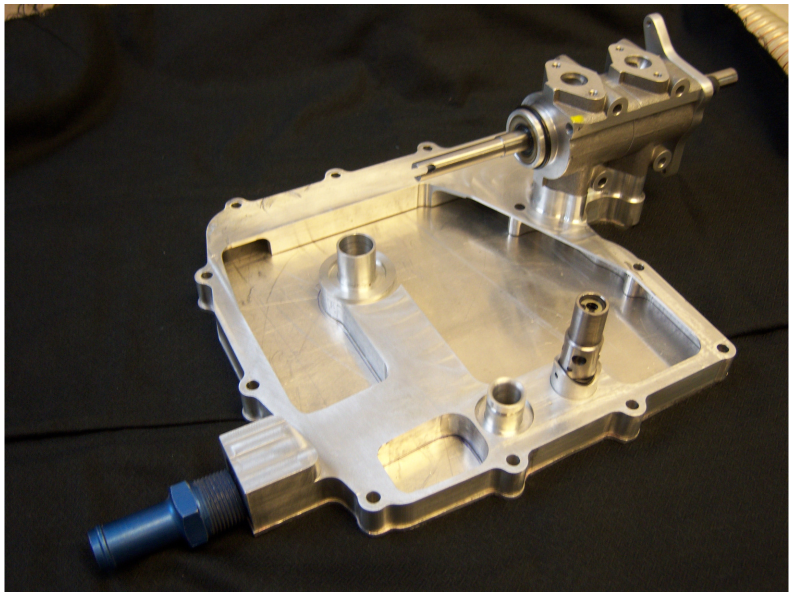


Figure 20 - Completed Oil Pan

3.2.2 Evaluation

The dry sump oil pan block was designed at a height of 0.75" and the plate at 0.125". When assembled the oil pan is 0.875" thick. The 2007 oil pan with welded external pickups is 1.25" in height; therefore the engine is able to be placed lower in the 2008 car allowing for a lower C of G.

The weight of the 2007 oil pan including external pickups and lines is 0.86 kg. The weight of the 2008 oil pan is 1.3 kg. As assumed the 2008 oil pan increased in weight, but is thinner.

Another positive attribute of the oil system is the decrease in size and effectively weight of the 2008 dry sump tank (Appendix C). The 2007 tank weighs 0.72 kg, while the 2008 tank is 0.56 kg. This helps offset the increase in weight of the oil pan.

Once the car begins testing on track, the qualitative reliability characteristic can be evaluated more closely. However, with integrated pickups, the 2008 oil pan should be less prone to leaks.

3.3 Rapid Prototyped Intake Runners

3.3.1 Design and Manufacturing

A brand new feature was the design of the intake plenum and runners in a Computer Aided Design program to have them rapid prototyped. The definition of rapid prototyping is:

"Rapid prototyping takes virtual designs from computer aided design (CAD) or animation modeling software, transforms them into thin, virtual, horizontal cross-sections and then creates each cross-section in physical space, one after the next until the model is finished [8]".

The focus of this thesis is the design of the intake runners. Before designing the 2008 runners, many dimensions and parameters had to be determined. This was accomplished through extensive engine dynamometer testing. A preliminary intake system including restrictor, plenum, and intake runners was designed to be adjustable. Both plenum volume and runner length were to be varied. This preliminary modular design was rapid prototyped and used for dynamometer testing. Inserts were used to vary volumes and lengths. Plenum volumes of 1.5 L and 3 L were tested against runner lengths of 8.5", 9.5", and 11.5".

The dynamometer testing showed that the 3 L plenum and 9.5" runner length was the optimal design (Figures 21 and 22).

The values in the legend of the graphs represent runner insert length, plenum insert length, and exhaust used. For runner insert length, a 1 represents a runner length of 8.5", a 2 represents 9.5", and a 4 represents 11.5". For plenum insert length, 0 represents 1.5 L and 4 represents 3 L. For the exhaust, 06 signifies the 2006 exhaust and 07 the 2007 exhaust.

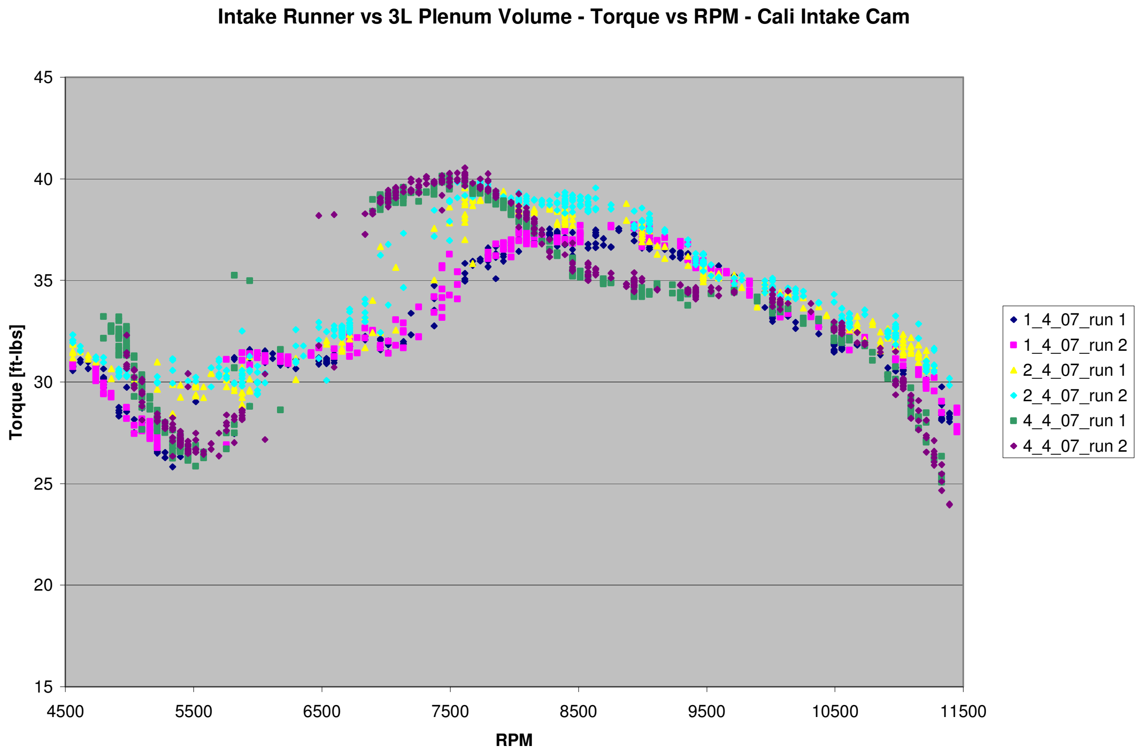


Figure 21 - Torque Curve: Intake Runner Length vs. Plenum Volume

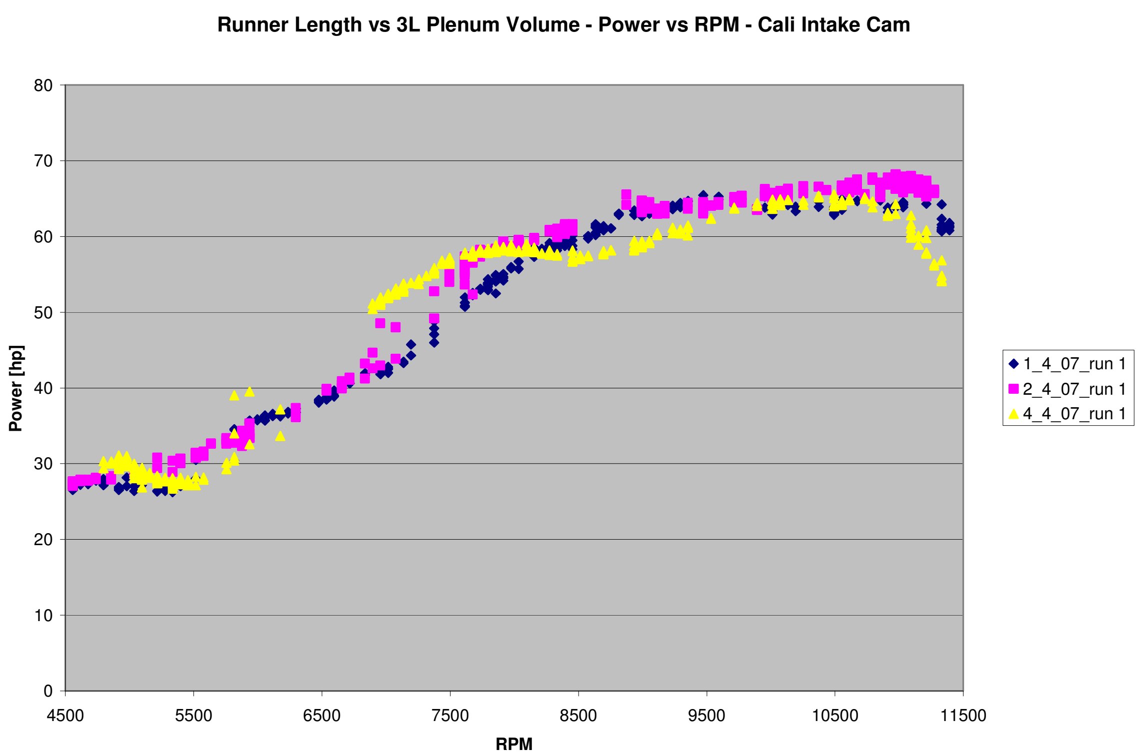


Figure 22 - Power Curve: Intake Runner Length vs. Plenum Volume

The pink power curve represents the 9.5” runner length, 3 L volume, and 2007 exhaust. The most power is generated when this combination is used. Another member on the team designed the plenum. The 2008 plenum was designed as a conical shape with the 4 intake runner holes central; this allows for equal air distribution to each intake port.

Using this plenum the intake runners were designed. The plenum was placed in the full car CAD model and the runners were developed to meet the plenum. The runners were designed such that runners at port 1 and 4 are together and runners at ports 2 and 3 are together. The runners have multiple bends and are a unique geometric shape in order to connect them to the plenum. This was one of the main factors to have the intake system rapid prototyped. Rather than bending aluminum tube, any shape can be manufactured in much less time and effort. Due to packaging constraints the achieved runner length was 10”. This was very close to the 9.5” target and deemed acceptable. The outside diameter of the runners is 1.5” to meet up with the intake ports.

The stiffness of the runners is another important parameter. Therefore, the thickness of the runners must be determined. The goal was to run a finite element analysis on different runner thicknesses, however the complex geometry of the runners did not allow for a complete meshing of the part. Also, it was an objective to make the rapid prototyped runners lighter than the aluminum runners. It was determined that a 0.125” wall thickness was needed to keep the runner weight slightly below that of the aluminum runners. To determine if this thickness would produce a rapid prototyped runner that was as stiff as or close to that of aluminum, a deflection of a cylinder subject to radial loading calculation was done on a 10” long, 1.5” diameter, and 0.125” thick cylinder. The radial load used was 14 psi; atmospheric pressure.

The deflection equation is:

$$\delta = \left(\frac{6.5 \times P}{E \times t}\right)\left(\frac{r}{t}\right)^{3/2}\left(\frac{l}{r}\right)^{-3/4}$$

Therefore, the deflection of a cylinder made of the rapid prototyped material which has an elastic modulus of 230 000 psi (Data Sheet, Appendix D) is:

$$\begin{aligned}
\delta &= \left(\frac{6.5 \times P}{E \times t}\right)\left(\frac{r}{t}\right)^{3/2}\left(\frac{l}{r}\right)^{-3/4} \\
&= \left(\frac{6.5 \times 14}{230000 \times 0.125}\right)\left(\frac{0.75}{0.125}\right)^{3/2}\left(\frac{10}{0.75}\right)^{-3/4} \\
&= 0.0067''
\end{aligned}$$

The deflection for a 10” long, 1.5” diameter, and 0.065” thick aluminum cylinder is 0.0007”. The rapid prototyped material will not deflect that much more than an aluminum cylinder, therefore the thickness of 0.125” was used for the runner design.

Another main factor for having the runners rapid prototyped is that the injector bosses can be incorporated into the design. The injectors will be directed at the intake ports for increased fuel atomization (mixing of fuel and air).

Figure 23 shows the positioning of the injector bosses directed straight at the intake ports.

Figure 23 - Injector Bosses Relative to Intake Ports

The final step in the intake runner design was to decide how to connect the runners with the plenum. It was decided that a flange would be created around the bottom of the plenum and a half circle flange would be created on each runner pair (Figure 26). The plenum and two runner pairs would bolt together.

The final CAD design of the plenum and intake runners is shown in Figure 24.

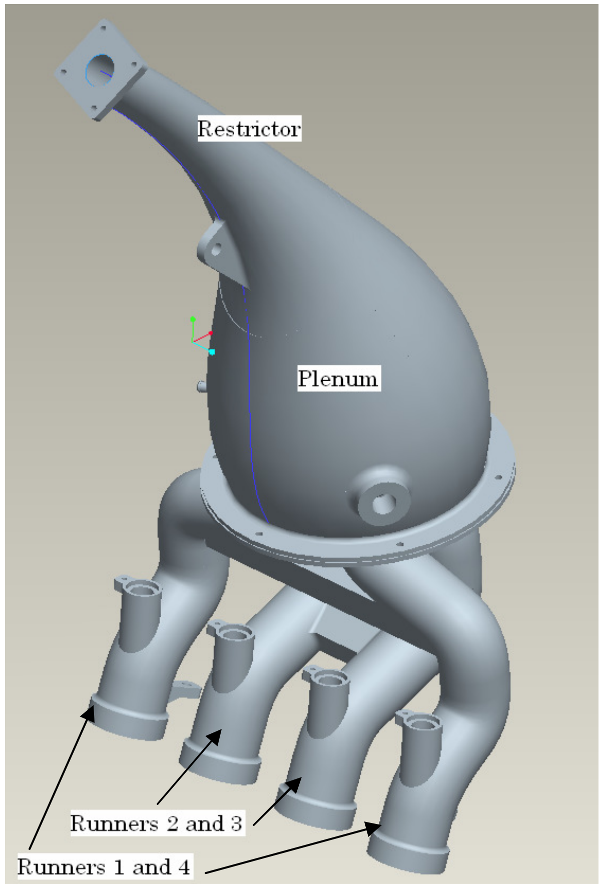


Figure 24 - CAD Model of Intake System

The CAD model was sent to our rapid prototype sponsor for manufacturing. Manufacturing the intake system out of aluminum components takes a great deal of time and manpower. By having the intake system rapid prototyped, this reduces the manufacturing time required by the team. This allows for the development of other systems and components for the car.

The intake plenum and runners are made of DuraForm PA (Polyamide) created by 3D Systems (Data Sheet, Appendix D), which is a type of nylon. This material was chosen because it can withstand a high temperature, it is stiff, and it can be used for functional use. The manufacturing process of this material is called Selective Laser Sintering (SLS), defined as:

"An SLS machine consists of two powder magazines on either side of the work area. The leveling roller moves powder over from one magazine, crossing over the work area to the other magazine. The laser then traces out the layer. The work platform moves down by the thickness of one layer and the roller then moves in the opposite direction. The process repeats until the part is complete. [9]."

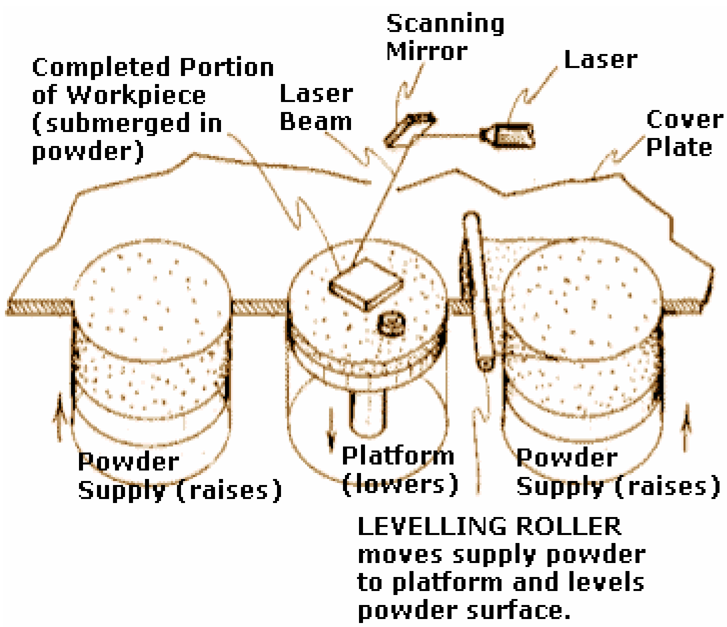


Figure 25 - SLS Process Schematic [9]

The rapid prototyped final intake runners are shown below in Figures 26.

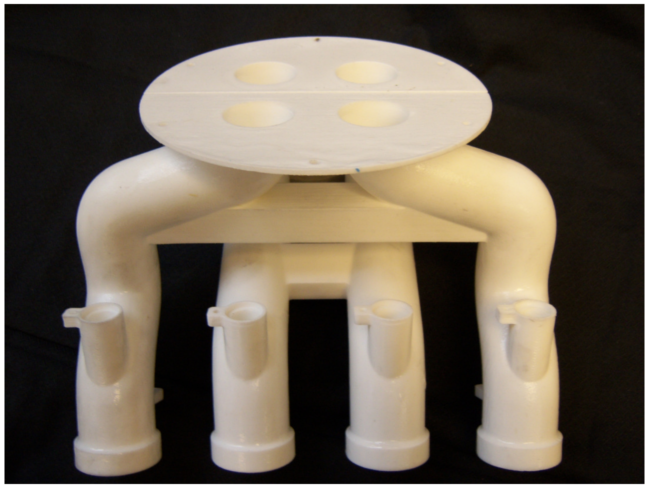


Figure 26 - 2008 Intake Runners

3.3.2 Evaluation

When the 2008 rapid prototyped intake system arrived back, the intake runners were compared to the 2007 design. The weights of runners 1 and 4 and runners 2 and 3 respectively were 0.282 kg and 0.273 kg. This is a total weight of 0.555 kg. The weight of 4 aluminum runners with welded injector bosses is 0.612 kg. Therefore, the 2008 rapid prototyped runners are lighter than those of aluminum.

The new rapid prototyped intake system was also put on the dynamometer and the results were compared to the 2007 system (Figure 27).

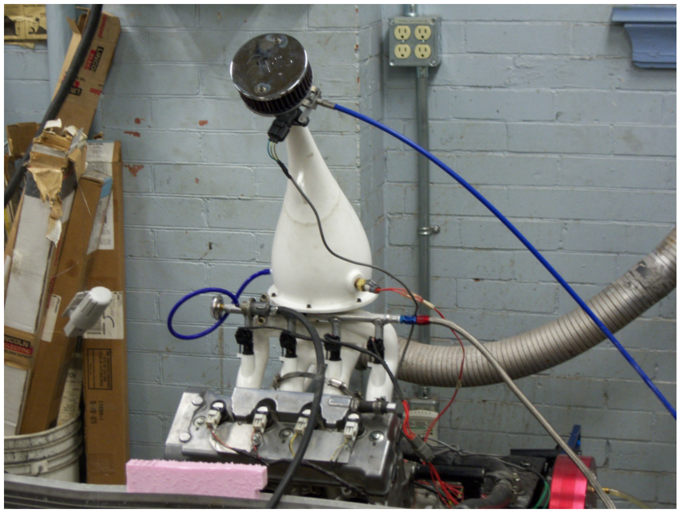


Figure 27 - Rapid Prototyped Intake System on Dynamometer

The results of the dynamometer testing are shown in Figures 28 and 29.

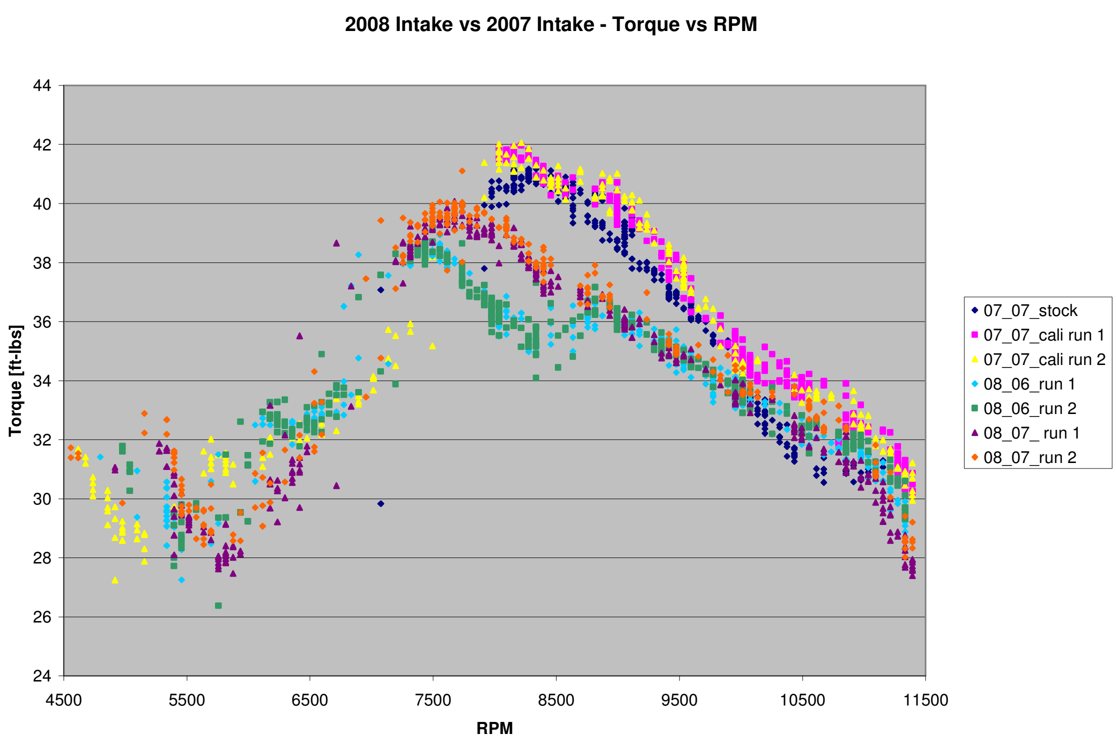


Figure 28 - Torque Curve: 2008 Intake System vs. 2007 Intake System

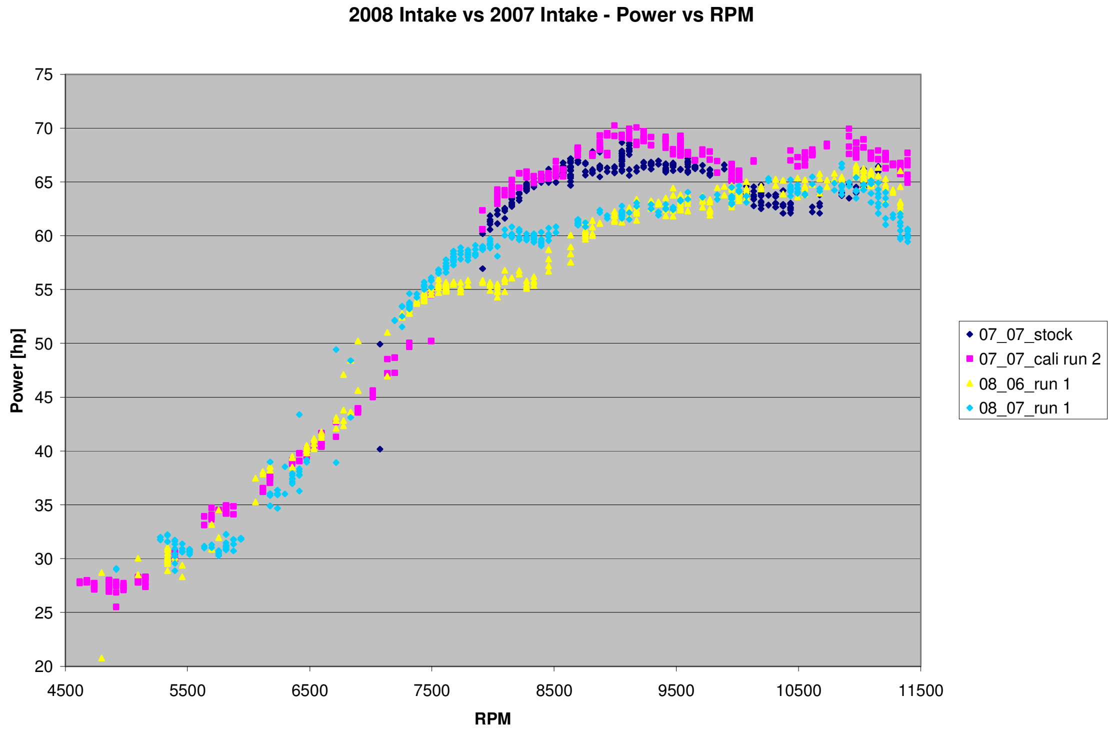


Figure 29 - Power Curve: 2008 Intake System vs. 2007 Intake System

The conclusive outcome from the dynamometer testing is in fact that the 2007 system is better than the 2008 system. However, due to packaging constraints the 2008 exhaust system cannot be the same length as the 2007 exhaust system. Therefore, more dynamometer testing will be conducted once the 2008 exhaust is finished to see if the 2008 intake system can be utilized. Due to timing, these results are not included.

The general pros of having the intake system rapid prototyped are the versatility of the design and the quick manufacturing time. The runners are able to be designed as any shape and the injectors are able to be directed at the intake ports. A FSAE team able to have an intake system rapid prototyped is of great value. With more development in the years to come the rapid prototyped intake system design and process can be optimized.

3.4 Engine Mapping for Fuel Economy

3.4.1 Experimental Design and Testing

The reason for engine mapping to increase fuel economy is that at the Formula SAE competition points are allocated toward fuel economy during the endurance race (Rule 5.7.3). Previously engine mapping for fuel economy was not done and at competition, the University of Toronto's fuel economy performance scores have been low.

The parameter that will be changed to increase fuel economy is the air-to-fuel ratio (AFR), also known as the stoichiometric ratio. The parameters that will be monitored closely are exhaust gas temperatures (EGT), injector pulse width, and the amount of oxygen in the exhaust gas.

The AFR for pure octane is 14.7:1. To determine the AFR for maximum power of a fuel injected system an equivalence ratio is used. The equivalence ratio is the ratio of fuel-to-oxidizer ratio to the stoichiometric fuel-to-oxidizer ratio [3]. The equation is:

$$\phi = \frac{\left(m_{fuel}/m_{ox}\right)}{\left(m_{fuel}/m_{ox}\right)_{st}}$$

The mass based fuel-to-oxidizer ratio of octane (atomic mass of carbon, hydrogen, and oxygen are 12, 1, and 16 respectively) is:

$$\frac{m_{C_8H_{18}}}{m_{O_2}} \frac{1\cdot(8\cdot 12+18\cdot 1)}{1(2\cdot 16)} = \frac{114}{32} = 3.5625$$

However, the amount of octane burned is not equal to the amount of oxygen. To compare it to the equivalence ratio the stoichiometric reaction of octane and oxygen must be looked at:

$$2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O$$

Therefore, the mass based stoichiometric fuel-to-oxidizer ratio of octane is:

$$\left(\frac{m_{C_8H_{18}}}{m_{O_2}}\right)_{st} \frac{2\cdot(8\cdot 12 + 18\cdot 1)}{25(2\cdot 16)} = \frac{228}{800} = 0.285$$

The equivalence ratio of octane is then:

$$\phi = \frac{(m_{fuel}/m_{ox})}{(m_{fuel}/m_{ox})_{st}} = \frac{3.5625}{0.285} = 12.5$$

The AFR that has been used in the past for the endurance race has been close to 12.5:1. This value is used for maximum power; therefore a large amount of fuel is used during the race. The value of 12.5:1 will be used as the test starting point.

Before beginning to map the race engine on the dynamometer some preliminary parameters had to be determined. By increasing the AFR, the engine will run lean (more air than fuel) and hotter. When monitoring exhaust gas temperature, it was decided that the maximum temperature would be 700˚C. This is due to the fact that aluminum has a melting point around 660˚C and thermal stresses to the block of the engine should be avoided. However, the hot exhaust gases are only in the combustion cylinder for a very short time, therefore running the EGT at 700˚C will not damage the material.

If the engine is run too hot there are also two phenomena that may occur, which will damage the engine: detonation and pre-ignition.

Detonation is "the spontaneous combustion of the end-gas (remaining fuel/air mixture) in the cylinder chamber. It always occurs after the normal combustion is initiated by the spark plug. The initial combustion at the spark plug is followed by a normal combustion burn. The end-gas in the cylinder chamber spontaneously combusts due to an increase of heat and pressure" [12].

Pre-ignition is "the ignition of the mixture prior to the spark plug firing. Anytime something causes the mixture in the cylinder chamber to ignite prior to the spark plug event it is classified as pre-ignition" [12].

When detonation occurs a 'knocking' in the engine can be heard. The engine can be run for a significant amount of time during detonation before damage occurs. However, it is very difficult to detect pre-ignition and it will cause immediate engine failure. By not running the engine hotter than 700˚C, any damages to the engine will be avoided, which would be devastating to the development of the Formula SAE car.

The RMP range that the car mainly drives in during a race is around 5500 to 9000. The fuel economy testing was designed to hold the engine at 5500, 8000, and 9000 RPM until steady-state was reached. Each of these RMP values were run at different air-to-fuel ratios stating with 12.5:1 and working up to an AFR that would not cause the exhaust gas temperature to exceed 700˚C. The EGT was logged using the program LabVIEW Measurment. The average exhaust gas temperature was calculated in Excel (Appendix E).

Other AFR values tested were 14.5:1 and 15:1. The fuel map was re-mapped for each AFR value. The dynamometer computer program (DTA Swin) outputs the fuel used in L/hr. It does this by using the time the fuel injectors are open and a sensor in the intake which measures mass airflow. The value in L/hr was recorded when steady-state was achieved.

The results of the engine mapping for fuel economy are shown in Table 2 and Figure 30:

AFR	RPM	Fuel Consumption (L/hr)	Average EGT (˚C)
12.5:1	5500	9.8	635.9
	8000	19.5	624.3
	9000	21.2	649.2
14.5:1	5500	8.2	672.7
	8000	14.5	652.6
	9000	15.6	686.3
15:1	5500	7.1	635.8
	8000	11.9	644.72
	9000	12.4	684.1

Table 2 - Fuel Economy Results

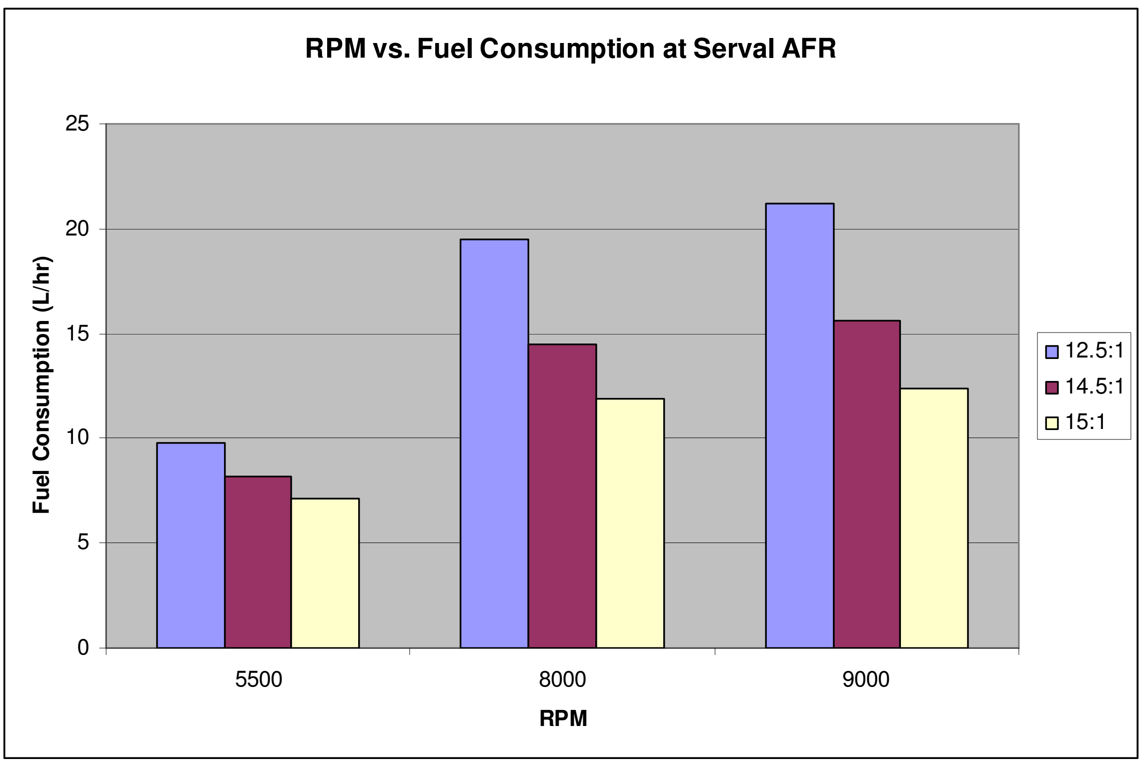


Figure 30 - Fuel Economy Results

The AFR was able to be raised to 15:1, without causing any harm to the engine. Therefore, it is safe to run the engine at an AFR of 15:1 and much less fuel will be consumed. When comparing the fuel used at 9000 RPM, an AFR of 12.5:1 produces a fuel usage of 21.2 L/hr, whereas an AFR of 15:1 produces only 12.4 L/hr. This is a difference of 8.8 L/hr. Therefore, the endurance fuel map which is a matrix of RMP vs. Throttle position was created with an AFR of 15:1. The injector pulse width or the amount of time the injector stays open was decreased in each cell, increasing the amount of air in the mixture, resulting in a higher AFR.

3.4.2 Evaluation

The engine mapping for fuel economy was successful. The University of Toronto Formula SAE Race Team now has a fuel economy map that will save them fuel during the endurance race. This map will be tested on track when the car is complete and evaluated further based on performance and lap time. During competition last year 4.5 L of fuel were used during the endurance race. Running the 15:1 AFR map will decrease the amount of fuel used, however it could cause lap times to be slower. Therefore, the on track testing will reveal what AFR to use in the compromise of fuel economy and lap time. However, the main goal for creating and testing an engine map specifically for fuel economy is fuel will be saved, correlating to a higher point score in this section of the competition.

4 Recommendations

Several recommendations can be made for future Formula SAE members to consider or research on the four key design elements of the 2008 fuel and oil systems.

4.1 Location and Size of Fuel Tank

A big step was made in the packaging and design of the 2008 fuel tank. However, due to running a full composite chassis, the filler neck had to be made removable causing it to be heavier than intended. Depending on the design of the 2009 FSAE car, more attention should be paid to the filler neck design if the car is similar to 2008.

4.2 Oil Pan with Integrated Pickups

The engine sits parallel to the ground in the 2008 FSAE car. The oil pan was designed with the integrated pickups both at one end of the pan. The pickups are situated to the rear of the pan facing toward the front of the car, therefore when the car is accelerating forward, the oil will travel to this region. However, when the car is under breaking the oil will travel to the front of the pan. The total breaking time is a lot less than the total forward acceleration time of the car; however it would be beneficial to design one of the pickups toward the middle of the pan facing toward the rear of the car. This will ensure that oil is being scavenged while the car is under breaking.

4.3 Rapid Prototyped Intake Runners

A great deal of work went into the design of the first iteration of the rapid prototyped intake system; both the intake plenum and runners. Due to this being a totally new objective, this process was a learning experience. It was difficult to determine what thickness the parts should be for the intake system to be stiff enough because this was a new material. The 2008 intake system was designed to be over-built. The thickness of the parts is greater than they need to be. Now that more is known about the material the weight of the rapid prototyped system can be reduced by decreasing the thickness of the parts.

There are also other rapid prototype materials that are similar to the DuraForm PA, but may work better for our application. The material is DuraForm EX. Our sponsor was not able to provide us with this material, but it would be beneficial to find a company that has this material. DuraForm EX has the injection molded toughness of polypropylene and ABS, and it has a greater impact resistance. The Young's Modulus is also greater than that of the DuraForm PA. By using DuraForm EX the thickness of the parts could again be decreased, allowing the parts to be lighter.

4.4 Engine Mapping for Fuel Economy

With a completed engine map tuned for fuel economy using the dynamometer, advanced tests can be run on track. The maximum AFR reached on the dynamometer was 15:1 because when mapping on the dynamometer the engine remains at a constant RPM which causes the engine to run hot. When testing on track the AFR can be increased slightly higher because the engine sweeps through RMP ranges and does not run as hot. By testing on track the balance between fuel economy and lap time performance can be optimized.

5 Conclusion

Great strides were made in the 2008 design of the fuel and lubrication systems. These new designs and concepts are a basis for future FSAE development. By taking a close look at the fuel and lubrication systems, an analysis was done to determine which components should be improved. Creating new designs for the first time does not always produce perfection. While working on this thesis, other useful concepts were thought of after having a design finalized. However, the designs are of substantial improvement over previous years. This thesis allows for future iterations and provides design recommendations for upcoming FSAE members. Four key design features were developed to improve the packaging, reliability, and performance of the 2008 car. The location and size of the fuel tank, an oil pan with integrated pickups, rapid prototyped intake runners, and engine mapping for fuel economy were the four design concepts studied.

As with any design, compromises must be made. This fact remains when considering these four designs. The oil pan is heavier, but is more reliable and allows the engine to be placed lower in the car. The engine map will save fuel, but running the engine leaner may affect the power and overall lap times. Regardless, the four design features outlined in this thesis are an immense step forward for the design of the 2008 FSAE car. The designs and concepts can be used by any team as a design model and baseline.

6 References

[1] Formula SAE RULES

[2] Nice, Karim. "How Fuel Injection Systems Work." Howstuffworks. 2007. 09 Nov 07 <http://auto.howstuffworks.com/fuel-injection3.htm>.

[3] McVea, Dr. William Mark. The Basics of Internal Combustion Engines Seminar.

[4] Technical Articles. "Fuel Pressure Regulator." 09 Nov 07 <http://www.type2.com/bartnik/reg.htm>.

[5] Brain, Marshall. "What does octane mean?" Howstuffworks. 2007. 09 Nov 07 <http://auto.howstuffworks.com/question90.htm>.

[6] "Why do some engines use a dry sump oil system?" Howstuffworks. 2007. 10 Nov 07 <http://auto.howstuffworks.com/question331.htm>.

[7] Harley, Mike. "Synthetic Motor Oils." J.D. Power and Associates. 2007. 10 Nov 07 <http://www.jdpower.com/articles/article.aspx?ID=208>.

[8] "What is Rapid Prototyping?" Wohlers Associates, Inc. 2005. 06 Nov 2007. <http://wohlersassociates.com/rapid-prototyping.html>.

[9] "Rapid Prototyping, SLS." Efunda Engineering Fundamentals. 2007. 06 Nov 2007. <http://www.efunda.com/processes/rapid_prototyping/sls.cfm>.

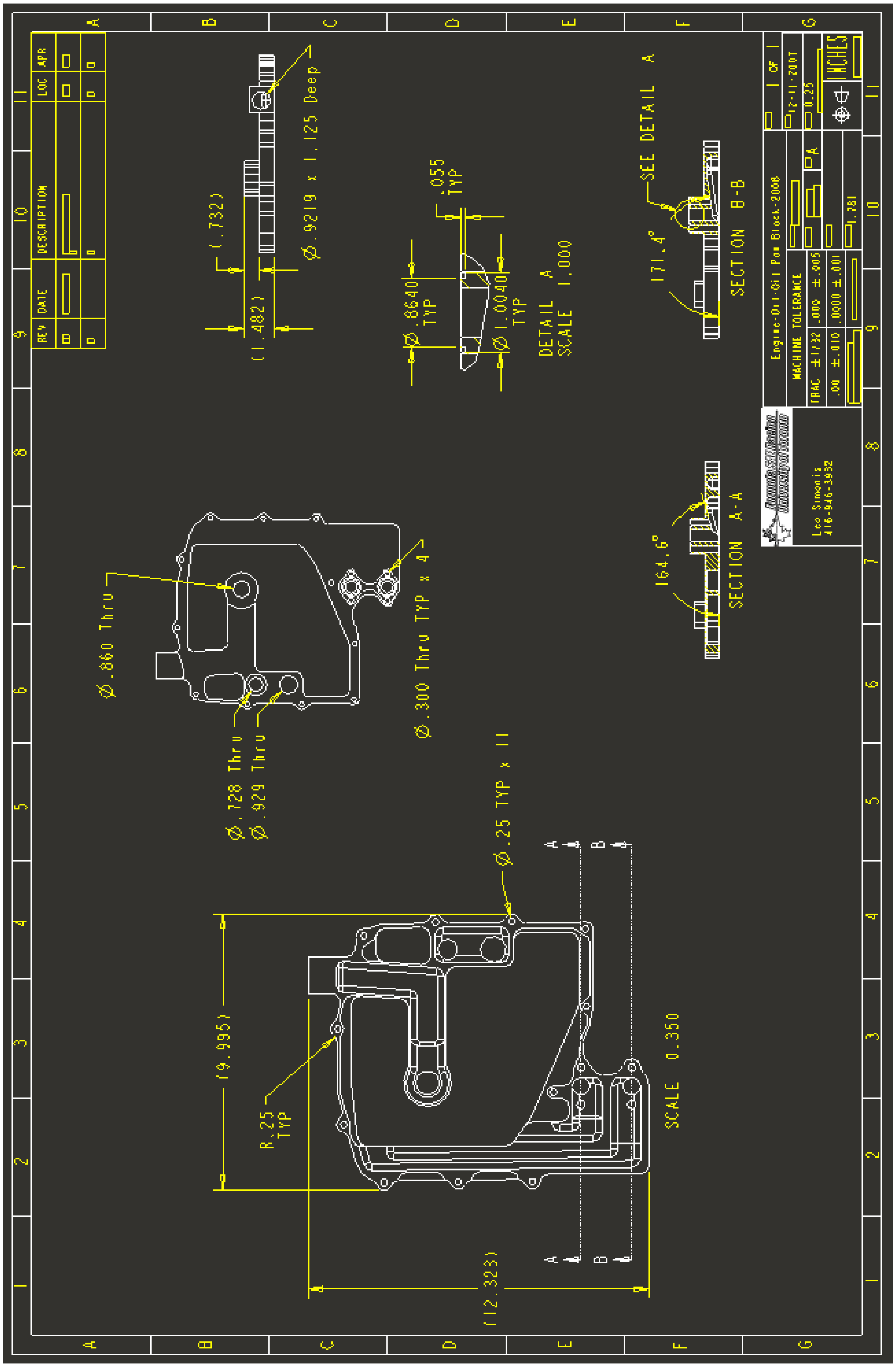
[10] "Grove Design for O-rings." Hi-Tech Seals Inc. 2007. 08 Nov 2007. <http://142.179.166.227/hitechseals/oringgroovedesign.asp>.

[11] White, Frank M. Fluid Mechanics, Fifth Edition. McGraw Hill: New York, 2003.

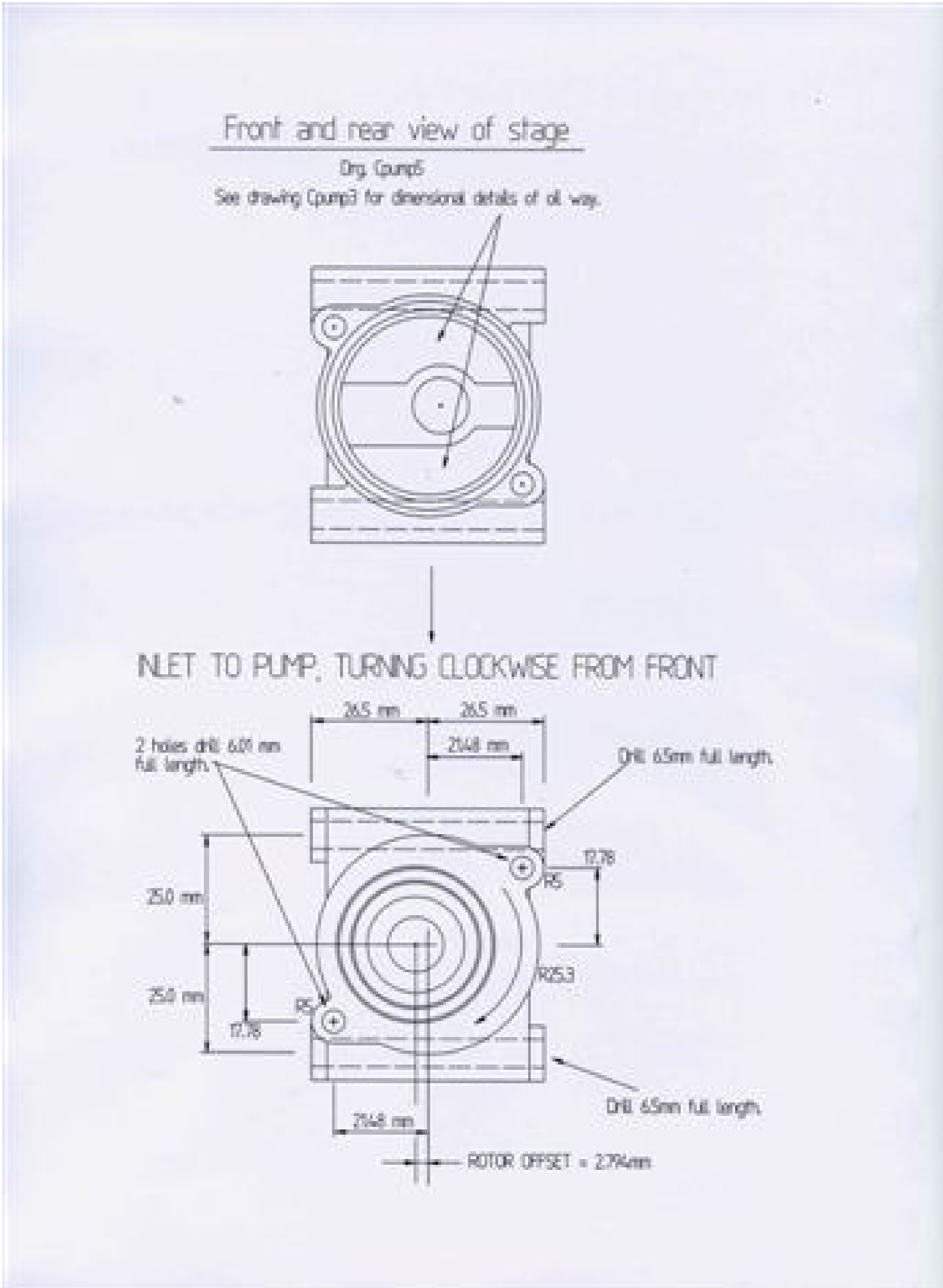
[12] Cline, Allen W. "Engine Basics: Detonation and Pre-ignition". Streerod Stuff of Ohio Inc. 2007. 07 Jan 2008. <http://www.streetrodstuff.com/Articles/Engine/Detonation/index>.

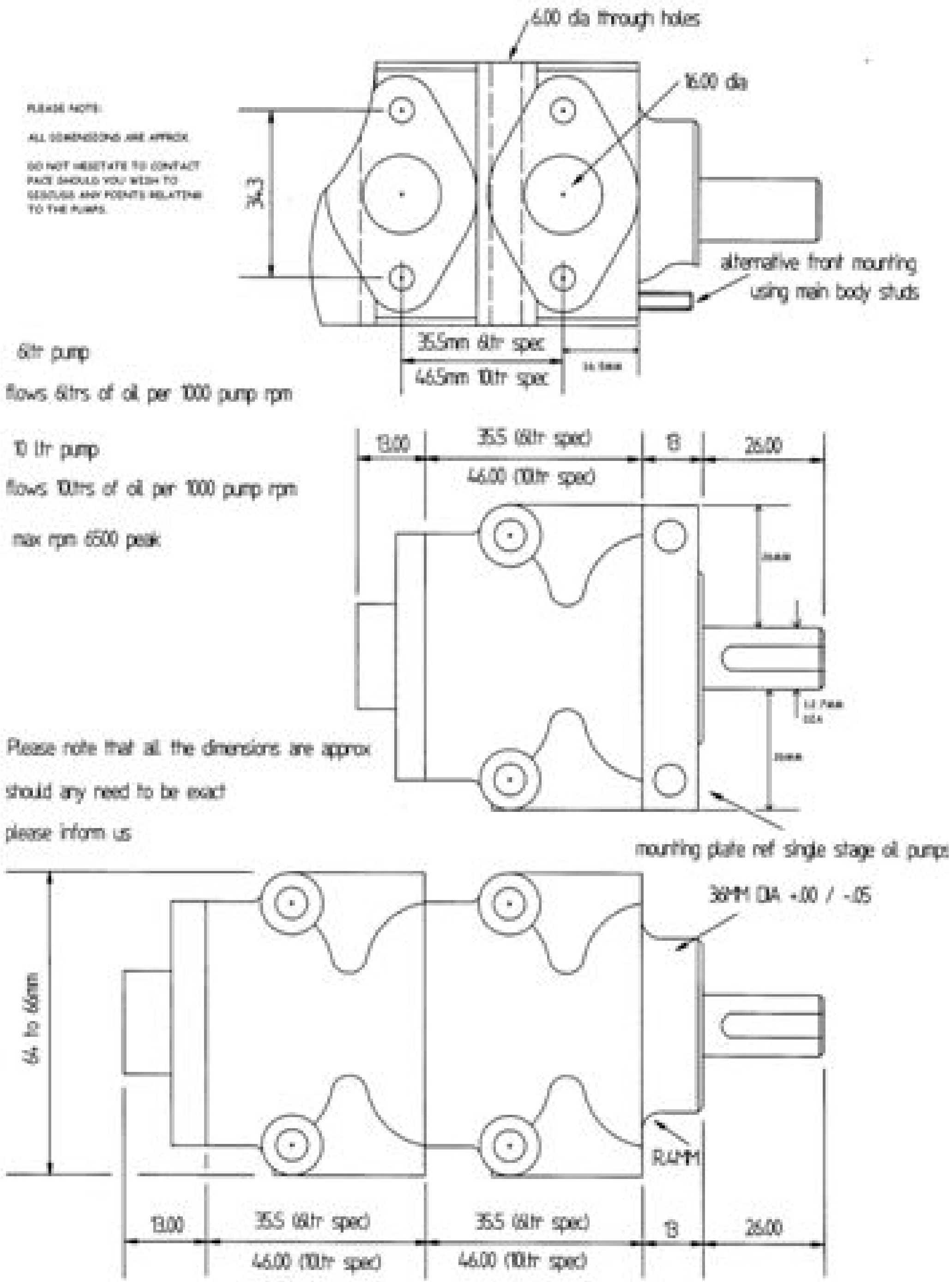
[13] "DuraForm LS Materials: Datasheets." 3D Systems. 2005. 23 Nov 2007. < 3dsystems.com/products/solidimaging/lasersintering/datasheets.asp>

Appendix A – Engineering Drawing of Oil Pan Block



Appendix B – Dimensions of Dry Sump Pump




6.00 dia through holes
16.00 dia
34.3
alternative front mounting
using main body studs
35.5mm 6ltr spec
46.5mm 10ltr spec
6ltr pump
flows 6ltrs of oil per 1000 pump rpm
10 ltr pump
flows 10ltrs of oil per 1000 pump rpm
max rpm 6500 peak
13.00
35.5 (6ltr spec)
46.00 (10ltr spec)
13
26.00
Please note that all the dimensions are approx
should any need to be exact
please inform us
mounting plate ref single stage oil pump
36MM DIA +.00 / -.05
64 to 66mm
R4MM
13.00
35.5 (6ltr spec)
46.00 (10ltr spec)
35.5 (6ltr spec)
46.00 (10ltr spec)
13
26.00

Appendix C – 2008 Dry Sump Tank

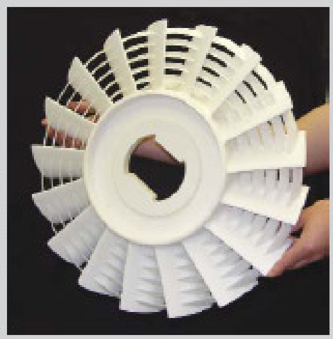
Appendix D – 3D Systems DuraForm PA Data Sheet

3D SYSTEMS

DuraForm® PA plastic

for use with all selective laser sintering (SLS®) systems

Durable polyamide (nylon) material for real-world physical testing and functional use


APPLICATIONS

- Complex, thin-wall ductwork
  - Motorsports
  - Aerospace
- Housings and enclosures
- Impellers and connectors
- Consumer sporting goods
- Vehicle dashboards and grilles
- Snap-fit designs
- Functional prototypes that approach end-use performance properties
- Appropriate for low- to mid-volume rapid manufacturing
- Medical applications requiring USP Class VI compliance, or biocompatibility
- Parts requiring machining or joining with adhesives
- Complex production and prototype plastic parts
- Form, fit, or functional prototypes

FEATURES

- Excellent surface resolution and feature detail
- Easy-to-process
- Compliant with USP Class VI testing
- Compatible with autoclave sterilization
- Good chemical resistance and low moisture absorption

BENEFITS

- Nicely balanced mechanical properties and processability
- Build prototypes that withstand functional testing
- Produce durable end-use parts without tooling
- Create accurate and repeatable parts as demanded by manufacturers
- Machinable and paintable for demonstration parts

3D SYSTEMS CORPORATION

TRANSFORM YOUR PRODUCTS

DuraForm® PA plastic

For use with all selective laser sintering (SLS®) systems

TECHNICAL DATA

General Properties

MEASUREMENT	METHOD/CONDITION	METRIC	U.S.
Specific Gravity	ASTM D792	1.00 g/cm³	1.00 g/cm³
Moisture Absorption - 24 hours	ASTM D570	0.07 %	0.07 %

Mechanical Properties

MEASUREMENT	METHOD/CONDITION	METRIC	U.S.
Tensile Strength, Yield	ASTM D638	N/A*	N/A*
Tensile Strength, Ultimate	ASTM D638	43 MPa	6237 psi
Tensile Modulus	ASTM D638	1586 MPa	230 ksi
Elongation at Yield	ASTM D638	N/A*	N/A*
Elongation at Break	ASTM D638	14 %	14 %
Flexural Strength, Yield	ASTM D790	N/A*	N/A*
Flexural Strength, Ultimate	ASTM D790	48 MPa	6962 psi
Flexural Modulus	ASTM D790	1387 MPa	201 ksi
Hardness, Shore D	ASTM D2240	73	73
Impact Strength (notched Izod, 23°C)	ASTM D256	32 J/m	0.6 ft-lb/in
Impact Strength (unnotched Izod, 23°C)	ASTM D256	336 J/m	6.3 ft-lb/in
Gardner Impact	ASTM D5420	2.7 J	2.0 ft-lb

Thermal Properties

MEASUREMENT	METHOD/CONDITION	METRIC	U.S.
Heat Deflection Temperature (HDT)	ASTM D648 @ 0.45 MPa @ 1.82 MPa	 180 °C 95 °C	 356 °F 203 °F
Coefficient of Thermal Expansion	ASTM E831 @ 0 - 50 °C @ 85 - 145 °C	 82.6 μm/m-°C 179.2 μm/m-°C	 45.9 μin/in-°F 99.6 μin/in-°F
Specific Heat Capacity	ASTM E1269	1.64 J/g-°C	0.392 BTU/lb-°F
Thermal Conductivity	ASTM E1225	0.70 W/m-K	4.86 BTU-in/hr-ft^2-°F
Flammability	UL 94	HB	HB

Electrical Properties

MEASUREMENT	METHOD/CONDITION	METRIC	U.S.
Volume Resistivity	ASTM D257	5.9 x 10^{13} ohm-cm	5.9 x 10^{13} ohm-cm
Surface Resistivity	ASTM D257	7.0 X 10^{13} ohm	7.0 x 10^{13} ohm
Dissipation Factor, 1 KHz	ASTM D150	0.044	0.044
Dielectric Constant, 1 KHz	ASTM D150	2.73	2.73
Dielectric Strength	ASTM D149	17.3 kV/mm	439 kV/in

* N/A = Data not applicable for this test condition

Data was generated by building parts under typical default parameters. DuraForm PA plastic was processed on a base-level Sinterstation HiQ SLS system at 13 watts laser power, 200 inches/sec [5 m/sec] scan speed, and a powder layer thickness of 0.004 inches [0.1 mm].

TRANSFORM YOUR PRODUCTS

3D Systems Corporation
333 Three D Systems Circle
Rock Hill, SC 29730 U.S.A.
Tel: 803.326.4080
Toll-free: 800.889.2964
Fax: 803.324.8810
moreinfo@3dsystems.com
www.3dsystems.com
NASDAQ: TDSC

PN 70715 Issue Date - 10 Dec 07

Appendix E – Exhaust Gas Temperature Data

Fuel Economy Test (AFR = 12.5)					
RPM	TPS	Torque	EGT 1	EGT 2	EGT 3
7974.919	100	84.225072	627.463	626.498	612.4592
7974.919	100	84.124123	627.463	626.498	612.4592
7974.919	100	84.434195	627.9299	626.6848	613.5175
7974.919	100	84.729848	627.9299	626.6848	613.5175
7974.919	100	84.740671	628.5214	627.5875	613.144
7974.919	100	84.477465	628.5214	627.5875	612.5837
7974.919	100	83.976296	628.6771	627.5875	612.5837
7974.919	100	83.82847	628.6771	627.7743	612.8638
7974.919	100	84.365693	628.6771	627.7743	612.8638
7974.919	100	84.621684	628.5837	627.8677	612.3347
7974.919	100	83.82847	628.6771	628.179	613.5175
7974.919	100	84.715428	628.7704	628.6771	613.5175
7974.919	100	83.889767	628.7704	628.6771	613.7043
7974.919	100	83.936634	629.4864	628.6771	613.7043
7974.919	100	84.434195	629.4864	628.9261	612.4903
7974.919	100	84.437803	629.4864	628.9261	612.4903
7974.919	100	84.250314	629.8911	629.2062	614.0467
7974.919	100	83.965484	629.8911	629.2062	614.0467
7974.919	100	84.18542	630.7626	630.1712	612.5526
7974.919	100	84.408963	631.3229	630.3891	612.5526
7974.919	100	84.524332	631.9144	630.7938	613.144
7974.919	100	83.723914	631.9144	630.7938	613.144
7974.919	100	84.477465	632.3502	631.7587	614.5759
7974.919	100	84.304396	632.0389	631.7587	614.5759
7974.919	100	84.81278	632.0389	632.0389	613.5798
7974.919	100	83.864525	632.0389	632.0389	613.5798
7974.919	100	84.614469	632.2568	632.4747	614.6381
7974.919	100	84.762295	632.2568	632.4747	614.6381
7974.919	100	84.008743	632.7238	632.6926	614.7626
7974.919	100	85.487007	632.7238	632.6926	614.7626
		AVGERAGE EGT	630.0415	629.4366	613.4117
		AVGERAGE TOTAL	624.2966		
5516.485	100	62.837112	638.6693	634.8405	622.9805
5516.485	100	63.186847	639.105	634.8405	622.9805
5516.485	100	62.584724	639.105	635.8677	622.5136
5516.485	100	62.627989	639.105	635.8677	622.5136
5516.485	100	62.469345	639.3229	636.9261	623.4163
5516.485	100	62.786633	639.3229	636.9261	623.4163
5516.485	100	62.599144	639.9455	637.5798	624.1012
5516.485	100	62.970514	639.9455	637.5798	624.1012
5516.485	100	63.208482	640.1012	638.5759	624.1012
5516.485	100	62.638806	640.1012	638.5759	625.0039
5516.485	100	62.898404	641.0973	638.5759	625.0039
5516.485	100	62.653231	641.0973	638.9183	626.7471

5516.485	100	62.793842	641.0973	638.9183	626.7471
5516.485	100	63.49692	641.0973	639.3229	628.9261
5516.485	100	62.613569	640.9728	639.6342	628.3969
5516.485	100	63.10392	641.4086	639.6342	628.3969
5516.485	100	62.736158	641.4086	640.2257	627.8365
5516.485	100	63.039021	641.4086	640.2257	627.8365
5516.485	100	62.73976	641.6265	640.6304	628.2413
5516.485	100	62.725341	641.6265	640.6304	628.2413
5516.485	100	63.323856	642.4047	640.8483	629.2062
5516.485	100	63.298619	642.4047	640.9417	629.4241
5516.485	100	62.999358	642.8716	641.2529	629.2374
5516.485	100	62.707313	642.9961	641.8132	629.0506
5516.485	100	62.469345	642.7471	642.3735	629.6732
5516.485	100	62.548669	643.0584	642.3735	629.6732
5516.485	100	63.093103	643.463	642.965	629.8288
5516.485	100	62.887587	643.463	642.965	629.8288
5516.485	100	63.150793	643.1206	642.6226	629.8288
5516.485	100	62.404445	643.1206	642.6226	630.4202
		AVGERAGE EGT	641.2405	639.5025	626.9224
		AVGERAGE TOTAL	635.8885		
8994.269	100	76.848172	640.4747	638.856	621.9844
8994.269	100	77.731533	638.3891	638.856	621.9844
8994.269	100	77.15104	642.5292	642.3735	632.3502
8994.269	100	77.403423	642.5292	642.3735	632.3502
8994.269	100	77.140228	650.965	649.8755	633.4708
8994.269	100	76.988794	650.965	649.8755	634.5603
8994.269	100	76.498437	662.9805	659.8677	638.5136
8994.269	100	76.426328	663.7276	660.0545	638.2957
8994.269	100	76.923889	663.7276	660.0545	638.2957
8994.269	100	77.032053	664.8171	660.7393	638.2957
8994.269	100	77.078931	664.8171	660.7393	639.8521
8994.269	100	77.475532	665.5331	660.7393	639.8521
8994.269	100	77.205122	665.5331	661.0506	640.6304
8994.269	100	77.10777	665.5331	661.0506	640.6304
8994.269	100	77.089743	666.965	661.2374	641.9377
8994.269	100	78.1065	666.965	661.2374	641.9377
		AVGERAGE EGT	657.2782	654.3113	635.9339
		AVGERAGE TOTAL	649.1744		

Fuel Economy Test (AFR = 14.5)					
RPM	TPS	Torque	EGT 1	EGT 2	EGT 3
7974.919	100	84.308004	646.607	647.2918	625.4397
7974.919	100	84.81278	645.8288	646.9805	625.4397
7974.919	100	84.967811	645.8288	646.9805	627.5253
7974.919	100	84.318816	645.5798	646.9805	627.5253
7974.919	100	84.582022	645.5798	646.9805	626.965
7974.919	100	84.315219	645.5798	646.9805	626.965

7974.919	100	84.308004	645.0506	646.8871	626.8716
7974.919	100	84.102488	645.0506	646.8871	626.8716
7974.919	100	84.603657	644.8016	646.7004	626.8716
7974.919	100	84.351274	644.8016	646.7004	625.8444
7974.919	100	84.935364	644.7393	646.7004	625.8444
7974.919	100	84.719036	644.7393	646.2957	625.7198
7974.919	100	84.390936	643.7743	646.2957	625.7198
7974.919	100	84.582022	643.7743	646.1712	626
7974.919	100	84.437803	643.7743	646.1712	626
7974.919	100	84.264734	642.5603	644.8016	623.7276
7974.919	100	84.246707	615.7899	621.4241	605.4241
7974.919	100	84.603657	615.7899	621.4241	605.4241
7974.919	100	84.881282	675.6187	673.1595	652.895
7974.919	100	85.19857	675.6187	673.9689	652.2101
7974.919	100	84.246707	681.6265	678.6381	658.249
7974.919	100	85.094013	681.6265	678.6381	660.5526
7974.919	100	84.466642	684.1168	680.5681	662.3891
7974.919	100	84.639711	685.3308	681.7821	662.3891
7974.919	100	84.383721	685.3308	681.7821	665.1595
7974.919	100	84.326031	687.0117	681.7821	665.1595
7974.919	100	83.929419	687.0117	682.8093	667.9922
7974.919	100	84.44141	687.0117	682.8093	667.9922
7974.919	100	84.538762	697.1284	687.1984	673.1907
7974.919	100	85.011081	697.1907	687.572	672.5681
		AVGERAGE EGT	659.1424	658.6454	639.6975
		AVGERAGE TOTAL	652.4951		
5516.485	100	64.711983	669.642	667.0272	651.4319
5516.485	100	64.54613	668.9261	667.0272	651.4319
5516.485	100	63.702436	668.6148	666.6226	650.9027
5516.485	100	64.236052	668.6148	666.6226	650.9027
5516.485	100	63.359911	668.8638	666.3424	651.8988
5516.485	100	63.774545	668.8638	666.3424	651.8988
5516.485	100	63.987271	669.2062	666.498	653.9222
5516.485	100	64.019723	669.7977	667.8988	655.2918
5516.485	100	64.48123	669.7977	667.8988	655.2918
5516.485	100	64.48123	672.5059	671.0739	659.6187
5516.485	100	64.340613	672.5059	671.0739	659.6187
5516.485	100	63.713253	676.9883	675.4008	659.6187
5516.485	100	63.778153	707.1829	695.9144	682.5292
5516.485	100	63.565427	704.5992	694.2335	682.5292
5516.485	100	63.49692	700.5837	690.3424	672.4436
5516.485	100	63.291409	700.5837	690.3424	672.4436
5516.485	100	63.80339	695.0739	685.393	667.7743
5516.485	100	63.706043	695.0739	685.393	667.7743
5516.485	100	63.093103	690.0623	681.035	664.537
		AVGERAGE EGT	680.9203	675.9201	661.1505
		AVGERAGE TOTAL	672.6637		
8994.269	100	76.541707	670.3268	670.0778	647.5408

8994.269	100	77.471935	671.572	670.8871	649.1907
8994.269	100	77.677441	671.572	670.8871	649.1907
8994.269	100	77.601734	673.9689	673.6265	649.1907
8994.269	100	77.497167	673.9689	673.6265	653.8911
8994.269	100	77.425058	678.3268	673.6265	653.8911
8994.269	100	76.783278	678.3268	678.8871	660.1168
8994.269	100	76.804913	678.3268	678.8871	660.1168
8994.269	100	77.767588	684.3969	685.144	667.4319
8994.269	100	77.086135	684.3969	685.144	667.4319
8994.269	100	77.161852	717.642	706.9027	709.7354
8994.269	100	77.4503	718.0156	708.179	703.572
8994.269	100	77.010429	718.0156	708.179	703.572
8994.269	100	77.497167	717.1751	707.5564	703.572
8994.269	100	77.100566	717.1751	707.5564	696.2568
8994.269	100	77.039268	714.0623	707.5564	696.2568
8994.269	100	77.389003	714.0623	704.6615	688.0389
8994.269	100	76.786885	714.0623	704.6615	688.0389
		AVGERAGE EGT	694.1885	689.7804	674.8353
		AVGERAGE TOTAL	686.2681		

Fuel Economy Test (AFR = 15)					
RPM	TPS	Torque	EGT 1	EGT 2	EGT 3
8034.88	100	84.070041	616.0701	612.3658	598.2646
8034.88	100	84.44141	617.3463	614.8249	598.2646
8034.88	100	84.300789	621.7665	621.642	604.3969
8034.88	100	85.18415	621.7665	621.642	604.3969
8034.88	100	85.032716	623.4163	623.1673	604.3969
8034.88	100	84.235894	623.4163	623.1673	605.0195
8034.88	100	85.84035	625.1284	624.7238	608.8483
8034.88	100	85.122853	628.7704	628.5526	612.6148
8034.88	100	85.267072	645.2996	643.4941	630.9494
8034.88	100	85.050743	645.2996	643.4941	630.9494
8034.88	100	79.581167	670.6693	659.7743	651.8988
8034.88	100	80.626764	673.0039	661.2374	651.8988
8034.88	100	80.525804	673.0039	661.2374	655.9455
8034.88	100	79.299934	675.712	661.2374	655.9455
8034.88	100	78.441815	683.1517	666.5914	673.4397
8034.88	100	78.142555	683.5875	666.1245	673.4397
8034.88	100	72.979443	684.3969	662.1712	665.2841
8034.88	100	73.080403	684.6459	663.0117	668.1168
8034.88	100	67.931717	686.2646	668.179	679.3541
8034.88	100	66.132557	687.6031	669.5486	677.6732
7974.919	100	83.88616	615.0428	610.6537	596.6148
7974.919	100	84.250314	616.0701	612.3658	598.2646
7974.919	100	84.390936	657.4397	652.895	638.0156
7974.919	100	84.78393	657.4397	652.895	641.6887
7974.919	100	73.4698	684.3969	662.4202	662.8249

7974.919	100	72.903737	684.3969	662.1712	665.2841
		AVERAGE EGT	653.2733	644.2149	636.6842
		AVERAGE TOTAL	644.7241		
5516.485		62.837112	638.6693	634.8405	622.9805
5516.485		63.186847	639.105	634.8405	622.9805
5516.485		62.584724	639.105	635.8677	622.5136
5516.485		62.627989	639.105	635.8677	622.5136
5516.485		62.469345	639.3229	636.9261	623.4163
5516.485		62.786633	639.3229	636.9261	623.4163
5516.485		62.599144	639.9455	637.5798	624.1012
5516.485		62.970514	639.9455	637.5798	624.1012
5516.485		63.208482	640.1012	638.5759	624.1012
5516.485		62.638806	640.1012	638.5759	625.0039
5516.485		62.898404	647.0973	638.5759	625.0039
5516.485		62.653231	647.0973	638.9183	626.7471
5516.485		62.793842	647.0973	638.9183	626.7471
5516.485		63.49692	647.0973	639.3229	628.9261
5516.485		62.613569	640.9728	639.6342	628.3969
5516.485		63.10392	641.4086	639.6342	628.3969
5516.485		62.736158	641.4086	650.2257	627.8365
5516.485		63.039021	641.4086	640.2257	627.8365
5516.485		62.73976	641.6265	640.6304	628.2413
5516.485		62.725341	641.6265	640.6304	628.2413
5516.485		63.323856	642.4047	640.8483	629.2062
5516.485		63.298619	642.4047	640.9417	629.4241
5516.485		62.999358	642.8716	641.2529	629.2374
5516.485		62.707313	642.9961	641.8132	629.0506
5516.485		63.323856	642.7471	642.3735	629.6732
		AVERAGE EGT	641.7995	639.261	626.3237
		AVERAGE TOTAL	635.7948		
8994.269		77.601734	673.9689	673.6265	649.1907
8994.269		77.497167	673.9689	673.6265	653.8911
8994.269		77.425058	678.3268	673.6265	653.8911
8994.269		76.783278	678.3268	678.8871	660.1168
8994.269		76.804913	678.3268	678.8871	660.1168
8994.269		77.767588	684.3969	685.144	667.4319
8994.269		77.086135	684.3969	685.144	667.4319
8994.269		77.161852	717.642	706.9027	709.7354
8994.269		77.4503	718.0156	708.179	703.572
8994.269		77.010429	718.0156	708.179	703.572
8994.269		77.497167	717.1751	707.5564	703.572
8994.269		77.161852	671.572	670.8871	649.1907
		AVERAGE EGT	691.1777	687.5538	673.476
		AVERAGE TOTAL	684.0692		