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# FSAE TURBO-SYSTEM DESIGN 2010

A Major Qualifying Project
submitted to the Faculty
of the
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for
the Degree of Bachelor of Science

By


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# Abstract

Formula SAE (FSAE) is a student design competition, organized by the Society of Automotive Engineers (SAE International). Teams from around the world compete to create the best, small, formula-style racecar, which is meant to be evaluated from many different perspectives as a production item.

The goal of this project is to determine the performance gains associated with adding a turbocharger to a naturally aspirated engine, used in a Formula SAE race car. This involves selecting the correct turbocharger for the engine, designing and fabricating the entire turbo-system, selecting and configuring an engine management system, tuning various engine variables, and performing before and after tests to determine any performance gains. This project is meant to provide future teams with design information to help them determine whether or not using a turbocharger is a viable design consideration.

# Acknowledgements

The team would like to thank several individuals for the help and guidance they offered throughout the project. This aid proved to be critical for the team's success, since their knowledge in certain, specific areas was necessary to keep the team going forward and staying on the right track.

First and foremost, the group extends their regards to Professor Eben C. Cobb who advised the project, critiqued the team's work in order to ensure its quality, and often suggested approaches to solving specific problems. The group also thanks Barbara Furhman for her help with purchasing the necessary components needed to complete the project. In addition, the team would also like to thank Adam Sears and Alexander Segala for advising the fabrication of custom parts.

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**Note:** The writing portions are not intended to reflect the contribution to the project by each team member.

# Chapter 1: Introduction

## 1.1 Society of Automotive Engineers

SAE International (Formerly: Society of Automotive Engineers) is a professional organization for engineers in the aerospace, automotive, and commercial vehicle industries. At first, SAE served as a forum where automotive engineers could share their experience and showcase recent innovations. Today, the work completed by automotive engineers is typically classified, proprietary information that is rarely shared with competitors.

The Society of Automotive Engineers is also very involved in creating automotive standards, as well as protecting the patents owned by the diverse companies in the automotive field. For example, motor oils are currently designated according to their viscosity characteristics by a system developed by the SAE. The viscosity is measured by observing the time required for a standard amount of oil to flow through a standard orifice, at standard temperatures. The result of this test will be a number (0, 5, 10, 15, 20, 25, 30, 40, 50 or 60), where a higher number denotes more time required to complete the test. The classification also allows for a 'W' to suffix this number, which denotes that the motor oil is tested at a lower temperature and therefore is more appropriate for cold-starts during the winter. The viscosity of motor oil is logarithmically proportional to the temperature of the oil and the temperature range the oil is exposed to is often quite large. Engines must be able to both start in the cold winter months and be able to operate through high loads in the summer months. For this reason multi-grade oils have been developed. These oils contain special polymer additives, known as viscosity index improvers (VIIs), which results in a relatively small change in the viscosity of the oil in different conditions, compared to the great temperature differences that may occur otherwise. The SAE designation for multi-grade oils includes two viscosity grades. For example 10W-30 denotes the motor oil exhibits viscosity characteristics similar to a 10W motor oil grade at low temperatures and viscosity characteristics of a 30 motor oil grade at high temperatures. [**SAE Number (Motor Oil)]**

Furthermore, the Society of Automotive Engineers has also developed a list of common tool sizes, which makes the use of interchangeable parts easier and allows for a mechanic to have one set of tools, which can accomplish most necessary tasks. One example of this tool size standard is the common use of sockets in 1/16 inch increments.

Diagnostic Trouble Codes (DTCs) are SAE-proposed codes, which are used by the On-Board Diagnostics II (OBD II) system. This system will alert the operator through the use of a check-engine light when an engine or any other vehicular problem is detected. After bringing the car to a service station, a trained technician can quickly determine the problem by using an OBD II scanner.

To aid in the transfer of knowledge amongst automotive engineers, the SAE holds an annual conferences known as SAE World Congress. The SAE also hosts a bi-annual conference, known as Convergence, which focuses on electronics in automotive applications. These events are very well-known in the automotive world, which shows the impact of the SAE in this respective field. **[SAE Convergence: Convergence History]**

## 1.2 Formula SAE

Formula SAE is a student design competition that was started in 1978 by the Society of Automotive Engineers. The completion focuses on the design of a small, formula-style race car, which is evaluated for its potential as a production item. Each student team must design, fabricate, and test a race car, based on a set of rules (see 'Appendix 1: Applicable 2010 FSAE Rules' to view the rules that apply to this project). The vehicle is then tested by several judges in various categories, in order for its quality to be determined. The categories include design, cost & manufacturing analysis, presentation, acceleration, skid-pad performance, autocross performance, fuel economy, and endurance. **[About Formula SAE]**

## 1.3 Project Overview

The *FSAE Turbo-System Design 2010* Major Qualifying Project (MQP) involved taking an existing Formula SAE vehicle, used in a past competition, and modifying it with the addition of a turbocharger system. One such system includes a turbocharger, an intercooler, and all of the associated charge and exhaust piping. These components, when properly matched, provide a more useable and efficient powerband. The amount of airflow (and therefore power) is increased through a majority of the powerband. The vehicle was tested via a chassis dynamometer (dyno) before and after the addition of the turbo-system, in order to determine whether or not the project was a success.

After the project's conception, preliminary design stages took place. The basic stages included a literature review, background data acquisition, and thermodynamic analysis. The literature review involved exploring what other teams have done in the past, gathering of technical papers, and reviewing engineering concepts learned during the team members' education at the Worcester Polytechnic Institute (WPI). Gathering books on the subject matter also proved beneficial. Finally, the thermodynamic analysis consisted primarily of modeling in Microsoft Excel. This modeling factored in every variable possible to helped the team properly size the necessary components.

After the preliminary stages were completed, the team concentrated on designing the turbo-system and selecting the proper components. Components were compared, pros/cons lists were compiled, and engineering decisions were made. Once this was finished, the implementation stages were initiated. During this phase, parts were purchased, fabricated, and installed. During the fabrication process, particular design flaws were discovered and engineering decisions were made to correct these failures.

After the vehicle was fully assembled, it was necessary to tune the engine management system, which is responsible for the operation of the engine and the turbo-system as a whole. Through testing, the tune and therefore the functionality of the system were optimized.

## 1.4 Previous Projects

In 2007, an MQP team at WPI attempted to design a turbocharged system for a future FSAE race car. The platform used in this project would be the 2008 WPI FSAE car, which was not yet completed at the time. The primary goal of the team was to maximize the horsepower-to-weight ratio of the turbocharged engine, while creating a system that could easily be integrated into a future vehicle, built for competition. The team began the design process by first deciding whether the goal was to maximize the peak horsepower of the engine or to instead enhance the overall powerband of the vehicle. The need for a reduction in turbocharger lag was also discussed, since it would improve drivability. Lastly, the team discussed how to increase the reliability of the engine by reducing the additional heat added to the system charge flow by the turbocharger. After selecting the necessary turbocharger geometries, in order to optimize the system, the 2007 MQP team also listed the qualities of a turbocharger that they rendered desirable. An example is using a turbocharger, which features a water jacket for the bearings, so that the lubricating oil does not get broken down as easily, which could result in oil contamination inside the compressor housing. **[FSAE Turbocharger Design and Implementation]**

A year before the 2007 project took place, the 2006 Turbo MQP team focused on the design, manufacturing, and assembly of a turbocharger system for the 2007 Formula SAE race car. The system was designed so that it could be bolted onto the car with minimal modification. The intake and exhaust systems were both optimized throughout the design phase. The turbocharger's wastegate system was configured in order to ensure reliable operation of the turbocharger at all engine RPMs. The intercooler was custom designed so that piping length could be minimized and so the system could fit within the packaging constraints, although this design was later rendered unnecessary. **[Turbocharging the Formula SAE Race Car]**

Both of the aforementioned projects produced only theoretical data, since neither one was successfully implemented onto an FSAE vehicle. Without actual test data, it is impossible to determine whether these projects enhanced the operation of the vehicle and therefore they provided virtually no valuable information to the team.

# Chapter 2: Technical Background

## 2.1 Internal Combustion Engines

An internal combustion engine is a piece of machinery that converts chemical energy into mechanical energy via a combustion process. Fuel is burned in a sealed chamber and the temperatures and pressures from the chemical reaction force a piston downwards in a linear motion, which is converted to rotational motion via a crankshaft. The produced power is then transmitted to the wheels of the vehicle via the drivetrain. This conversion of air and fuel into a radial force is a simple process, which involves complex variables and methods.

### 2.1.1 Basic Components

Despite the variety of available internal combustion engines, the one most commonly used in car and motorcycle applications is the 4 stroke, inline 4-cylinder engine. This engine employs 4 cylinders, arranged in a row. The largest assemblies in the engine are the cylinder head and block. These two separate assemblies contain many of the components required for power to be produced.

**The Cylinder Head:**

The cylinder head contains the camshafts, the valves, and all other associated hardware, such as springs and retainers. In order to maximize performance, designing the shape and size of the inlets and outlets of the head is a critical process. The selection of the camshaft to accompany the properties of these inlets and outlets is also important.

Nowadays, most cylinder heads contain camshafts that are built into the head. Engines with such a configuration are referred to as overhead cam engines. This design has historically been higher revving and higher flowing than the older, cam-in-block, “overhead valve (OHV)” engines. The Honda CBR600 F3, which is the engine used in the project, is a dual overhead cam (DOHC) engine. This engine configuration is optimal for the high RPM, high flowing requirements of a motorcycle engine.

## The Engine Block:

All of the thermodynamic work is performed in the engine block. The engine block is the assembly that contains the pistons, the connecting rods, the crankshaft, and all other associated bearings and hardware. The piston fits inside the cylinder walls and is connected to the crankshaft by the connecting rod. Combustion occurs on the face of the piston and the increased pressure forces it to linearly push down on the connecting rod. The connecting rod then transfers the linear motion into the crankshaft which then converts that energy into rotational motion.

## The Piston:

The piston is the component that attaches to the connecting rod. This cylindrically shaped object is typically made of an aluminum alloy, which often contains elements such as copper, magnesium, and silicone, to name a few. Pistons can be cast or forged. The amount of silicon in a piston determines if it is termed hypereutectic, eutectic, or hypoeutectic. Most performance vehicles use hypereutectic (containing at least 16-18% silicon) as this results in a lower rate of thermal expansion. The necessity to control the thermal expansion originates from the heat ranges that the piston is exposed to. The vehicle needs to be able to start when temperatures are below $0^{o}$F and it also needs to be able to withstand very high combustion temperatures. The most common type of piston is the eutectic piston, which contains about 12.5% silicon. A forged piston is typically stronger than a cast piston, as well as being more ductile. With this being said, forged pistons are more capable of withstanding detonation and they can generally be used in higher horsepower applications. The equation used to find the maximum force that a piston experiences is the one seen below in 'Eq. 1'

$$Max\ Force\ on\ Piston = (Max\ Combustion\ Pressure - Crankcase\ Pressure) * \left(\frac{Piston\ Diameter}{4}\right)^2 * \pi \quad [Eq. 1]$$

### The Connecting Rod:

The forces from the pressures due to combustion are transmitted to the crankshaft from the piston by the connecting rod. The connecting rod is typically made of a stronger material, since weaker materials such as aluminum would most likely fail. Forged connecting rods are recommended for forced induction applications as they can take more stresses than other, more basic types. The connecting rod is a fairly simple component that connects the piston on the "small end" by a wristpin and also connects to the crankshaft on the "big end" by the use of a cap. Oiled journal bearings are used in between the crankshaft and the rod in order to minimize friction. Compromising the proper functionality of these bearing usually results in complete engine failure.

### The Crankshaft:

The crankshaft transmits the linear motion from the piston into the rotational motion required to eventually rotate the wheels of the vehicle. The crankshaft mounts to the block, from below, by a set of caps. Journal bearings are used here as well, in order to reduce frictional losses. The camshafts, which control the opening and closing of the valves, as well as other critical accessories, such as the oil pump, are all indirectly connected to the crankshaft through the timing belt or timing chain.

## 2.1.2 Theory of Operation

In a dual overhead cam, inline 4-cylinder engine, which employs the Otto cycle (typical gasoline cycle), operation is fairly straightforward. A charge of air enters the cylinder through the open intake valve. The intake valve opens due to the displacement caused by the lobe on the camshaft. The charge enters the cylinder due to a combination of the vacuum created by the moving piston, as well as the higher pressure (boost) associated with the presence of a forced induction system. In addition, to a lesser extent, the low pressure behind the exhaust leaving through the exhaust valve during valve overlap can also increase the amount of charge flowing into the cylinder.

After the air/fuel mixture enters the engine, the piston continues to lower until it has reached bottom dead center (BDC). The intake valve then begins to close as the piston rises in the cylinder. This is called the compression stroke. The air/fuel mixture continues to increase in pressure until the position has been reached, in which the spark plug is fired. This ignition point is decided upon by the ECU and is based on multiple factors. At this point, the air/fuel mixture begins to combust, which produces very high temperatures and pressures. As a result, the generated force pushes down on the piston and continues to do so until the piston has reached bottom dead center. This is known as the power stroke. At approximately the point where the piston reaches BDC, the exhaust valve opens. The piston then rises and pushes the high temperature combustion products out of the cylinder. This is known as the exhaust stroke. When the combustion products leave the cylinder, they enter the exhaust manifold. If the engine is equipped with a turbocharger, the exhaust then enters the turbine housing radially and spins the turbine wheel of the turbocharger. The exhaust then leaves the turbine axially and continues to flow through the exhaust system until it reaches the ambient air outside of the vehicle.

The performance of an engine can be viewed in terms of its volumetric efficiency, which is discussed later on in this paper. The volumetric efficiency of an engine is simply the ratio of the actual mass of air inside the cylinder at a given instance, compared to the theoretical amount of mass, which can be held inside the cylinder. The goal of an engine designer is to maximize the volumetric efficiency of the engine for the typical RPM range, in which the vehicle operates.

### 2.1.3 Areas of Improvement

**Efficiency:**

The efficiency of the engine could be increased in many different ways. One way is to increase the compression ratio of the engine. Theoretically, a higher compression ratio will always result in a more efficient engine operation. However, too high of a compression ratio can result in detonation, especially when coupled with a turbocharger. Therefore, there are limitations set on selecting the compression ratio of an engine, which are based on the octane of the fuel that will be in use and the amount of airflow through the engine, per revolution.

Another way to increase the efficiency of the engine is to improve the quality of the intake charge, so that more of it is used up in the combustion reaction. The more charge that is left after the reaction, the less efficient the process is. This can be achieved by distributing fuel more effectively (improved mixing), by lowering the temperature of the charge, and by designing the head, so that the charge gets distributed evenly in the combustion chamber.

#### Effect of Restrictor on Turbo-System:

When an FSAE mandated restrictor is used, there becomes a set mass flow value that cannot be surpassed. At lower engine speeds, the pressure drop caused by the friction due to the restrictor (as well as the effect of friction on volumetric efficiency) is not very noticeable. However, at higher engine speeds, the flow through the restrictor will approach the speed of sound and the restrictor will begin to choke, which has significant implications on the power output of the engine.

## 2.2 Turbo-System

### 2.2.1 Basic Operation

A turbocharger (turbo) is a piece of rotating machinery that consists of a compressor, a turbine, and a center housing rotating assembly (CHRA). It is powered by kinetic and heat energy contained in the exhaust stream flowing from an engine. The high temperatures and high pressures generated during combustion create a differential in pressure and temperature between the inlet and the outlet of the turbine. This differential accelerates the turbine and therefore the compressor, which is connected to the turbine via a common shaft. On the compressor end, the spinning wheel contains blades which are essentially curved airfoils. These airfoils provide lift and therefore pressure is increased. As pressure increases, airflow is also increased. This enables the engine to produce more power per unit displacement.

### 2.2.2 Basic Turbocharger Design

Although turbocharger design varies from one manufacturer to another, all production model turbochargers contain a housed compressor wheel on one side and a housed turbine wheel on the other, which are supported by bearings in between. These bearings use seals, in order to prevent the high-pressure gases on both sides of the seals from contaminating the center assembly (CHRA), which houses the bearings. A generalized illustration of this can be seen below in 'Figure 1':

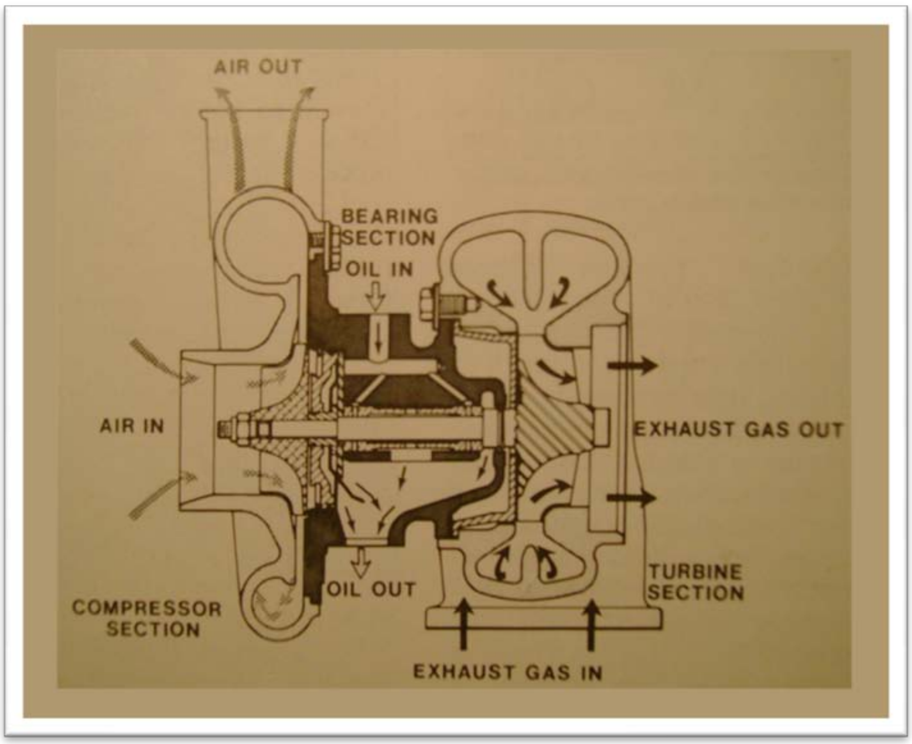



Figure 1 - Turbocharger Assembly

The compressor part of a turbocharger consists of three major components that must be matched for optimum efficiency – the impeller, diffuser, and compressor housing.

- The impeller rotates at very high speeds and its role is to accelerate the gas passing through it to a high velocity via centrifugal force.
- The diffuser acts as a nozzle in reverse to slow down the gas without causing turbulence. Doing so increases the pressure, compressing the air molecules together to

increase the amount of air going into the engine in a certain volume. Doing so unfortunately also increases the temperatures.

- The purpose of the compressor housing is to collect and direct this pressurized air.

There have been multiple, widely used impeller designs. The most basic one and the least efficient is the $90^o$ straight blade design, as seen in 'Figure 2'. This type of an impeller has not become very popular due to its low efficiency caused by shock losses at the inlet. It however is very easy to manufacture, which makes it the cheapest variation.

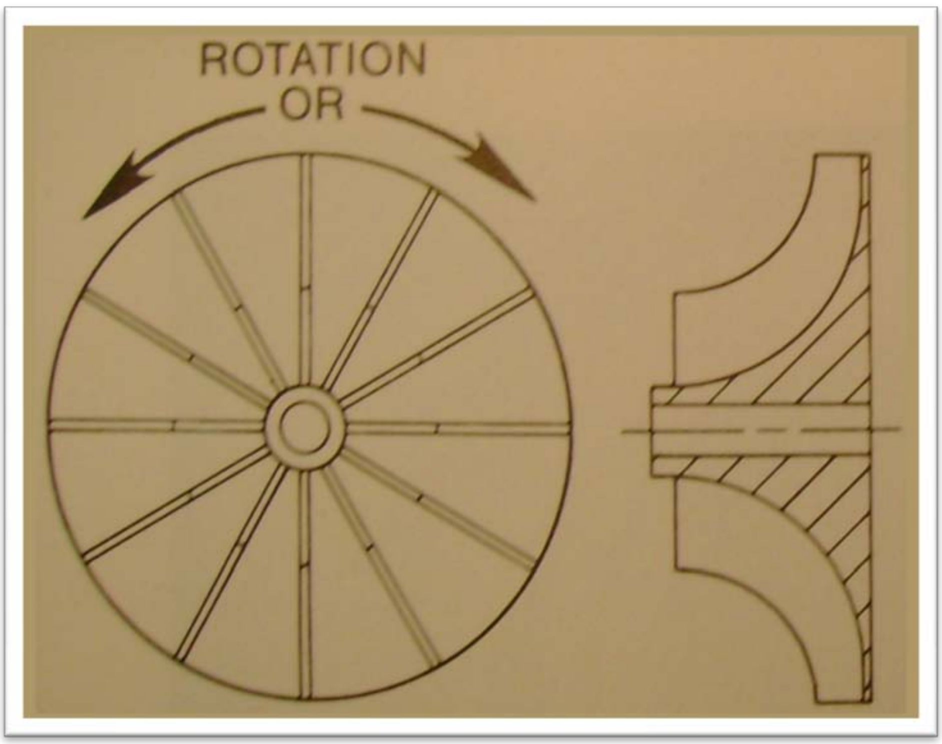



Figure 2 - Straight-Blade Impeller

The designs used today are different in the way the blades are shaped. Instead of being straight, the blades are curved, so that the air entering the impeller will be at approximately the same angle as the blades. This condition reduces the inlet losses and improves the efficiency. 'Figure 3' shows the general idea behind this revision. This type of wheel was originally much harder to manufacture because it required a separate plaster core for each gas passage and each core was pasted together by hand. This process has been greatly improved and simplified since then and therefore, the cost has come down significantly.

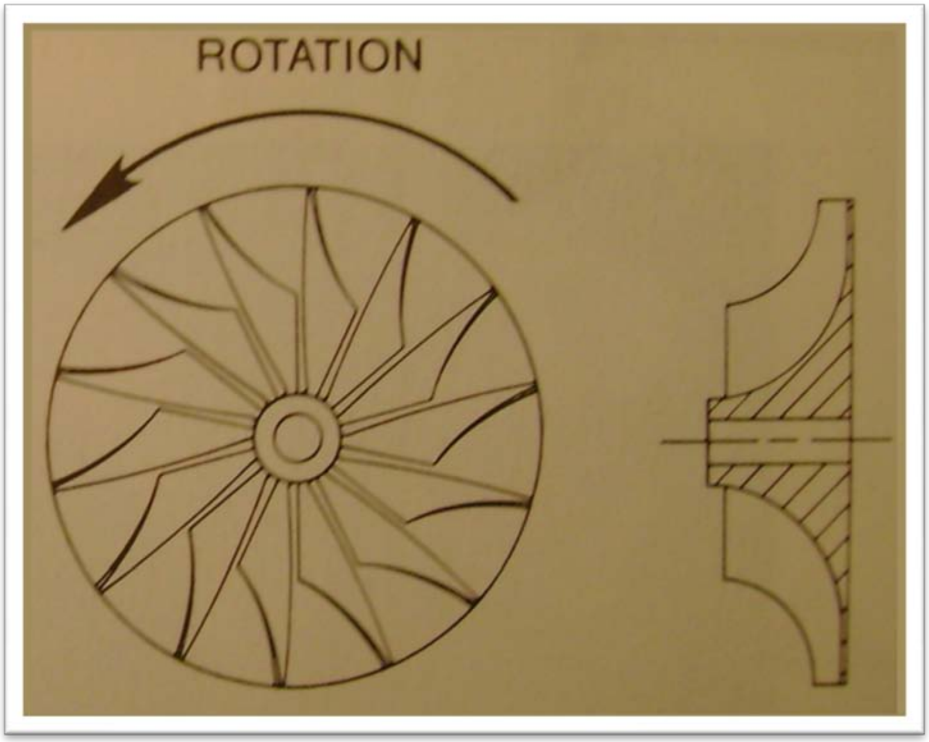



Figure 3 - Curved-Blade Impeller

There are different ways a blade can be curved. Some increase the efficiency and other are able to pressurize the air better and therefore increase the amount of boost. Most manufacturers today tend to settle for the more efficient, lower-boost turbochargers since they are used on most production cars.

As mentioned above, diffusers are used to increase the static pressure of the gas in the compressor. There are two major types of diffusers – scroll type and vane type. The preferred one is the scroll type since it is simpler and gives great results. It can be seen in 'Figures 4 and 5'. It appears that the diffuser is the entire housing but in actuality, only a part of the housing diffuses the air and therefore the two should be thought of as different components.

Figure 4 - Scroll-Type Diffuser

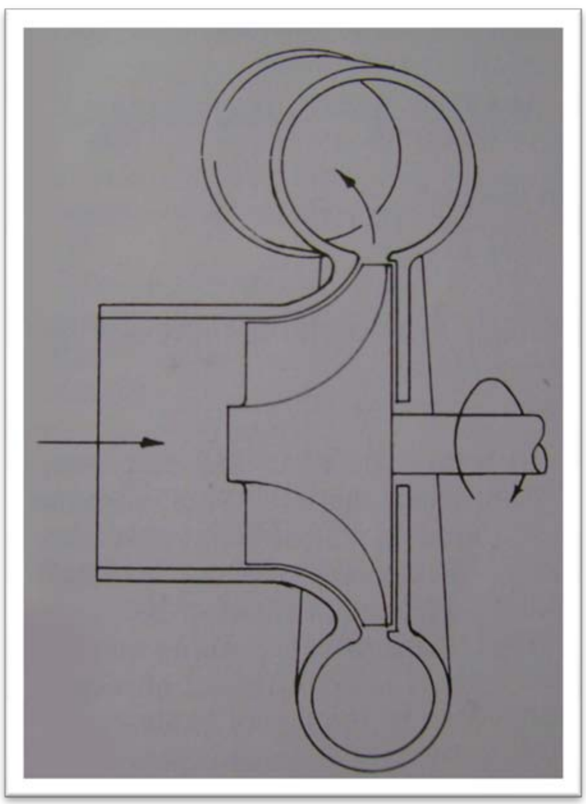


Figure 5 - Scroll-Type Diffuser - Cross Section View

The other commonly used diffuser is the vane type, which uses vanes designed to align with the direction of the gas flowing from the impeller ('Figure 6'). The vane curvature guides the gas to flow in a certain direction and slows it down to a certain degree, which is usually calculated to favor a certain horsepower or torque goal. These compressors are more efficient but more expensive and they also can work with a narrower range of engine displacements. On the turbine side, this approach is referred to as a variable nozzle turbine (VNT).

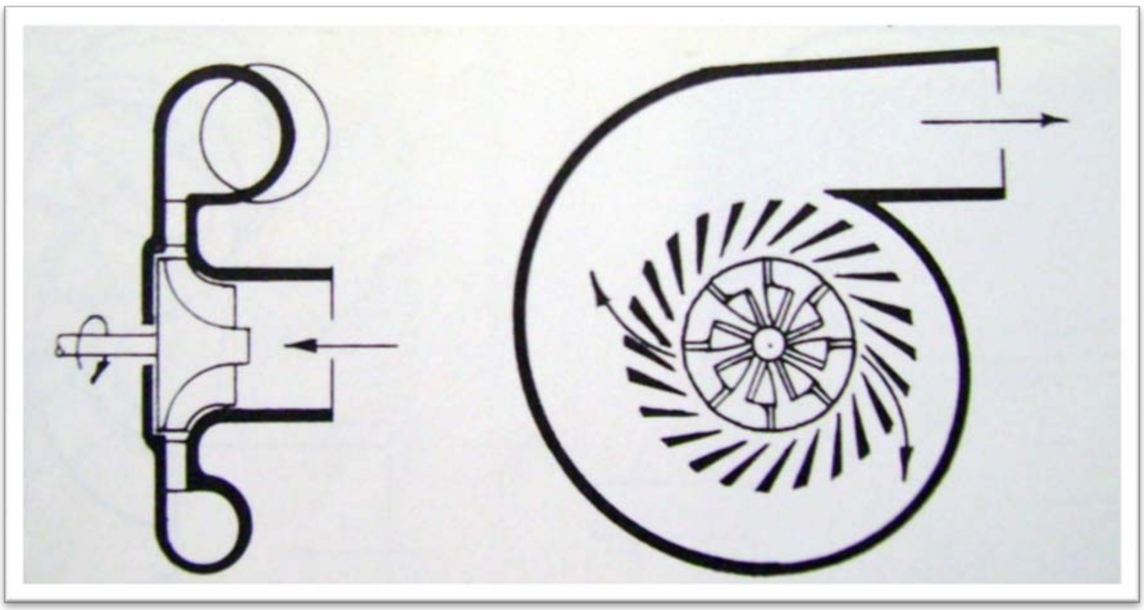


Figure 6 - Vane-Type Diffuser - Cross Section View

The turbine part of a turbocharger contains the same exact components. The difference there is the fact that their function is reversed. Therefore, the same basic information mentioned above can be used in designing the turbine.

### 2.2.3 Governing Equations

**Thermodynamic Equations:**

Pressure Ratio:

$$\frac{P2}{P1} = (\frac{T2}{T1})^{\frac{\gamma}{(\gamma-1)*\eta}} \quad [Eq. 2]$$

Density Ratio:

$$\frac{\rho 2}{\rho 1} = \left(\frac{P2}{P1}\right) * \left(\frac{T1}{T2}\right) \quad [Eq.3]$$

Compressor Outlet Temperature:

$$T2 = T1 * \left(\frac{P2}{P1}\right)^{\left(\frac{\gamma - 1}{\gamma * \eta}\right)} \quad [Eq.4]$$

Compressor Outlet Density:

$$\rho 2 = \rho 1 * \left(\frac{P2}{P1}\right) * \left(\frac{T1}{T2}\right) \quad [Eq.5]$$

Absolute Pressure:

$$P_{Absolute} = P_{Gauge} + P_{Atmospheric} \quad [Eq.6]$$

Nomenclature:

P2= compressor outlet pressure

P1= compressor inlet pressure

ρ2= compressor outlet density

ρ1= compressor inlet density

T2= compressor outlet temperature

T1= compressor inlet temperature

γ= ratio of specific heats for air (1.4)

η = compressor efficiency

**Geometry Equations:**

$$Compressor\ Wheel\ Trim = \frac{(Inducer\ Diamter)^2}{(Exducer\ Diameter)^2} * 100 \quad [Eq. 7]$$

$$Compressor\ A/R\ Ratio = \frac{Diameter\ of\ Outlet}{Radius\ From\ Turbo\ Centerline\ to\ Centroid\ of\ Outlet} \quad [Eq. 8]$$

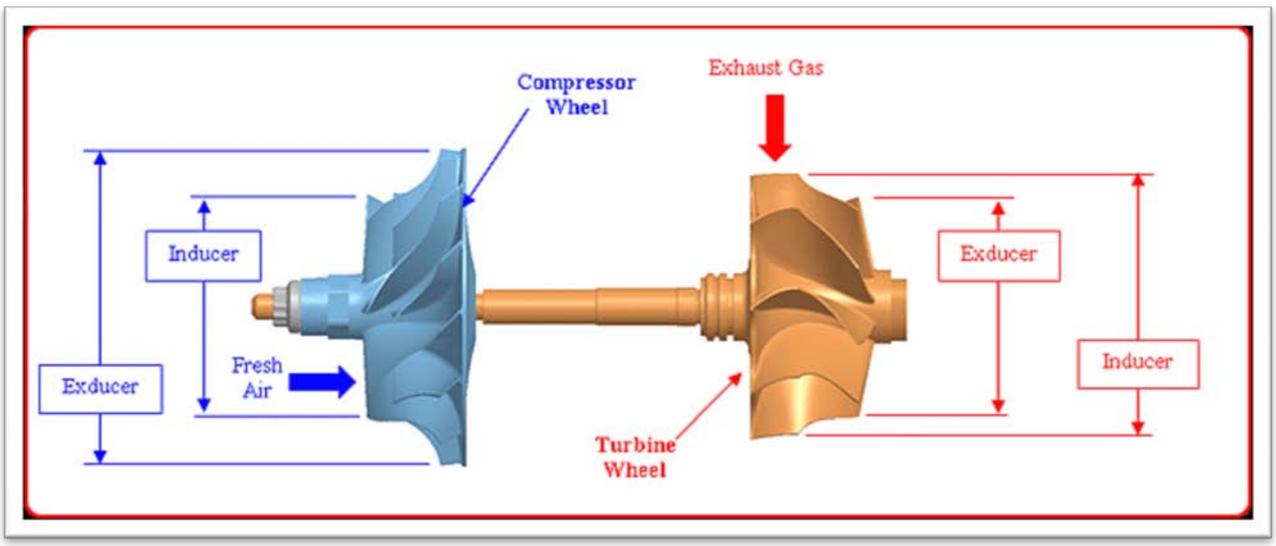



Figure 7 - Turbocharger Geometry Nomenclature

### 2.2.4 Automotive Applications

Turbochargers have been used in automobiles since the early 20th century. The use of forced induction allows for higher than atmospheric pressures in the intake manifold. This effectively increases the displacement of the engine. One of the largest drawbacks of an Otto cycle engine is the pumping losses created by having a throttle. With a smaller displacement engine, higher throttle angles (and therefore less pressure loss / pumping losses) are utilized, making the engine more efficient. The higher throttle angles (and forced induction) allow for a greater amount of air and fuel to enter the engine, in order to increase power output.

However, under lower load conditions, the engine can still run at lower manifold pressures. Therefore, using a turbocharger is a fairly simple way to extend the upper limit on the manifold pressure range (from idle to full boost) and therefore to increase the power produced by the vehicle. In this manner, a turbocharged 4-cylinder engine can perform the same duties as a 6-cylinder or even an 8-cylinder engine.

### 2.2.5 Turbo-System Accessories

#### Intercoolers:

Intercoolers are heat exchanger devices, which are used to transfer the heat from one fluid to another, without allowing the two fluids to make direct contact with one another. This is accomplished through an array of fins, which are typically made of highly conductive aluminum. Several examples of the design considerations for intercoolers are length, width, depth, material type, fin type, surface properties, end tank styles, pressure drops (both internally and externally), and location. Due to tight packaging constraints and generally lower flow rates, a smaller intercooler seems more fitting for this project. Since the expected pressure drop in the system is already large enough due to the restrictor, it was decided to use a design, which produces a minimal pressure drop ('Figure 9'). A decision was made to choose an intercooler used on a Volkswagen production vehicle ('Figure 8'), which was originally utilized to cool the charge exiting a turbocharger of a similar size to the one used in this project.

Figure 8 - VW Jetta Sidemount Intercooler

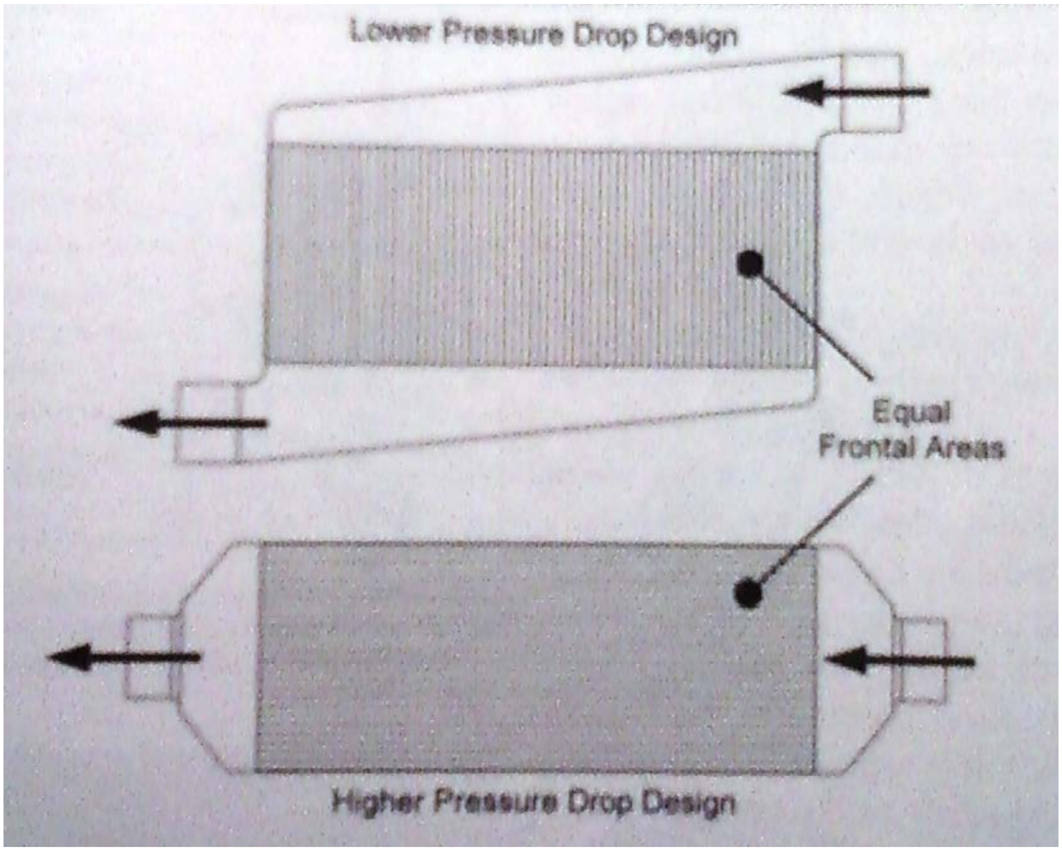



Figure 9 - Intercooler Types

### Wastegates:

A wastegate, also known as a turbine bypass valve, is a mechanical device used to bypass a fraction of the exhaust gases produced by the engine, so that they do not flow through the turbine housing of a turbocharger. In this manner, the rotating speed of the turbocharger and therefore the pressure output by the compressor can be controlled. There are two basic types of wastegates. The first and most common is the internally-gated type, which is built directly into the turbine housing. This makes for easier manufacturing and packaging, which usually lowers the associated cost. This design works well for most applications but it is usually not sufficient in higher flow situations.

The second type of wastegate is the externally-gated wastegate. This type of a wastegate is not built into the turbine housing, but rather it is installed at a point within the exhaust manifold. This location is usually the point where the individual runners meet, which is referred to as the exhaust collector.

All types of wastegates are composed of various devices, which allow them to convert a pressure differential into a mechanical force. This is accomplished through either a diaphragm-spring combination or a spring-piston combination. Either of these methods rely on a source of pressure from the intake manifold, which provides the force that opens the wastegate when a certain pressure is reached. 'Figure 10' below shows a diagram of a typical wastegate configuration:

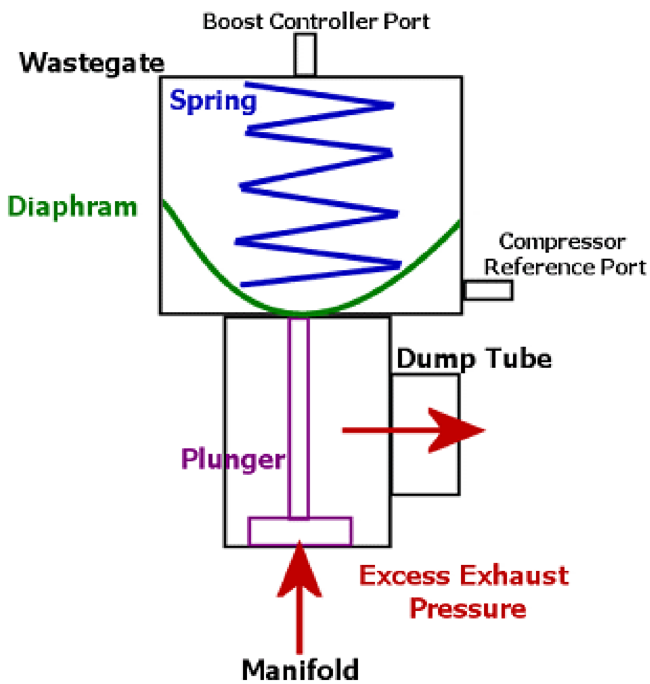



Figure 10 - Typical Wastegate Configuration

The team decided that the internally-gated wastegate, which comes standard on almost all small-size turbochargers, would be sufficient in this project. The benefits of an externally-gated wastegate would be the ability to have more control over the amount of exhaust flowing through the turbine. Based on this selection, issues might arise at higher engine speeds, due to the smaller magnitude of positive pressure in the intake manifold. This pressure from the manifold is relayed to the wastegate solenoid and then to the wastegate. If the pressure differential produced by the intake manifold is not greater than the spring pressure, then the wastegate will remain closed and continue to speed the turbocharger. If the turbocharger is spun at too great of a speed, it could possibly damage itself, as well as damage other components. This is known as turbocharger overspeed.

During a turbocharger overspeed, one method of failure is due to the temperatures in the bearing housing. When the temperatures are too great, the temperature of the oil becomes very high and its effectiveness as both a lubricant and a dampener are compromised. This usually results in the turbocharger shaft becoming 'welded' onto the bearings and seizing to rotate completely. The other dangers of overspeeding the turbocharger would be due to reaching various levels of vibrations within the turbocharger. Certain rotational speeds can cause various instabilities, which can produce displacements between the shafts and bearings. When this occurs, the tips of the compressor blades can physically touch the compressor housing, causing permanent damage to both components.

## 2.3 Engine Management System

### 2.3.1 Purpose

Engine management systems (EMS) have many names. They are called ECUs (Engine Control Unit), ECMs (Engine Control Module), and PCMs (Powertrain Control Module), to name a few, but they all have one responsibility - regulating the function of the engine. They are computers, running at millions of cycles per second, which monitor, calculate, and regulate engine operations. ECUs store numerous maps, which can generate an output for any given input produced by the sensors in the vehicle. The sensors and the ECU therefore act as a closed-loop system, which works well towards maintaining low emissions and a high combustion efficiency inside the engine. Unlike a carburetor, the ECU can adapt to virtually any condition automatically and instantaneously and that is what gives fuel-injected systems the advantage that has made carburetors fairly obsolete.

### 2.3.2 Related Hardware

The engine used for this project was converted from carbureted to fuel injected about a decade ago. Although the engine management system that has been in use since then is absolutely outdated when it comes to its computer interface, it remains very similar and capable in functionality when compared to the industry standards today. Therefore, the necessary hardware was already available on the car and very few changes were necessary.

In order to understand the closed-loop function of the engine management system, it is necessary to understand the function of the feedback mechanisms that the ECU relies on - the sensors. Sensors are devices that transform physical quantities into usable outputs. These outputs are primarily electrical and are received as inputs by the ECU, which uses this information to make various adjustments. Different types of sensors are used for different tasks. Therefore, they will also require a different method of interpreting a physical situation and translating it into a valid means of communication with the ECU.

Today, sensors seem irreplaceable but a few decades ago, sensors of this kind were rarely used. Their emergence came side by side with the use of engine management systems, which were developed to satisfy the newly mandated federal emissions regulations of that era. Ever since, sensors have been manufactured within very strict requirements. First, they have to be able to take accurate readings (usually, the allowed margin of error is within 1-3%). In addition, they also have to be precise, so that any two sensors will provide virtually identical outputs, which is necessary in order to ensure interchangeability. Finally, they must be able to endure a very wide range of temperatures, vibrations, and electromagnetic fluctuations. All of these combined ensure the quality and deliverability of the sensors found in the automotive market today, since they are vigorously tested before mass production.

### Throttle Position Sensor (TPS):

A throttle position sensor is used to monitor the position of the throttle plate, inside the throttle-body. It is usually attached to the rotation shaft of the throttle plate and its purpose is to sense rotation. In most cases, this sensor is simply a potentiometer, which is an electrical device that provides variable resistance based on its rotation. Variable resistance, in terms, results in variable voltage, which is normally the output that is read by the ECU. This sensor is critical for the operation of the engine, since the engine load depends on the airflow through the engine, which is regulated using the throttle body. 'Figure 11' below shows the schematic of a widely used throttle position sensor:

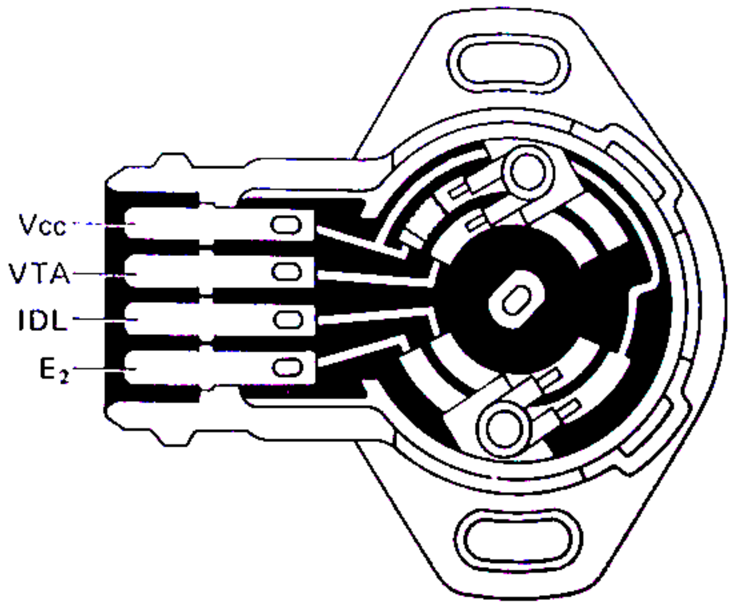



Figure 11 – Throttle Position Sensor Schematic

### Crank Position Sensor (CPS/KAS) / Camshaft Angle Sensor (CAS):

A crank position sensor is an electronic device responsible for determining the position of the crankshaft at any given instant. Identical to a camshaft angle sensor, the CPS usually consists of a rotating disk that is attached to the shaft of rotation. This disk contains one or more magnets, whose position can be determined by sensors located in the CPS assembly. Based on the magnetic field that the sensors experience, the position of the magnet(s) can be determined for any given instance. This generates a position and an angular velocity output, which is necessary in order for the ECU to fire the ignition coils at the correct angle of crankshaft rotation.

### Mass Airflow Sensor (MAF/MAS):

The function of the mass airflow sensor is to determine the mass of the air that enters the combustion chamber. This information is primarily used by the ECU in order to make open-loop fuel adjustments by manipulating the pulse width of the injectors.

In order to understand how the MAF works, it must be clear what it measures. Air is mainly comprised of 78% Nitrogen and 20% Oxygen. The remaining 2% consists of a variety of other gases such as Carbon Dioxide and Hydrogen. Air also has the property of retaining moisture (humidity) and the more water is present in a volume of air, the denser the air is. The density of air also changes with elevation, temperature, and pressure, so calculating the mass of air is no simple task.

There are three major types of mass airflow sensors:

- The first mass-produced mass airflow sensor was the vane type. It was a simple device which utilized a flap connected to a potentiometer. As more air enters the passage, the flap rotates further and further and the output of the potentiometer changes. This output is then used by the ECU as a way to estimate the airflow.
- The vane system was replaced fairly quickly by the 'hot-wire' sensor. This type of a MAF uses a wire, heated due to current flow. As more air flows around the wire, its temperature changes and its resistance drops. This fluctuation creates a change in voltage, so by monitoring the voltage output of the sensor, the ECU obtains an airflow reading.
- An alternative to the 'hot-wire' sensor is the 'cold-wire' sensor. It is primarily used in GM vehicles and it utilizes an oscillator circuit, which changes in frequency as more air flows over a tiny sensor. This is due to the sensor's inductance changing, which in terms affects the oscillation frequency – the output to the ECU.

There are several assumptions that are made by the modern sensors, which unless true, would yield faulty results. First, mass airflow sensors assume a smooth, laminar flow. Major turbulence could throw-off the reading substantially, so the position of the sensor should be chosen with careful considerations, in order to ensure the correct functioning of the sensor. In addition, the ECU assumes that all of the air that had passed through the MAF has entered the engine and that additional air is not drawn through some other part of the intake system, which is not monitored by the MAF. In other words, air leaks and especially positive pressure leaks (boost leaks) should be avoided for the sake of the proper overall operation of the engine. Luckily, most cars also have oxygen ($O_2$) sensors, which are used as a backup to check on the fuel adjustments made by the ECU. Unfortunately, their functionality is limited, so fully relying on an $O_2$ sensor to compensate for an erroneous MAF is not recommended and it is most likely not possible.

The MAF also requires an intake air temperature (IAT) sensor and a Barometric Ambient Pressure (BAP) sensor in order to operate properly. Without these sensors, the ECU will have to assume a certain ambient air density, specific to a unique condition, which will be erroneous in most situations. This would throw-off the calculation and corrupt the fuel adjustment, forcing the ECU to rely primarily on the closed-loop feedback of the $O_2$ sensor.

Some systems utilize a manifold absolute pressure (MAP) sensor, mounted in the intake manifold, which can be used to automatically calibrate the reading of the MAF. This is done by comparing theoretical manifold pressures calculated by the ECU and the actual pressure as measured by the MAP. The percentage difference between the two is then used as an offset variable, which is an additional adjustment to the fuel settings. The MAF could get miscalibrated due to leaks, aftermarket parts, or simple wear due to aging.

Finally, it is necessary to mention that most MAFs do not produce a linear output. Instead, they produce a concave-up curve, as seen below in 'Figure 12'. This has no impact on its ability to generate a single output for a single input. Instead, it makes it harder to predict a given voltage from a known airflow and vice versa.

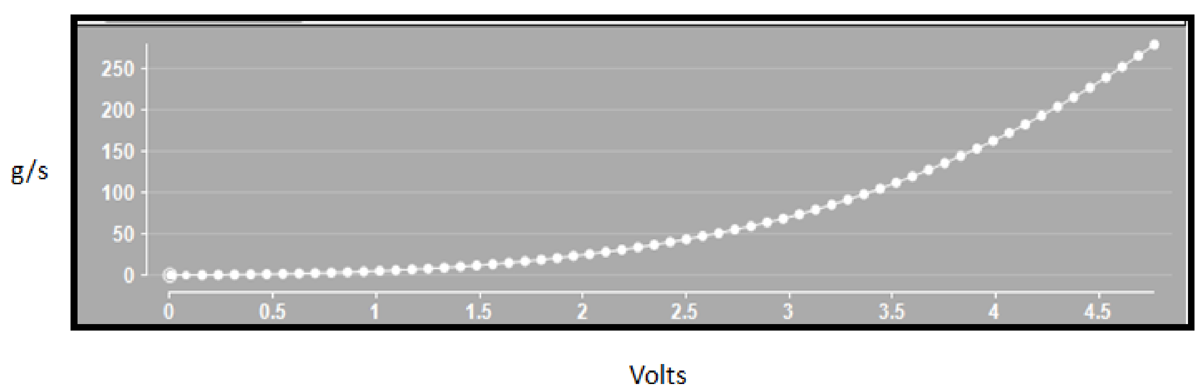



Figure 12 – Mass Airflow Sensor - Output Graph

### Manifold Absolute Pressure (MAP) Sensor:

The function of a MAP sensor is to measure the absolute pressure in a given environment. The first step in understanding how it works is to be able to differentiate between absolute and gauge pressure. Absolute pressure is the observed pressure with respect to vacuum. The Earth is surrounded by an atmosphere, which is comprised of multiple types of gases. Gases flow and are therefore considered fluids. Every type of fluid has weight (in the presence of gravity) and therefore the atmosphere exerts its weight on the environment. This pressure due to the weight of the atmosphere is called the ambient pressure. At sea level, ambient pressure is 14.7psia or 1 atmosphere. Gauge pressure is the pressure measured in a pressurized system, which is zero-referenced against the ambient pressure. The formula that can be used to reference these three types is the following:

$$Absolute\ Pressure\ (psia) = \ Gauge\ Pressure(psig) + \ Ambient\ Pressure(psia) \quad [Eq. 9]$$

So what do these mean in the automotive world? Turbocharged cars usually have boost gauges, which are used to measure the pressure that the turbocharger is generating when compressing the intake charge. These gauges read gauge pressure. Therefore, if a boost gauge reads 20psig at the intake manifold then the absolute pressure at the manifold is actually:

$$20psi\ (gauge) + 14.7psi\ (ambient) = 34.7psi\ (absolute)$$

Naturally aspirated (NA) cars have a manifold pressure equal to the ambient pressure, so a MAP sensor in an NA car would ideally read 14.7psi at sea level.

Using a MAP sensor serves three primary purposes:

- First, it can be used for logging pressure in aftermarket automotive applications. This is not the reason why this sensor was developed but this function does prove to be quite convenient.

- Second, the MAP can be used to compare the ECU-calculated pressure estimate to the real pressure reading, in order to determine if the MAF that the car uses may be miscalibrated. This helps by improving the fuel adjustment accuracy in the cases where air leaks are present.
- Third, MAP sensors are often used together with IAT sensors in a speed-density system. Speed-density is an alternative to a MAF and it measures the mass of air that flows into the combustion chamber. (More on Speed Density in 'Section 2.4.3')

MAP sensor are entirely linear, so in addition to producing a single output for a single input, the voltage produced can be predicted by knowing a given pressure and vice versa. This relationship can be seen in 'Figure 13' below:

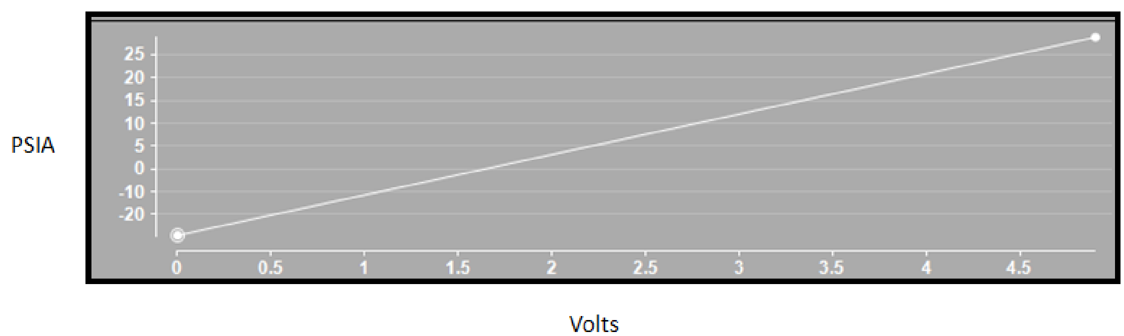



Figure 13 – Manifold Absolute Pressure Sensor - Output Graph

### Intake Air Temperature (IAT) / Coolant Temperature Sensor (CTS):

Intake Air Temperature (IAT) sensors are used to measure the temperature of the intake charge of a vehicle. This is critical since air temperature directly affects charge density and burn rate. The colder the air, the denser it is. Higher density means that a larger amount of air molecules are available to react with the fuel molecules, which in terms would imply a bigger combustion reaction and, therefore, more power. IATs are used together with either a MAF or a MAP sensor (for speed-density) in order to calculate the mass of air that flows into the cylinders.

These sensors are very similar to Coolant Temperature Sensors (CTS). The only significant difference is that they are unshielded, unlike a CTS, because they are not exposed to extensive heat. They work by varying the voltage output in a circuit through the change of resistance brought about by different temperatures.

Just like MAF sensors, these sensors do not produce a linear relationship between the input and the output. Instead, they produce a concave-up curve, which becomes mostly linear as voltage increases. This relationship can be seen below in 'Figure 14'.

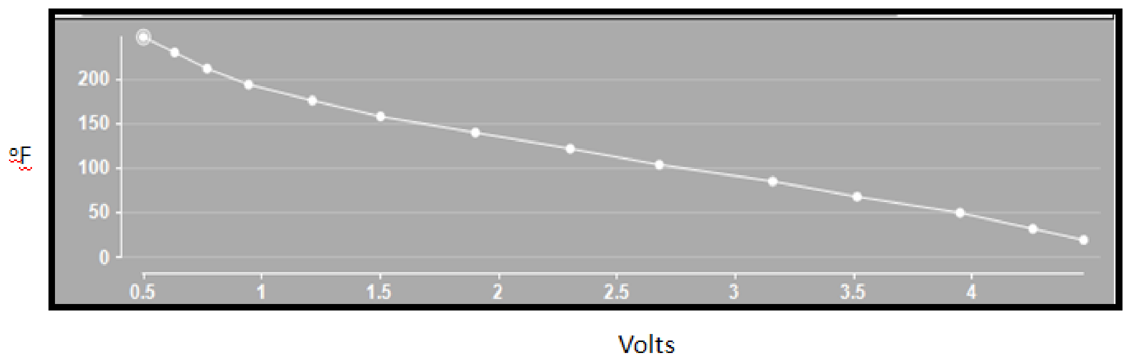



Figure 14 – Intake Air Temperature Sensor - Output Graph

### Knock Sensor:

In a spark-ignition engine, knock occurs when the combustion of the air-fuel mixture inside the cylinder starts off correctly, in response to the spark plug firing, but one or more pockets of this mixture explode outside the envelope of the normal combustion front. In other words, the air-fuel mixture does not burn properly but instead it explodes, causing much higher pressures and temperatures inside the combustion chamber. This condition is called detonation and the main reasons it occurs are the following:

- High combustion chamber pressures (high load)
- High intake temperatures
- High coolant temperatures
- Low octane fuel
- Excessive turbulence in the combustion chamber

Knock sensors are tuned to listen for a specific frequency, depending on the engine block and its components. This frequency is generated when the block begins to resonate due to the increased pressures in the combustion chamber(s). When this frequency is reached (typically 4,000Hz - 11,000Hz), a piezoelectric crystal inside the sensor is agitated, producing voltage. This voltage is received by the ECU and adjustments are then made, in order to prevent engine damage.

### Oxygen ($O_2$) Sensor:

The Air/Fuel Ratio (AFR) of an engine is the mass of air divided by the mass of fuel during combustion. $O_2$ sensors are designed to check the composition of the exhaust gas being analyzed, in order to determine what portion of the gas is comprised of air. This is crucial when it comes to monitoring the combustion process, which in term is necessary in order to keep a certain balance between performance, mileage, and emissions.

The sensing element of the $O_2$ sensor is made of a ceramic cylinder, plated inside and out with platinum electrodes. This element is protected by a grounded metal gauze. One side of the ceramic cylinder is exposed to exhaust gases and the other to ambient air. Depending on the mixture of the exhaust gases and the conditions inside the exhaust pipe, different amounts of air will flow through the cylinder, thus changing its resistance and inducing voltage. This flow occurs due to a process called molecular diffusion, in which molecules in a region of higher concentration will be transported to a region of a lower concentration. The lower concentration region in this scenario is the exhaust piping and the oxygen concentration in this piping could vary depending on various engine conditions. Therefore, oxygen sensors do not directly measure oxygen concentration but instead, they send a reading to the ECU and the ECU makes all the necessary calculations, in order to get an estimate of the Air/Fuel Ratio.

Oxygen sensors also require being heated in order to work properly. In the past, some of them relied on the exhaust temperature to get to their required temperature but nowadays, it would be very rare to see an $O_2$ sensor without a built-in heating element, since they get up to temperature very quickly and there is very little lag in the closed-loop process when the vehicle was just started.

There are two types of oxygen sensors – narrowband and wideband. Narrowband sensors do not produce a linear output for a given AFR and, therefore, they are only accurate for a narrow range around 14.7:1 AFR (gasoline), which is also called the stoichiometric reading. At 14.7:1, the oxygen atoms react completely with the fuel atoms and therefore, ideally, there are no left over air or fuel atoms. This is roughly where cars are designed to idle and operate at low throttle. This is why narrowband sensors only target this value and its immediate range. When the mixture becomes rich or lean, it is virtually impossible for a narrowband to estimate the AFR. This can be better understood using the graph shown in 'Figure 15' below:

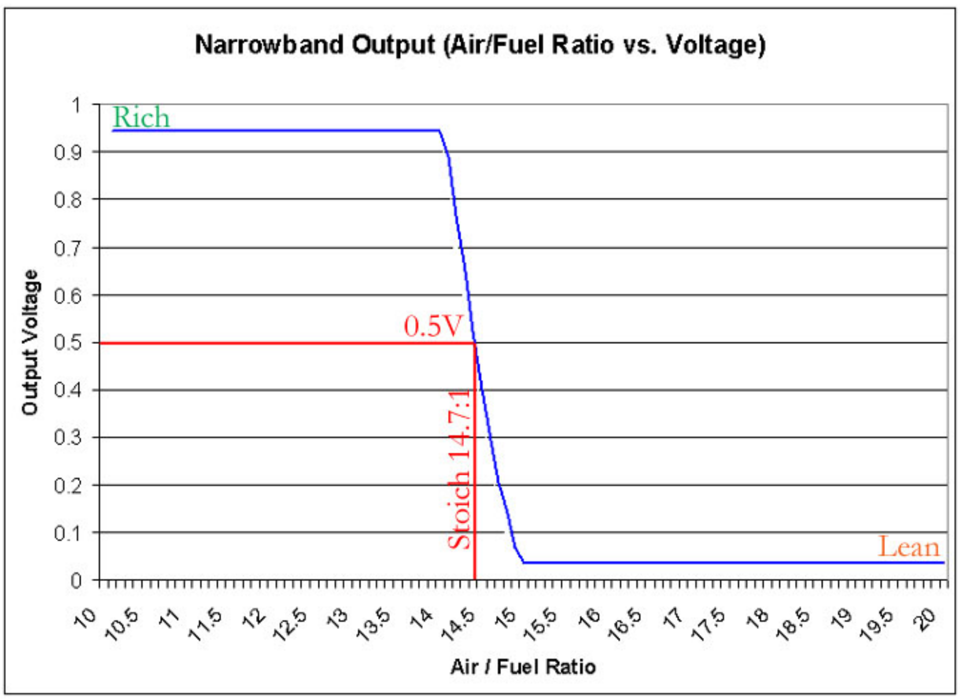



Figure 15 – Narrowband $O_2$ Sensor – Output Graph

Wideband $O_2$ sensors work slightly different. They incorporate an electrochemical gas pump, which delivers oxygen into a measuring chamber, instead of relying on diffusive flow. This way, measuring the air concentration becomes very much direct and the sensor does not need to communicate with the ECU in order to estimate an AFR. Wideband sensors are also able to produce a specific output for a given oxygen concentration, which makes it possible to obtain an AFR reading for a range much wider than the one of a narrowband. ‘Figure 16’ shows an example output graph of a wideband:

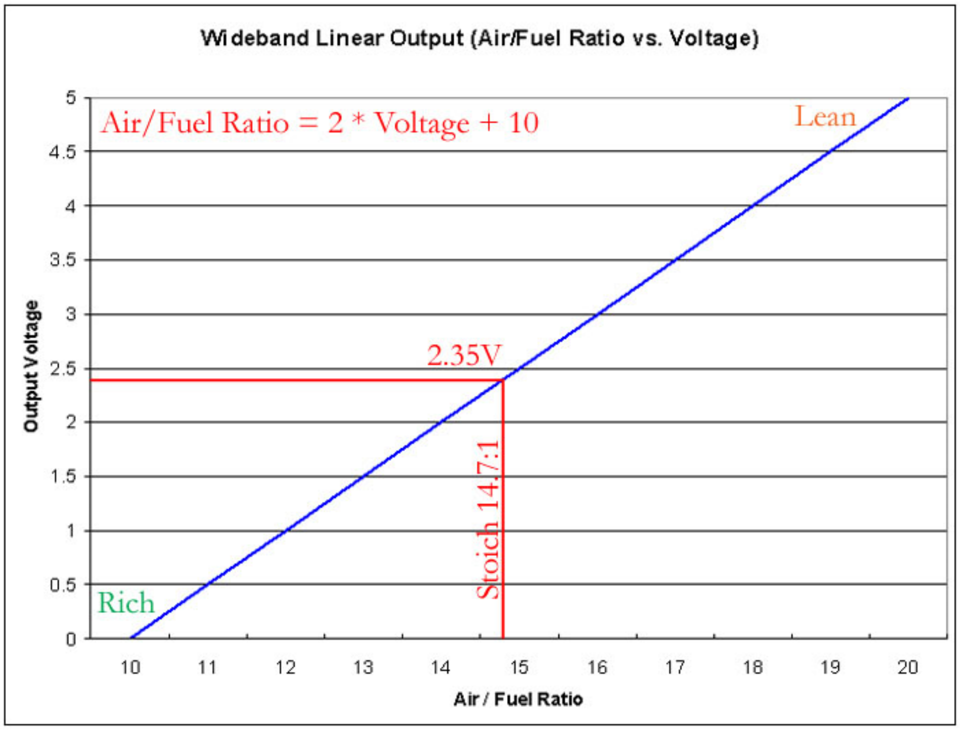



Figure 16 – Wideband $O_2$ Sensor – Output Graph

An alternative method of measuring the Air/Fuel Ratio is through a variable called lambda. Lambda has a value of 1 at 14.7:1 AFR (gasoline). Therefore, lambda is a way of comparing the gas concentration to the stoichiometric ratio. For example, 11.7:1 is a lambda value of 0.8 and 17.68:1 is a lambda value of 1.2. Therefore, a lambda value lower than 1 means a rich mixture and a value higher than one equates to a lean mixture. Understanding lambda is quite necessary when using fuels that do not contain 100% gasoline, which is by no means uncommon. The average 93 octane sold at a gas station in the North-East contains 10% ethanol. This means that the stoichiometric ratio of this fuel is no longer 14.68:1 (for 100% gasoline) but instead 14.0:1 (90% gasoline, 10% ethanol). Luckily, narrowband sensors actually measure lambda instead of AFR. Therefore, whether the gas has a stoichiometric value of 14.7:1 or 14.0:1, its stoichiometric lambda would be 1 regardless and the closed loop operation will be unaffected. This is also valid for other fuels such as E85, where lambda of 1 is actually 9.87:1 AFR. If the narrowband measured AFR, then the ECU would see a very rich mixture and it would max-out the fuel trims, which are responsible for offsetting fuel delivery.

Most wideband $O_2$ sensors measure lambda. The ones which do not are either only used for a certain fuel or they have to be told what fuel is used in order to work correctly. The common wideband though does not need this information since it virtually re-calibrates itself to any given fuel mixture. Nevertheless, if 0.8 lambda were to be the goal for both 93 octane gasoline and E85, then E85 can be tuned to 11.7:1, since that is the value that the wideband would show (unless re-programmed to E85 scale). In reality though, 0.8 lambda for E85 is actually 7.9:1 AFR, so the Air/Fuel Ratio shown by the wideband is incorrect but still very functional.

## 2.4 ECU Tuning

### 2.4.1 Purpose

Whether a vehicle is stock or modified, tuning it is an important step in maximizing its efficiency. A well-tuned car can yield more power, higher mileage, or even longer life, depending on what the goal of tuning is and depending on the efficiency of what process is being maximized. Therefore, it should be clear that different tunes are customized for different reasons and conditions.

So why doesn't the manufacturer optimize all of these at the factory? Because there is no way all three of these categories (power, mileage, component life) can be optimized without affecting one or more of the other two. Manufacturers usually settle for a mix of these three but this can vary depending on the vehicle. This is why, tuning can produce valuable improvements, given it is possible to sacrifice one of the other areas mentioned above.

### 2.4.2 Tuning Basics

Tuning is a complicated task, since so many different variables are involved. An improper tune can create a skyrocketing rise in emissions, it can lower fuel efficiency drastically, and it can even cause fatal damage to the engine. Therefore, tuning must be left to automotive engineers and professional tuners. Nevertheless, there are many hobbyists who manage to tune their personal vehicles with great success, which shows that tuning does not have to be such a complicated process, especially when the ECU does most of the work for the tuner.

Despite the fact that an ECU monitors dozens of variables and that it manages many more, there are two important elements that usually comprise the majority of tuning - fueling and timing. Assuming that regardless of tuning the airflow through the cylinders is constant and that the engine is not physically modified, then the power produced by the vehicle only relies on the amount of fuel inserted into the combustion chamber (Air/Fuel Ratio) and the ignition timing.

### Fueling:

The required fuel flow is calculated by the ECU as a function of the airflow measured by the MAF/MAS or by Speed Density (SD). The necessary fuel flow is obtained by 'Eq. 10' below:

$$Fuel\ Flow = \frac{Air\ Flow}{Air/Fuel\ Ratio} \quad [Eq. 10]$$

In other words, the ECU receives the airflow signal and then divides it by the pre-programmed AFR for the conditions specific to that instant. Next, based on the number of injectors and the properties of the injectors, the timeframe for which the injectors are kept open (pulse width) is calculated. If the AFR matches the ideal lambda value for this instant, the vehicle will make power most efficiently. If the AFR does not match, the vehicle will not only lose power but it can also be more susceptible to knock.

For maximum power, the goal lambda value is the rich best torque lambda, which for gasoline is roughly 0.86 lambda. This equates in an air/fuel ratio of roughly 12.6:1. Naturally aspirated cars can be tuned for this value safely. On 93 octane, a turbocharged car will most likely not be able to run this lambda value safely, since the increased pressures and temperatures due to the turbocharger make the system more susceptible to knock. Therefore, turbocharged cars usually require a lower rich best torque value, so that the vehicle can operate safely. This value is usually 0.78 lambda (11.5:1 AFR) or lower. 'Figure 17' and 'Figure 18' show lambda values with respect to power produced and fuel economy respectively:

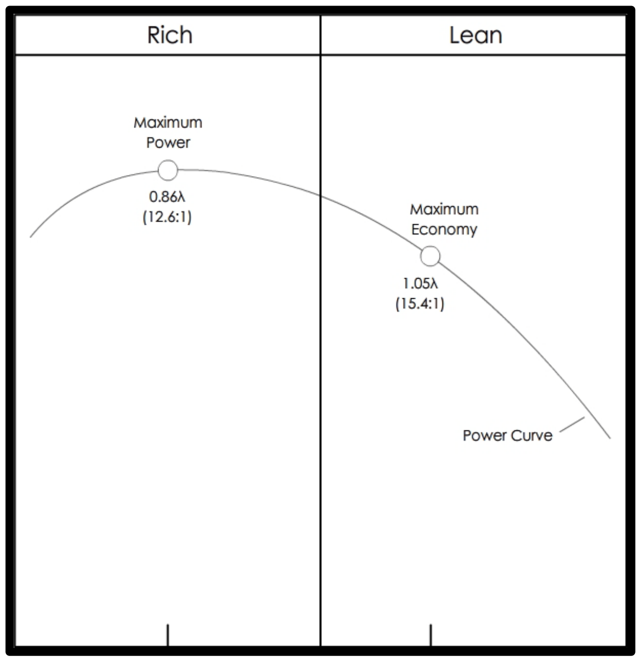



Figure 17 – Lambda vs. Power Produced

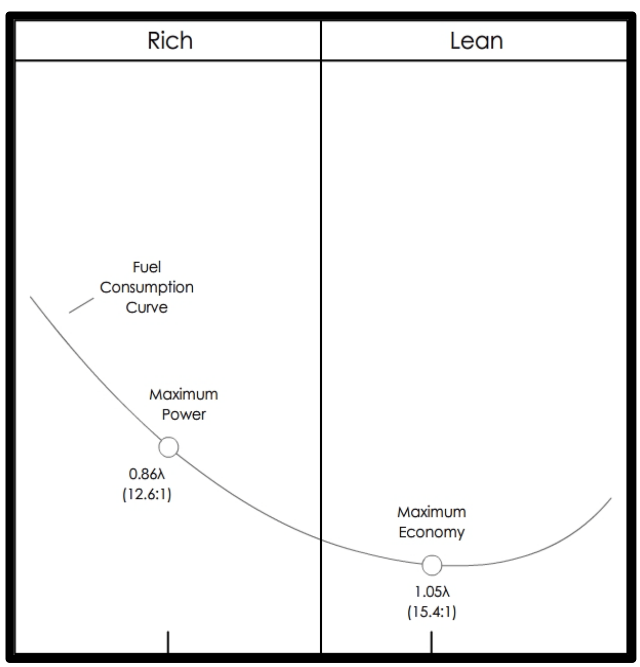



Figure 18 – Lambda vs. Fuel Economy

The reason why richening the mixture produces a more knock-resistant combustion is directly related to the laminar flame propagation speed for different lambda values, as well as the combustion temperatures for different lambda values. As fuel is richened, the flame speed and the combustion temperatures both drop. This trend continues as lambda is decreased but eventually the combustion reaction is required to run so rich that it becomes unstable. In such cases (usually below 10.0:1 AFR), rich detonation can occur. 'Figure 19' shows the relationship between flame speed and the equivalence ratio (inverse of lambda). 'Figure 20' shows the combustion temperature with respect to lambda.

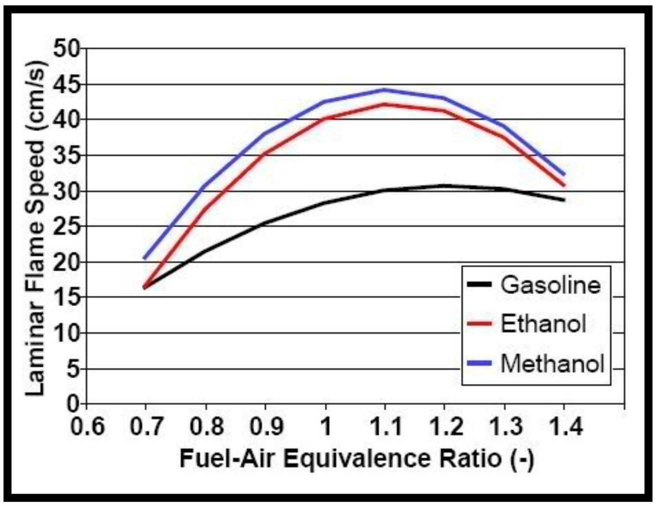



Figure 19 – Equivalence Ratio vs. Laminar Flame Speed

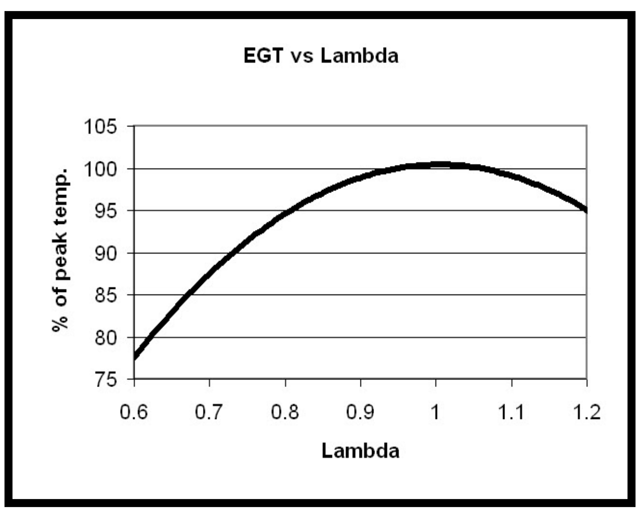



Figure 20 – Lambda vs. Combustion Temperature

### Ignition Advance:

Ignition timing is the other critical element needed to sustain an optimized, efficient combustion process. No matter what fuel is used, it will not burn instantaneously as the spark is fired. Instead, the flame front travels through the air-and-fuel mixture and eventually burns all of the fuel (ideally). This delay is the reason ignition timing is important. The spark must be fired a number of degrees before the piston reaches the topmost position in its travel - top dead center (TDC). This degree is known as the timing advance. If the spark is fired too early, the piston may not reach top dead center before the peak combustion pressure occurs and this can be very harmful to the engine components, since the fuel reaction is opposing the direction of movement. If the spark is fired too late, the pressure in the combustion chamber will not be as noticeable, since the piston is on its way down. In other words, low timing advance produces a larger reaction volume and therefore less torque. This results in a loss of power. Therefore, it takes careful consideration to determine what the ideal timing advance would be for any given engine. This can be best determined using a dynamometer since torque can be monitored. As timing is advanced, torque should increase until the peak timing advance is reached. After this point, the torque will begin to slowly drop, since more of the downwards force exerted by the piston goes towards bearing friction.

### 2.4.3 Speed Density

Speed Density (SD) is a very capable alternative to the industry-dominating Mass Airflow sensor (MAF/MAS) systems. Instead of directly measuring the mass of air, like a MAF/MAS, Speed Density relies on the inputs received from a Manifold Absolute Pressure (MAP) sensor and a Intake Air Temperature (IAT) sensor. Knowing these inputs and the Volumetric Efficiency (VE) of the engine at a given instant, the Speed Density calculation can accurately calculate the mass flow through the system.

In order to completely comprehend how Speed Density works, it is necessary to understand what Volumetric Efficiency signifies. Simplistically, VE is the ratio of the actual volumetric airflow (AVAF) through the engine, divided by the theoretical maximum volumetric airflow (TVAF):

$$Volumetric\ Efficiency\ (VE) = \frac{Actual\ Volumetric\ Airflow\ (AVAF)}{Theoretical\ Volumetric\ Airflow\ (TVAF)} \quad [Eq. 11]$$

The formula for calculating the TVAF can be seen below in 'Eq. 12':

$$Theoretical\ \ Volumetric\ Airflow\ (TVAF) = \frac{Displacement * RPM}{Engine\ Stroke * Correction\ Factor} \quad [Eq. 12]$$

For imperial units, the displacement used must be in cubic inches (CID), the correction factor is 1728 (to convert cubic inches to cubic feet), and the airflow units are cubic feet per minute (CFM). If metric units are to be used, the displacement is in liters, the correction factor is 1000, and the airflow units are cubic meters. Cubic centimeters (cc) can also be used for displacement but the correction factor has to be increased to 1,000,000. The airflow units will remain the same. Finally, regardless of units, the engine stroke value will be 2 for a 4-stroke engine and 1 for a 2-stroke engine.

Using the known VE value for a specific instant, as well as the real-time data received from the MAP and IAT sensors, the mass flow of the system at that given instant can be calculated. First, the actual volumetric airflow (AVAF) must be calculated. This is done by using the abovementioned equation for TVAF and multiplying its result by the VE. Here is an example:

*2005 Lancer Evolution XIII - 4 cylinder, 2.0L engine @ 7000RPM @ 95% VE*

$$TVAF = \frac{Displacement * RPM}{Engine\ Stroke * Correction\ Factor} = \frac{(2L) * (7000\ \frac{1}{min})}{(2) * (1000\,\frac{L^3}{m^3})} = 7\ \frac{m^3}{min}$$

$$AVAF = VE * TVAF = (0.95) * \left(7\ \frac{m^3}{min}\right) = 6.65\ \frac{m^3}{min}$$

Now that the volumetric flow rate is known, the mass flow rate can be obtained through the following equations:

$$Density = \ Ambient\ Density * \frac{Ambient\ Temperature}{Measured\ Temperature} * \frac{Measured\ Pressure}{Ambient\ Pressure} \quad [Eq. 13]$$

$$Mass\ AirFlow\ (MAF) = Volumetric\ AirFlow\ (AVAF) * Calculated\ Air\ Density \quad [Eq. 14]$$

The 'measured temperature' value would be the IAT reading, while the 'measured pressure' value would be the MAP sensor reading. It is critical to convert the values to the same unit system. For example, in the metric system, density would have units of kg/m$^3$, temperature would be in Kelvin (K), and pressure would be in Pascals (Pa). There are many available unit converters online, including Google Search.

Using the example above, the MAP sensor reads 25psig at 7000RPM, and at the same time the IAT reading is 90F. The ambient conditions are assumed to be 14.7psia for pressure and 68F for temperature. Changing units yields 172,369Pa, 305K for the charge air and 101,325Pa, 293K for the ambient air. Notice that the MAP sensor reads gauge pressure and therefore the ambient pressure must be added to its value, in order to produce absolute pressure. The MAP sensor reading, converted to PA will be:

$$172{,}369\ Pa + 101{,}325\ Pa = 273{,}772\ Pa$$

Inserting these values and assuming 1.204g/L for the ambient air:

$$Density = \ 1.204\ g/L * \frac{293\ K}{305\ K} * \frac{273722\ Pa}{101325\ Pa} = 3.125\ g/L$$

The last step is calculating the mass flow rate:

$$MAF\ = \ AVAF\ *\ Density\ = \left(6.65\ \frac{m^3}{min}\right) * \left(3.122\frac{kg}{m^3}\right) = 20.76\frac{kg}{min}\ or\ 45.77\frac{lb}{min}$$

# Chapter 3: Problem Statement

During the past decade, multiple groups at the Worcester Polytechnic Institute alone have tried to create a turbocharger system, which produces powerband gains that outweigh the added expenses and labor related with this process. This has been done in hopes of gaining slight advantage over the rest of the teams competing in the Formula SAE competition but unfortunately, the results have been rather discouraging. The objective of this project is to design such a turbocharger system from the ground up and to achieve the success that the other teams have failed to find. This way, any future teams that build an FSAE race car for WPI will have the ability to duplicate the system and ideally produce the same powerband gains.

# Chapter 4: Methodology

## 4.1 Initial Steps

The very first step that was taken towards completing this project was to assess the condition of the FSAE vehicle in its naturally aspirated configuration and to bring it back to operating ability. The car needed little work to be able to start and rev properly. Once this was accomplished, the vehicle was taken to 'New England Dyno & Tuning', located in Douglas, MA, where it was placed on a dynamometer in order to obtain baseline readings.

A dynamometer (dyno) is a device that measures the horsepower and torque output of a vehicle, after it has experienced the losses associated with the vehicle's drivetrain. It does so by measuring the angular acceleration of the drum that the vehicle drives (DynoJet). Through knowing several other variables, the torque produced at the wheels of the vehicle is calculated. Horsepower is then derived from this torque value.

At the dyno, the vehicle produced 66 horsepower and 33 lb*ft of torque (at the rear wheels). The timing advance was set to 32 degrees and the car was revved to 11,000 RPM, at which point it recorded its peak horsepower. These numbers were used to compare the before and after results of this project, which would therefore allow the team to determine the level of success of this project.

## 4.2 Engineering Decisions

### 4.2.1 Turbocharger Selection

After the thermo-fluid analysis was completed, it was determined that a small selection of turbochargers were available that suited this application. The primary limitation for the selection would be the mass flow rate allowed by the restrictor. This was cited by the manufacturer of the restrictor (through CFD analysis) to be about 80 grams per second (10.5lb/min). Once this flow value is reached, the restrictor will develop shockwaves as the air stream reaches the speed of sound. 'Eq. 15' below shows the mass flow rate as a function of the discharge coefficient, density, velocity, and area:

$$Mass\ Flow\ Rate = Discharge\ Coefficient * Density * Velocity * Area \quad [Eq. 15]$$

A basic calculation using the speed of sound as the maximum velocity and 0.7 (typical) for the smooth entry restrictor discharge coefficient yields a maximum flow of 81g/s, which only confirms the data received from the manufacturer:

$$Maximum\ Mass\ Flow\ Rate = 0.7 * \frac{1.2kg}{m^3} * \frac{340m}{s} * \left(.\frac{019m}{2}\right)^2 * 3.1415 = \frac{81g}{s}$$

With these theoretical numbers in place for the maximum flow condition, the team weighed the benefits and drawbacks of each of the available compressors. 'Table 1' below shows the 'pros' and 'cons' for each of the turbochargers considered to be used in this project. In addition, compressor maps were acquired and compared from the various turbocharger manufacturers. Those can be viewed in 'Appendix 3: Turbocharger Selection – Compressor Maps'.

| **Manufacturer** | **Model** | **Max Flow (g/s)** | **Price** | **Pros** | **Cons** |
|---|---|---|---|---|---|
| Garrett | GT12 | 98 | Free | Simplicity, availability | Somewhat large |
| Garrett | GT15VNT | 91 | Free | Variable Nozzle Technology (VNT) | VNT Control Complexity |
| Borg Warner | KP31 | 65 | $1,000+ | Quickest Spool | Slightly too small, Europe only |
| Borg Warner | KP35 | 93 | $1,000+ | Aero Match | European lead time / cost |

Table 1 – Turbocharger Selection Table

The KP31 was eliminated since it was not able to produce the maximum flow value of the restrictor. With a sponsorship available from Honeywell (Garrett), it was quickly determined that the team should use one of the two Garrett turbochargers, in order to minimize cost. The GT12 was selected over the GT15VNT, since the team would not have to configure the rather complex variable geometry system that the GT15VNT employs.

### 4.2.2 Intercooler Selection

Most turbocharger systems that run more than 5-6psig of manifold pressure will typically require an intercooler. Despite the ill effects of the restrictor, positive pressure will still be attainable by the turbocharger. However, the turbocharger is most likely not running at its optimal efficiency range. When the compressor is operating in an inefficient location on the compressor map, high compressor discharge temperatures occur. Without an intercooler, high discharge temperatures (typically greater than 140°F) can lead to detonation, which can be harmful to the engine. Therefore, it was necessary to determine the expected compressor outlet temperature, so that the use of an intercooler could be justified. After all, intercoolers represent yet another restriction in the system and they also increase the weight of the vehicle, as well as the cost of the build. 'Eq. 16' below was used to find the aforementioned compressor outlet temperature:

$$T_2 = T_1 * (\frac{P_2}{P_1})^{(\frac{\gamma - 1}{\gamma * \eta})} \quad [Eq. 16]$$

With a low pressure ratio of 2:1, and compressor efficiency of 50% (assumed low as a safety factor), the outlet temperature was determined to be 343°F:

$$T_2 = 300 * [2]^{\left[\frac{1.4-1}{1.4*0.5}\right]} = 446K = 343^o F$$

Another basic analysis for the sizing of the intercooler would be to calculate the heat flow rate of the air charge, using 'Eq. 17' below:

$$Heat\ Flow\ Rate(W) = Specific\ Heat\ \left(\frac{J}{kg * K}\right) * MAF\ \left(\frac{kg}{s}\right) * IAT\ (K) \quad [Eq. 17]$$

$$Heat\ Load\ (W) = \left(\frac{1000J}{1KG} * K\right) * \left(.\frac{07kg}{s}\right) * 446K = 31220W = 31.22kW$$

Under the modeled conditions, which are likely to occur at some point in operation, engine damage is highly plausible if an intercooler is not used. In order to reduce the risk of harming the engine, as well as to maximize performance, the team decided to use an intercooler. It was decided that a good fit would be the OEM Valeo intercooler used in some Volkswagen vehicles. This intercooler is coupled by the manufacturer with a turbocharger of a similar size and it is also widely available and quite cheap when purchased used. Additionally, its end tanks are oriented in an efficient manner, allowing for a low pressure drop solution in a vehicle that is already constrained due to the large pressure drop caused by the restrictor.

### 4.2.3 Engine Management System Selection

A turbocharged system introduces more variables, which have to be monitored and controlled by the ECU. Therefore, it was imperative that an engine management system was selected, which had the capability to control all the different variables in the system in the most efficient and user-friendly way. There were several choices – MegaSquirt, AEM EMS, and Haltech. MegaSquirt was the least expensive option that would provide reasonable control over the turbo-system and the engine. It was the simplest of the three ECUs though and the team determined that its limited control was not enough to manage a complicated system like the one associated with this design. In addition, it appeared that MegaSquirt was most complicated to install. The benefit of the low cost was therefore quickly outweighed by the aforementioned disadvantages.

AEM Engine Management System (AEM EMS) is arguably the best aftermarket engine management system in the world. Unfortunately, it is also known to be very complicated to use and also quite expensive. Therefore, the team strived to find an ECU with similar capabilities as AEM EMS but with a more user-friendly interface. One such system is the Australian-based Haltech EMS. The Haltech Platinum Sport 2000 has similar abilities to AEM EMS, it costs about $1000 less, and is fairly easy to install and set up. Therefore, the team determined that the best choice for this project would be this very system. A detailed comparison between AEM EMS and Haltech Platinum Sport 2000 can be seen in 'Appendix 4: Engine Management System Comparison'.

### 4.2.4 Fuel Type Selection

The two fuel types allowed in the FSAE competition are 93-octane gasoline and E85. E85 is a blend consisting of 85% ethanol and 15% gasoline. Since E85 provides outstanding benefits, which will be discussed in this section, a restrictor of a smaller size (19mm vs. 20mm) is required to be used with E85. Therefore, it was important to determine whether or not the benefits of using E85 in this project outweigh the larger hurdle that a smaller diameter restrictor imposes.

'Table 2' shows several of the important characteristics of the major automotive fuels that are used today. Gasoline (93) and E85 are bolded, since they are the only possible choices in this project.

| Fuel Type<br>- | Lower Heating Value<br>(kJ/kg) | Octane<br>(R+M)/2 | Density<br>(kg/L) | Stoichiometric Ratio<br>(kg/kg) |
|---|---|---|---|---|
| Gasoline (87) | 42.7 | 87.0 | 0.740 | 14.80 |
| **Gasoline (93)** | **43.5** | **93.0** | **0.755** | **14.68** |
| Methanol | 19.7 | 104.5 | 0.790 | 6.47 |
| Ethanol | 26.8 | 104.2 | 0.790 | 9.00 |
| **E85** | **29.2** | **101.6** | **0.783** | **9.87** |
| Diesel | 42.5 | 25.0 | 0.835 | 14.50 |

Table 2 – Fuel Type Characteristics

As the table shows, gasoline has a much higher lower heating value than E85. Simplistically explained, this parameter signifies the energy that the fuel releases during combustion. Therefore, gasoline has more stored energy per unit volume than E85. Energy release and power output are clearly linked, so gasoline has the advantage in this first parameter.

The aforementioned advantage is quickly rendered irrelevant due to the stoichiometric ratio of the two fuels. As explained earlier in this paper, stoichiometric ratio signifies the ideal ratio of air to fuel for a combustion reaction. This ideal value would produce the most efficient chemical reaction, since 100% of the air and 100% of the fuel will ideally be consumed. This 100% efficiency is not realistic but the stoichiometric ratio is still the most efficient ratio for the combustion reaction. The fueling goals calculated by the ECU are a function of this stoichiometric ratio (lambda values) and therefore, the stoichiometric value for different fuels is very important. E85, has a stoichiometric ratio of 9.87:1 AFR and gasoline has a stoichiometric ratio of 14.68:1 AFR. The 2:1 advantage in the lower heating value of gasoline is rendered irrelevant by the 2:1 volumetric fuel flow when using E85. In other words, E85 has lower energy per unit volume but a larger volume is required in order to support combustion. Therefore, the two characteristics cancel each other out.

Furthermore, E85 has a higher density than gasoline. Therefore, when all is accounted for, E85 produces slightly more energy than gasoline. This is not the reason why E85 was considered. As the table above shows, E85 has a higher octane rating than gasoline (101.6 vs. 93). The octane rating represents the ability of the fuel to resist detonation. Detonation (also known as knock) is defined earlier in the paper under 'Knock Sensor' in 'Section 2.3.2'.

In addition to everything mentioned so far in this section, there are more advantages to running E85:

- E85 has a higher auto-ignition temperature than gasoline (657$^{O}$F vs. 475$^{O}$F). This enables E85 to be more knock-resistant, which allows for higher manifold pressures, more timing, and a wider range of air/fuel ratios.
- E85 has a higher latent heat of vaporization than gasoline (760KJ/kg vs. 300KJ/kg), which removes more heat from the intake charge. This further increases knock resistance.
- E85 has a lower rich best torque (RBT) lambda value than gasoline. This means that the optimum air/fuel ratio for making power requires that more fuel is used. More fuel signifies a higher energy release, so this gives E85 yet another advantage, which proves that it can generate more energy in virtually any scenario that gasoline.

E85 also has a few cons associated with its use:

- Since E85 has a lower air/fuel ratio, it requires a much larger fuel mass flow. This implies using fuel components with large flow capabilities, which are almost exclusively aftermarket and always more expensive. In regards to this project, the E85 flow requirements were not an issue since the airflow is limited to a low number. Also, the injectors that were available for use (260cc/min) were rather large for this application, so the team gained some resolution by using E85.
- Even though E85 is not considered corrosive, it can be damaging to certain parts in the fuel system due to its affinity to attract and retain water.

Nevertheless, E85 was selected as the fuel of choice in this project for two main reasons - its properties make it much more resistant to detonation and its charge cooling characteristic will work towards ameliorating the high charge temperature condition, associated with using a turbocharger.

### 4.2.5 Custom Part Fabrication

Since the GT12 is one of the smallest commercially available turbochargers, the aftermarket support associated with its use is very limited. The GT12 oil inlet/return flange was the only item that could be purchased by the team. The turbine inlet and outlet flanges had to be custom designed and manufactured. In addition, the diameter of the turbine inlet was 30mm (1.18in) and the rest of the existing exhaust piping was 2 inches in diameter. Therefore, two reducer pieces were designed and manufactured.

The turbine inlet uses a simple 3-hole flange that was originally designed to have an outlet pipe, which would allow it to be attached to the rest of the system. It was decided that the reducer, which attaches the exhaust manifold to the turbocharger, would be able to be welded to the turbine inlet flange. This removed the need to perform complex machining on the inlet flange. The flange design with the attached reducer can be seen below in 'Figure 21':

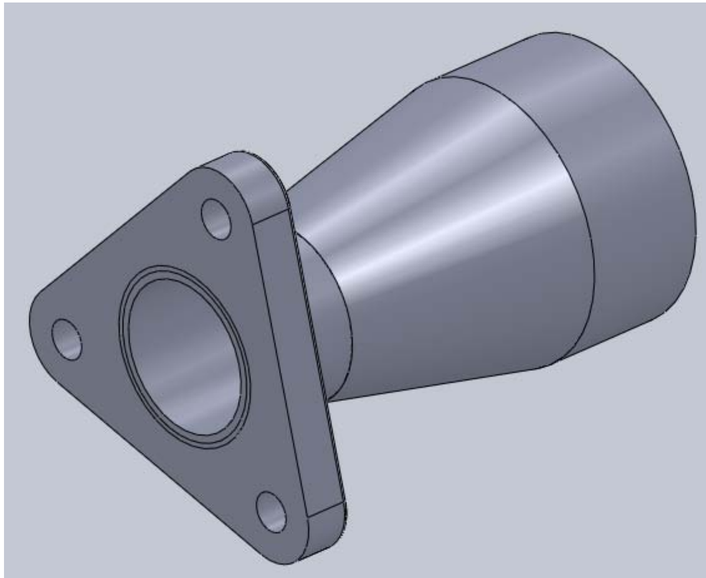


Figure 21 – Turbine Inlet Flange w/ Added Reducer

The turbine outlet flange required another adaptation.  This flange had a very different shape than the inlet flange due to the internal wastegate used in this turbocharger.  The wastegate complicated the design since the flange outlet was not a simple circular shape, but instead a complex, oval-like shape.  The geometry of the flange is shown below in 'Figure 22':

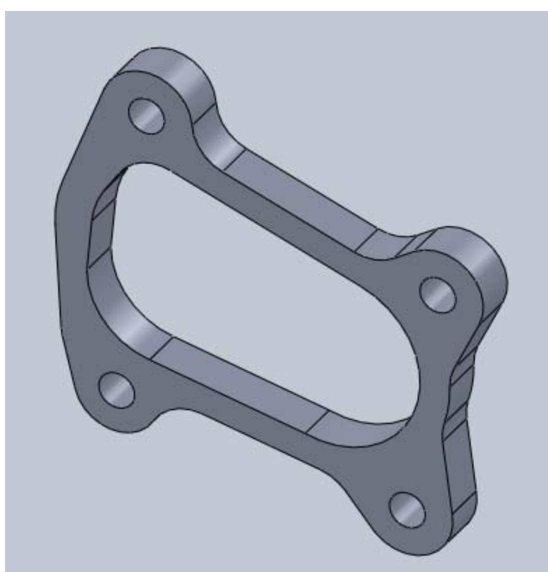


Figure 22 – Turbine Outlet Flange

After this flange was created, it was then adapted to collect into a circular pipe with a diameter of 1.54 inches. Selecting the right diameter for this opening was critical, since maximum flow had to be obtained, while allowing for this part to be machined using a CNC device. If the diameter of the hole was too large, the profile created would not have been able to be made.

Finally, a loft that connects the flange and its exiting hole was created. This smooth transition was important as it insured clean flow throughout the entire part. Wall thicknesses were set to 0.1 inches, which allowed for easier machining and higher durability. ‘Figure 23’ shows the final result, which was machined from a single block of steel:

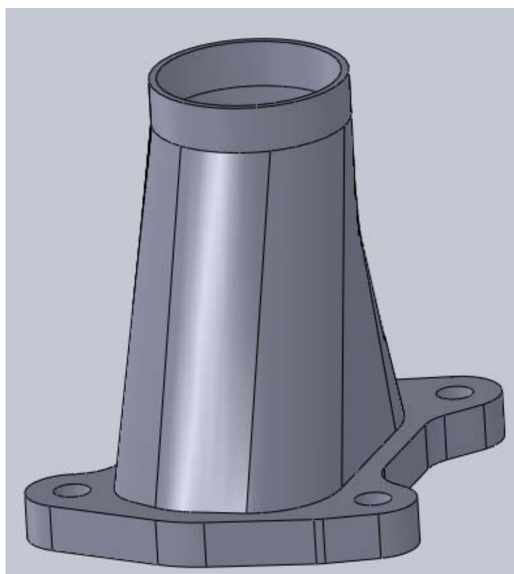


Figure 23 – Turbine Outlet Flange w/ Built-In Lofted Adapter

The materials selection was very straightforward. Since loading was low and mostly irrelevant, the material was mainly selected due to its availability. Both reducers were machined out of 2 inch diameter, solid 1018 cold-rolled steel, which was available at WPI. The inlet flange was made from a 0.5 inch steel plate, which was also already available. The outlet piece was machined out of a 4 inch cube of 1018 cold rolled steel, which had to be purchased separately. All the part drawings can be viewed in 'Appendix 5: Custom Part Drawings'.

## 4.3 Hardware Acquisition

As with any engineering design project, many parts were required. Luckily, this design used an existing vehicle, so numerous parts were already available. Since it was decided that a Garrett GT12 turbocharger would be a viable design choice in this project, Honeywell was contacted about sponsorship. The oil feed and return flange was offered by 'ATP turbo'. Also, a wideband oxygen sensor was needed to upgrade the narrowband sensor already in the vehicle. The LC1 wideband oxygen sensor kit and digital readout were acquired through sponsorship from DynoTune Nitrous, a local automotive performance shop.

The intake system was designed to be easily assembled or disassembled. In order to allow for this, several silicone couplers were purchased from Extreme PSI. Aluminum intake piping and a fuel pressure regulator were also bought from Extreme PSI. The intercooler was purchased from a team member who had one available. Small parts such as oil lines, coolant lines, and fittings were purchased locally. The remaining items needed were not available commercially and were custom made.

## 4.4 Packaging

The main goal of this project was to quantify the gains in power acquired by adding a turbo-system to an existing FSAE racecar. Therefore, it was not imperative to adhere to the packaging rules, set for the FSAE competition. Instead, the geometry of the existing car, as well as the geometry of the various components used within the car, dictated the packaging of the system.

The turbocharger had to be placed as close to the exhaust manifold as possible, in order to eliminate thermal and pressure losses, which in terms would affect the operation of the turbocharger. In addition, the turbocharger needed to be located in an area that would allow for air to access to the compressor inlet. Furthermore, the turbine outlet needed to be facing toward the rear of the vehicle, in order to eliminate the need for additional exhaust pipe fabrication. Upon inspection of the project vehicle, it was determined that the existing exhaust header would be sufficient for the addition of the turbocharger, since its provided adequate means of mounting and powering the turbocharger. The rest of the exhaust was removed. As mentioned previously, several new exhaust parts were fabricated. These parts made it possible to mount the turbocharger onto the car, so that the rest of the components, related to the turbocharger, could be configured and positioned.

Since an intercooler was to be used, the placement of the intercooler would be determined by the available charge piping, so the compressor outlet could be connected to the intake manifold. With the existing intake and chassis roll bar, there were only two options for placement of the intercooler, which would minimize the pipe length. The first option was placing the intercooler above the exhaust and the turbocharger. The second option was mounting it immediately behind the top loop of the roll bar. The additional heat rising up from the exhaust would hinder performance and therefore the decision was made to place the intercooler at the second location. The aluminum charge piping was cut to fit the arrangement in this system and the pipes were connected using silicone couplers and metal clamps.

On the intake side of the system, the restrictor was coupled to a reducer that was attached to the inlet of the turbocharger. This placed the system intake to the left of the driver. The restrictor was braced to the chassis to prevent movement and possible failure due to vibration or shock.

An exhaust flange was fabricated to adapt the exhaust outlet of the turbo to a typical round exhaust pipe. A reducer was added to this adapter to allow for the existing exhaust pipe, which leads into the muffler, to be used. The need for placing an oxygen sensor on the exhaust pipe immediately before the muffler necessitated leaving approximately 4 inches of standard exhaust pipe between the reducer and the muffler.

The last piece of hardware to be added was the fuel pressure regulator. This was fairly simple as the regulator could be attached to the existing fuel rail using standard fittings. The pre-existing fuel return line could also be used with a simple fitting adaptation.

Finally, the new engine management system was attached to the car in the same place as the old engine management system, thus requiring no additional fabrication.

## 4.5 EMS and Electrical Installation

This section will explain the installation of the Haltech engine management system and will also cover the miscellaneous electrical components used in the vehicle. A wiring harness was supplied with the ECU to provide connections to the ECU's 34-pin and 26-pin connectors. Due to an ordering error, the team used the Platinum Sport 1000 wiring harness with the Platinum Sport 2000 EMS, which was decided to be sufficient enough for this application. The two harnesses differ only in the number of ignition and injector connections that they offer. Installation was done with the attempt to follow as closely as possible the recommendations and suggestions provided by Haltech and to match the provided engine management system wiring diagrams. Wiring that was already installed in the vehicle was utilized whenever possible and components were physically mounted and located as close to each other as possible to avoid excessive wire lengths. The majority of components including the ECU, the ignition control module, the relays, and the fuses were mounted to a panel on the right side of the vehicle where similar components had been mounted for the previous engine management system. This panel is covered by a body piece that protects the various electronics from bad weather and physical damage.

The layout of the wires was generally chosen to be as short and simple as possible. Breakout boards were used for the switched 12 volt power supply, the ground, and the 5 volt sensor supply. In this manner, multiple devices could be connected together, while easily allowing for installation of more devices or removal of existing ones in the future. All wire splices were soldered together and covered with heat shrink tubing to protect against shorts or weather intrusion. Weatherproof plugs were utilized in the connections for most of the sensors and switches to allow for easy disconnection. Connections to relays used spade connectors that were also covered in heat shrink tubing to help prevent shorts or weather intrusion. Wires were generally selected by color, using red or orange for positive power connections and black for negative or ground connections. Wire gauges were selected that would be capable of sustaining the current they were required to carry. Sensor wires were routed in such a way to avoid being located close to the ignition and spark plug wires as much as possible, as the high current in these wires can cause interference and distorted signal readings. Some sensors were connected using shielded cables provided with the ECU wiring harness to avoid interference. The shielding of such cables is connected internally in the ECU to ground. Please refer to 'Appendix 6: Electrical System Schematic' for the full schematic used for this project.

### 4.5.1 Relays and Fuses

The first step taken in integrating the wiring and electronics for the vehicle was to install the relays and fuses that would power each of the other systems and components. A relay is an electrically controlled switch. When a voltage is applied across the control pins, a connection is made between the input and output pins of the relay. In automotive applications relays are typically used to allow a large voltage or amperage to be controlled by a smaller one. In this project, a switched 12 volt supply is used to control each of the six relays. When power is supplied from the vehicle's power switch, located in the dash, each relay is turned on and power is allowed to flow from the battery to the system or component connected to the relay. This allows for safe operation of each system, since the switch that the operator has control over does not have a high current flowing directly through it. Relays were installed to control power to the ECU, ignition coils, fuel injectors, fuel pump, radiator fan, and oxygen sensor control unit. Each system also requires the use of a fuse to protect against excessive current draw. The ECU was fused with a 10 Amp fuse, the ignition module with a 15 Amp fuse, the fuel injectors with a 20 Amp fuse, the fuel pump with a 20 Amp fuse, the radiator fan with a 20 Amp fuse, and the oxygen sensor control unit with a 5 Amp fuse. The fuses were connected in series with the relays from the battery positive terminal to the positive power connections for each of the systems and components. The negative connections of the systems and components were connected to the common chassis ground of the vehicle, as was the negative terminal of the battery. The fuses for the ECU, ignition, fuel injectors, and fuel pump were installed in a four fuse block, while the radiator fan and oxygen sensor control unit were given separate inline fuse holders. The starter motor for the engine is also controlled using a relay with a built-in 30 Amp fuse. This was left as previously installed on the vehicle and it is controlled by a pushbutton located on the dash.

### 4.5.2 12 Volt Switched Power

Each system in the vehicle was given power through a relay, and each relay was connected to a 12 volt switched power supply. In a typical car with a key ignition, the switched 12 volt supply is turned on when the key is in the 'on' position. In this project vehicle, this 12 volt supply is controlled by three switches in series. Two of the switches are used as safety devices. When the switched 12 volt supply is turned off, all of the relays are turned off and all of the systems in the vehicle lose power. With the ECU, fuel pump, fuel injectors, and ignition all disabled, the car will not run. Therefore per FSAE rules, a switch is placed beneath the brake pedal such that in the event of a brake failure, where the pedal is depressed beyond the point where it could be depressed in normal operation, it will trigger a switch to open and cut off the switched 12 volt power supply. Another safety switch is located on the top of the vehicle, so that in case of emergency, power can be cut easily. The final switch to control 12 volt power is the main vehicle power switch, located on the dash. Only when both safety switches are in their normal closed positions and the main vehicle power switch is closed will each of the electrical systems in the vehicle be operational and will the engine be capable of being started.

### 4.5.3 Fuel Pump and Radiator Fan

The fuel pump and radiator fan are each controlled by relays which are powered by the switched 12 volt supply, but both are also controlled by an additional power switch located on the dash. The Haltech engine management system is capable of controlling each of these devices through the fuel pump trigger output (pin 24) of the 34 pin connector for the fuel pump, and through any of the ECU's digital output pins for the radiator fan. However it was decided that control of these devices by the ECU provided no benefits in this project and that it would be preferable to leave control up to the operator of the vehicle through the power switches located on the dash, as it was previously installed on the vehicle.

### 4.5.4 Ignition Control and Trigger Sensor

Engine management systems usually employ two sensors and signals to establish the state and timing of engine operation, a trigger signal and a home signal. The trigger signal is typically provided by a crankshaft position sensor, and the home signal by a camshaft position sensor. Because a Honda CBR 600 F3 engine was used, which was originally a carbureted engine, these sensors were not provided with the engine. Previous installation of an engine management system on this engine included the use of a Dynatek Dyna 2000 ignition controller, which included a crankshaft sensor. Operation of the engine management system to control fuel with a trigger signal but no home signal is possible, but ignition control using the Haltech system for more than one channel is not. This engine uses two ignition coils and therefore requires two ignition channels. Therefore the Dynatek Dyna 2000 ignition control system was utilized in this design, as it had been previously. The crankshaft position sensor was connected to the Dyna 2000 module with two sensor wires, a sensor power supply wire, and a ground wire. This provides the information necessary for the Dyna 2000 to control ignition and timing. The Dyna 2000 was then connected to the negative side of each coil so that it can close the connection to ground and trigger the coils to fire the spark plugs at the correct times. The Dyna 2000 module also provides an output signal wire, which is typically used to connect to a tachometer to monitor engine RPM. This wire was connected to the trigger input of the ECU on pin 1 of the ECU's 26 pin connector, allowing for the ECU to control fuel injection.

### 4.5.5 Fuel Injectors

The fuel Injectors were powered through the injector control relay and controlled by the ECU. The injector for each cylinder was connected to the corresponding ECU injector outputs on pins 19 through 22 of the ECU's 34 pin connector. It was important that each injector be connected to the correct injector control output so the timing of fuel injection to each cylinder matches up with the mechanical timing of the engine. Normally the ECU connections to the fuel injectors are open circuits. When the ECU triggers the injectors to operate, it connects the ECU side of the injectors to ground, creating a 12 volt difference across the injectors which causes them to turn on and inject fuel.

### 4.5.6 System Sensors

The team's implementation of the Haltech engine management system utilizes a manifold absolute pressure sensor (MAP sensor), a throttle position sensor (TPS), an intake air temperature sensor, a coolant temperature sensor, and a wideband oxygen sensor. An ECU-controlled boost control solenoid, used to manipulate the wastegate of the turbocharger, was also wired to the ECU, although not utilized. The boost control solenoid could be used in future applications to allow the ECU to control the turbocharger's output. The ECU has an internal MAP sensor, but it was decided for a higher resolution external MAP sensor to be used as the main pressure sensor. The internal MAP sensor could be employed to monitor pressure in another area of the intake system for data gathering purposes. The external MAP sensor was connected to pin 15 of the ECU's 34 pin connector, as well as to ground and the 5 volt sensor voltage supply. The TPS was also connected to the 5 volt sensor voltage supply and ground, and to the ECU through pin 14 of the 34 pin connector. The intake air temperature sensor was connected to pin 3 of the ECU's 26 pin connector and to the ECU's signal ground connection, which is shared by pins 14, 15, and 16 of the ECU's 26 pin connector. The signal ground pins were connected as directly as possible to the negative terminal of the battery to reduce potential signal distortion. The coolant temperature sensor was connected to pin 4 of the ECU's 26 pin connector and to signal ground as well.

For the oxygen sensor, it was decided that a wideband oxygen sensor should be used instead of a narrowband sensor. The oxygen sensor input of the ECU is only capable of taking readings from a narrowband sensor, so an external oxygen sensor control unit was needed. Connection to the ECU was made through the analog voltage input number 1 on pin 13 of the ECU's 26 pin connector and the ECU programming was configured to use an externally controlled wideband sensor, instead of a narrowband sensor controlled by the ECU. The external oxygen sensor chosen was a LC-1 controller. This controller required a separate power supply controlled by a relay with a 5 Amp fused power supply. In addition to the ECU connection, a 'DynoTune Nitrous' air/fuel ratio gauge was also utilized, which was connected to a second output from the LC-1. This provided a digital display mounted on the dash that shows the air/fuel ratio at any given instant.

## 4.6 Tuning

### 4.6.1 Creating Baseline Maps

Engine management systems use tuning 'maps', which are tables that produce an output for a specific input. It was necessary to populate these maps from scratch (using Microsoft Excel), so that there was as little guesswork as possible when tuning the vehicle. All of these maps were created in excel and were then transferred onto the Haltech ECU upon necessity.

The first table that was generated was the uncorrected airflow table, which produced an airflow in grams/second for a specified manifold pressure and RPM. The equation used to estimate this airflow value is shown as 'Eq. 18' below:

$$Uncorrected\ Airflow = \frac{RPM * Displacement(m^3) * Intake\ Manifold\ Pressure(kPa) * 1{,}000{,}000}{2 * 60 * 287 * Intake\ Manifold\ Temperature\ (K)} \qquad [Eq. 18]$$

The uncorrected airflow table can be seen below in 'Figure 24'. The cells highlighted in light blue request an airflow that is higher than the possible flow through the restrictor.

| Load (MAP) vs. RPMs - Uncorrected Airflow in g/s | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Load (PSIA) | 500 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 | 6500 |
| 40.4 | 8.09 | 16.19 | 24.28 | 32.37 | 40.46 | 48.56 | 56.65 | 64.74 | 72.83 | 80.93 | 89.02 | 97.11 | 105.21 |
| 36.7 | 7.35 | 14.70 | 22.05 | 29.41 | 36.76 | 44.11 | 51.46 | 58.81 | 66.16 | 73.52 | 80.87 | 88.22 | 95.57 |
| 33.1 | 6.63 | 13.26 | 19.89 | 26.52 | 33.15 | 39.78 | 46.41 | 53.04 | 59.67 | 66.30 | 72.93 | 79.57 | 86.20 |
| 31.2 | 6.25 | 12.50 | 18.75 | 25.00 | 31.25 | 37.50 | 43.75 | 50.00 | 56.25 | 62.50 | 68.75 | 75.00 | 81.25 |
| 29.4 | 5.89 | 11.78 | 17.67 | 23.56 | 29.45 | 35.34 | 41.22 | 47.11 | 53.00 | 58.89 | 64.78 | 70.67 | 76.56 |
| 27.6 | 5.53 | 11.06 | 16.59 | 22.11 | 27.64 | 33.17 | 38.70 | 44.23 | 49.76 | 55.29 | 60.82 | 66.34 | 71.87 |
| 25.7 | 5.15 | 10.30 | 15.44 | 20.59 | 25.74 | 30.89 | 36.04 | 41.18 | 46.33 | 51.48 | 56.63 | 61.78 | 66.93 |
| 23.9 | 4.79 | 9.58 | 14.36 | 19.15 | 23.94 | 28.73 | 33.51 | 38.30 | 43.09 | 47.88 | 52.66 | 57.45 | 62.24 |
| 22.0 | 4.41 | 8.81 | 13.22 | 17.63 | 22.03 | 26.44 | 30.85 | 35.26 | 39.66 | 44.07 | 48.48 | 52.88 | 57.29 |
| 20.2 | 4.05 | 8.09 | 12.14 | 16.19 | 20.23 | 24.28 | 28.32 | 32.37 | 36.42 | 40.46 | 44.51 | 48.56 | 52.60 |
| 18.4 | 3.69 | 7.37 | 11.06 | 14.74 | 18.43 | 22.11 | 25.80 | 29.49 | 33.17 | 36.86 | 40.54 | 44.23 | 47.92 |
| 16.5 | 3.31 | 6.61 | 9.92 | 13.22 | 16.53 | 19.83 | 23.14 | 26.44 | 29.75 | 33.05 | 36.36 | 39.66 | 42.97 |
| 14.7 | 2.94 | 5.89 | 8.83 | 11.78 | 14.72 | 17.67 | 20.61 | 23.56 | 26.50 | 29.45 | 32.39 | 35.34 | 38.28 |
| 12.9 | 2.58 | 5.17 | 7.75 | 10.34 | 12.92 | 15.50 | 18.09 | 20.67 | 23.26 | 25.84 | 28.42 | 31.01 | 33.59 |
| 11.0 | 2.20 | 4.41 | 6.61 | 8.81 | 11.02 | 13.22 | 15.42 | 17.63 | 19.83 | 22.03 | 24.24 | 26.44 | 28.65 |
| 9.2 | 1.84 | 3.69 | 5.53 | 7.37 | 9.21 | 11.06 | 12.90 | 14.74 | 16.59 | 18.43 | 20.27 | 22.11 | 23.96 |
| 7.3 | 1.46 | 2.92 | 4.39 | 5.85 | 7.31 | 8.77 | 10.24 | 11.70 | 13.16 | 14.62 | 16.09 | 17.55 | 19.01 |
| 5.5 | 1.10 | 2.20 | 3.31 | 4.41 | 5.51 | 6.61 | 7.71 | 8.81 | 9.92 | 11.02 | 12.12 | 13.22 | 14.32 |
| 3.7 | 0.74 | 1.48 | 2.22 | 2.96 | 3.71 | 4.45 | 5.19 | 5.93 | 6.67 | 7.41 | 8.15 | 8.89 | 9.64 |
| 1.8 | 0.36 | 0.72 | 1.08 | 1.44 | 1.80 | 2.16 | 2.52 | 2.88 | 3.25 | 3.61 | 3.97 | 4.33 | 4.69 |
| 0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

| Load (PSIA) | 7000 | 7500 | 8000 | 8500 | 9000 | 9500 | 10000 | 10500 | 11000 | 11500 | 12000 | 12500 | 13000 | Load (kPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 40.4 | 113.30 | 121.39 | 129.48 | 137.58 | 145.67 | 153.76 | 161.85 | 169.95 | 178.04 | 186.13 | 194.23 | 202.32 | 210.41 | 279 |
| 36.7 | 102.92 | 110.27 | 117.63 | 124.98 | 132.33 | 139.68 | 147.03 | 154.38 | 161.73 | 169.09 | 176.44 | 183.79 | 191.14 | 253 |
| 33.1 | 92.83 | 99.46 | 106.09 | 112.72 | 119.35 | 125.98 | 132.61 | 139.24 | 145.87 | 152.50 | 159.13 | 165.76 | 172.39 | 228 |
| 31.2 | 87.50 | 93.75 | 100.00 | 106.25 | 112.50 | 118.75 | 125.00 | 131.25 | 137.50 | 143.75 | 150.00 | 156.25 | 162.50 | 215 |
| 29.4 | 82.45 | 88.34 | 94.23 | 100.12 | 106.01 | 111.90 | 117.79 | 123.67 | 129.56 | 135.45 | 141.34 | 147.23 | 153.12 | 203 |
| 27.6 | 77.40 | 82.93 | 88.46 | 93.99 | 99.52 | 105.05 | 110.57 | 116.10 | 121.63 | 127.16 | 132.69 | 138.22 | 143.75 | 190 |
| 25.7 | 72.07 | 77.22 | 82.37 | 87.52 | 92.67 | 97.81 | 102.96 | 108.11 | 113.26 | 118.41 | 123.55 | 128.70 | 133.85 | 177 |
| 23.9 | 67.03 | 71.81 | 76.60 | 81.39 | 86.18 | 90.96 | 95.75 | 100.54 | 105.33 | 110.11 | 114.90 | 119.69 | 124.48 | 165 |
| 22.0 | 61.70 | 66.10 | 70.51 | 74.92 | 79.32 | 83.73 | 88.14 | 92.55 | 96.95 | 101.36 | 105.77 | 110.17 | 114.58 | 152 |
| 20.2 | 56.65 | 60.70 | 64.74 | 68.79 | 72.83 | 76.88 | 80.93 | 84.97 | 89.02 | 93.07 | 97.11 | 101.16 | 105.21 | 139 |
| 18.4 | 51.60 | 55.29 | 58.97 | 62.66 | 66.34 | 70.03 | 73.72 | 77.40 | 81.09 | 84.77 | 88.46 | 92.15 | 95.83 | 127 |
| 16.5 | 46.27 | 49.58 | 52.88 | 56.19 | 59.49 | 62.80 | 66.10 | 69.41 | 72.71 | 76.02 | 79.32 | 82.63 | 85.94 | 114 |
| 14.7 | 41.22 | 44.17 | 47.11 | 50.06 | 53.00 | 55.95 | 58.89 | 61.84 | 64.78 | 67.73 | 70.67 | 73.62 | 76.56 | 101 |
| 12.9 | 36.18 | 38.76 | 41.35 | 43.93 | 46.51 | 49.10 | 51.68 | 54.27 | 56.85 | 59.43 | 62.02 | 64.60 | 67.19 | 89 |
| 11.0 | 30.85 | 33.05 | 35.26 | 37.46 | 39.66 | 41.87 | 44.07 | 46.27 | 48.48 | 50.68 | 52.88 | 55.09 | 57.29 | 76 |
| 9.2 | 25.80 | 27.64 | 29.49 | 31.33 | 33.17 | 35.02 | 36.86 | 38.70 | 40.54 | 42.39 | 44.23 | 46.07 | 47.92 | 63 |
| 7.3 | 20.47 | 21.93 | 23.40 | 24.86 | 26.32 | 27.78 | 29.25 | 30.71 | 32.17 | 33.63 | 35.10 | 36.56 | 38.02 | 50 |
| 5.5 | 15.42 | 16.53 | 17.63 | 18.73 | 19.83 | 20.93 | 22.03 | 23.14 | 24.24 | 25.34 | 26.44 | 27.54 | 28.65 | 38 |
| 3.7 | 10.38 | 11.12 | 11.86 | 12.60 | 13.34 | 14.08 | 14.82 | 15.56 | 16.31 | 17.05 | 17.79 | 18.53 | 19.27 | 26 |
| 1.8 | 5.05 | 5.41 | 5.77 | 6.13 | 6.49 | 6.85 | 7.21 | 7.57 | 7.93 | 8.29 | 8.65 | 9.01 | 9.37 | 12 |
| 0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0 |

Figure 24 - Uncorrected Airflow Table

Next, it was necessary to correct the airflow using a volumetric efficiency table. Since the maximum airflow was known for the highlighted cells above, it was possible to determine the VE values for those cells. For the remainder of the cells, personal tuning experience was used and the cells were blended for a smooth transition. The VE table resulting from this can be seen below in 'Figure 25':

| Load (MAP) vs. RPMs - Volumetric Efficiency | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Load (PSIA) | 500 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 | 6500 | 7000 | 7500 | 8000 | 8500 | 9000 | 9500 | 10000 | 10500 | 11000 | 11500 | 12000 | 12500 | 13000 | Load (kPa) |
| 40.4 | 60.0 | 64.0 | 67.0 | 71.0 | 77.0 | 83.0 | 87.0 | 90.0 | 88.0 | 86.0 | 84.0 | 77.0 | 71.0 | 66.0 | 61.0 | 57.0 | 54.0 | 51.0 | 48.0 | 46.0 | 44.0 | 42.0 | 40.0 | 38.0 | 37.0 | 35.0 | 279 |
| 36.7 | 60.0 | 62.0 | 66.0 | 70.0 | 76.0 | 82.0 | 86.0 | 89.0 | 91.0 | 89.0 | 87.0 | 83.0 | 78.0 | 72.5 | 68.0 | 63.0 | 60.0 | 56.0 | 53.0 | 51.0 | 48.0 | 46.0 | 44.0 | 42.0 | 40.5 | 39.0 | 253 |
| 33.1 | 59.0 | 61.0 | 65.0 | 69.0 | 75.0 | 81.0 | 84.0 | 89.0 | 90.0 | 91.0 | 89.0 | 87.0 | 83.0 | 80.0 | 75.0 | 70.5 | 66.0 | 62.0 | 59.0 | 56.0 | 53.0 | 51.0 | 49.0 | 47.0 | 45.0 | 43.0 | 228 |
| 31.2 | 58.0 | 60.0 | 64.0 | 68.0 | 74.0 | 80.0 | 83.0 | 88.0 | 89.0 | 90.0 | 90.0 | 89.0 | 87.0 | 83.0 | 80.0 | 75.0 | 70.0 | 66.0 | 63.0 | 60.0 | 57.0 | 54.0 | 52.0 | 50.0 | 48.0 | 46.0 | 215 |
| 29.4 | 57.0 | 59.0 | 63.0 | 66.0 | 73.0 | 78.0 | 81.0 | 86.0 | 89.0 | 89.0 | 90.0 | 89.0 | 88.0 | 86.0 | 83.0 | 79.0 | 74.0 | 70.0 | 67.0 | 63.0 | 60.0 | 57.0 | 55.0 | 53.0 | 50.5 | 48.0 | 203 |
| 27.6 | 56.0 | 57.0 | 61.0 | 65.0 | 72.0 | 77.0 | 80.0 | 85.0 | 88.0 | 88.0 | 88.0 | 89.0 | 88.0 | 87.0 | 86.0 | 83.0 | 79.0 | 75.0 | 71.0 | 67.0 | 64.0 | 61.0 | 58.0 | 56.0 | 54.0 | 52.0 | 190 |
| 25.7 | 55.0 | 56.0 | 60.0 | 64.0 | 70.0 | 76.0 | 80.0 | 84.0 | 86.0 | 86.0 | 87.0 | 88.0 | 88.0 | 88.0 | 87.0 | 86.0 | 82.0 | 80.0 | 76.0 | 72.0 | 69.0 | 66.0 | 63.0 | 60.0 | 58.0 | 56.0 | 177 |
| 23.9 | 54.0 | 56.0 | 58.0 | 63.0 | 69.0 | 75.0 | 79.0 | 82.0 | 85.0 | 85.0 | 86.0 | 87.0 | 88.0 | 88.0 | 89.0 | 88.0 | 84.0 | 83.0 | 82.0 | 78.0 | 74.0 | 71.0 | 68.0 | 65.0 | 62.0 | 60.0 | 165 |
| 22.0 | 53.0 | 55.0 | 57.0 | 62.0 | 68.0 | 73.0 | 77.0 | 81.0 | 84.0 | 85.0 | 85.0 | 86.0 | 87.0 | 88.0 | 89.0 | 89.0 | 87.0 | 86.0 | 84.0 | 85.0 | 81.0 | 77.0 | 73.0 | 70.0 | 68.0 | 65.0 | 152 |
| 20.2 | 51.0 | 54.0 | 56.0 | 60.0 | 67.0 | 72.0 | 76.0 | 80.0 | 82.0 | 84.0 | 84.0 | 86.0 | 87.0 | 87.0 | 88.0 | 88.0 | 89.0 | 87.0 | 85.0 | 85.0 | 82.0 | 84.0 | 80.0 | 77.0 | 74.0 | 71.0 | 139 |
| 18.4 | 50.0 | 52.0 | 55.0 | 59.0 | 64.0 | 71.0 | 74.0 | 78.0 | 81.0 | 83.0 | 83.0 | 85.0 | 86.0 | 87.0 | 87.0 | 87.0 | 88.0 | 88.0 | 87.0 | 85.0 | 83.0 | 83.0 | 80.0 | 77.0 | 74.0 | 72.0 | 127 |
| 16.5 | 48.0 | 50.0 | 53.0 | 58.0 | 62.0 | 68.0 | 72.0 | 76.0 | 79.0 | 81.0 | 82.0 | 84.0 | 86.0 | 86.0 | 86.0 | 86.0 | 87.0 | 88.0 | 86.0 | 84.0 | 83.0 | 82.0 | 79.0 | 77.0 | 73.0 | 72.0 | 114 |
| 14.7 | 46.0 | 48.0 | 52.0 | 56.0 | 60.0 | 66.0 | 69.0 | 72.0 | 77.0 | 79.0 | 80.0 | 83.0 | 84.0 | 84.0 | 85.0 | 85.0 | 86.0 | 86.0 | 85.0 | 83.0 | 82.0 | 81.0 | 79.0 | 76.0 | 72.0 | 72.0 | 101 |
| 12.9 | 44.0 | 47.0 | 51.0 | 55.0 | 55.0 | 61.0 | 64.0 | 69.0 | 74.0 | 78.0 | 79.0 | 81.0 | 82.0 | 83.0 | 84.0 | 84.0 | 84.0 | 85.0 | 84.0 | 82.0 | 81.0 | 80.0 | 78.0 | 75.0 | 72.0 | 70.0 | 89 |
| 11.0 | 42.0 | 46.0 | 49.0 | 51.0 | 52.0 | 58.0 | 60.0 | 66.0 | 71.0 | 75.0 | 76.0 | 78.0 | 81.0 | 82.0 | 85.0 | 83.0 | 83.0 | 84.0 | 83.0 | 80.0 | 79.0 | 79.0 | 77.0 | 74.0 | 71.0 | 69.0 | 76 |
| 9.2 | 40.0 | 45.0 | 48.0 | 49.0 | 50.0 | 55.0 | 56.0 | 59.0 | 68.0 | 72.0 | 74.0 | 76.0 | 79.0 | 80.0 | 81.0 | 82.0 | 82.0 | 82.0 | 81.0 | 79.0 | 78.0 | 77.0 | 74.0 | 72.0 | 70.0 | 69.0 | 63 |
| 7.3 | 39.0 | 44.0 | 46.0 | 47.0 | 47.0 | 51.0 | 54.0 | 57.0 | 64.0 | 69.0 | 70.0 | 74.0 | 76.0 | 78.0 | 80.0 | 80.0 | 80.0 | 80.0 | 79.0 | 77.0 | 76.0 | 74.0 | 72.0 | 71.0 | 69.0 | 68.0 | 50 |
| 5.5 | 38.0 | 42.0 | 43.0 | 44.0 | 45.0 | 48.0 | 52.0 | 54.0 | 59.0 | 64.0 | 68.0 | 72.0 | 73.0 | 74.0 | 76.0 | 76.0 | 76.0 | 76.0 | 75.0 | 74.0 | 72.0 | 71.0 | 70.0 | 69.0 | 68.0 | 66.0 | 38 |
| 3.7 | 38.0 | 40.0 | 41.0 | 42.0 | 43.0 | 46.0 | 50.0 | 51.0 | 56.0 | 59.0 | 65.0 | 67.0 | 68.0 | 69.0 | 71.0 | 73.0 | 73.0 | 73.0 | 72.0 | 71.0 | 70.0 | 69.0 | 69.0 | 68.0 | 67.0 | 65.0 | 26 |
| 1.8 | 38.0 | 40.0 | 41.0 | 41.0 | 43.0 | 45.0 | 47.0 | 48.0 | 52.0 | 57.0 | 59.0 | 60.0 | 63.0 | 66.0 | 68.0 | 70.0 | 71.0 | 72.0 | 71.0 | 70.0 | 68.0 | 68.0 | 67.0 | 66.0 | 65.0 | 64.0 | 12 |
| 0.0 | 38.0 | 40.0 | 41.0 | 41.0 | 42.0 | 43.0 | 45.0 | 47.0 | 51.0 | 53.0 | 55.0 | 59.0 | 62.0 | 64.0 | 66.0 | 68.0 | 69.0 | 70.0 | 69.0 | 67.0 | 64.0 | 64.0 | 64.0 | 64.0 | 63.0 | 63.0 | 0 |

Figure 25 - Volumetric Efficiency Table

Based on the volumetric efficiency table above, the uncorrected airflow table was corrected. The resulting table can be seen below in 'Figure 26':

| Load (MAP)vs. RPMs-Corrected Airflowing/s (Choke Limited to 75g/s) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Load (PSIA) | 500 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 | 6500 | 7000 | 7500 | 8000 | 8500 | 9000 | 9500 | 10000 | 10500 | 11000 | 11500 | 12000 | 12500 | 13000 | Load (kPa) |
| 40.4 | 4.86 | 10.36 | 16.27 | 22.98 | 31.16 | 40.30 | 49.28 | 58.27 | 64.09 | 69.60 | 74.78 | 74.78 | 74.70 | 74.78 | 74.05 | 73.81 | 74.29 | 74.29 | 73.81 | 74.45 | 74.78 | 74.78 | 74.45 | 73.81 | 74.86 | 73.64 | 279 |
| 36.7 | 4.41 | 9.12 | 14.56 | 20.58 | 27.94 | 36.17 | 44.26 | 52.34 | 60.21 | 65.43 | 70.35 | 73.22 | 74.55 | 74.62 | 74.99 | 74.10 | 74.99 | 74.10 | 74.03 | 74.99 | 74.10 | 74.40 | 74.40 | 74.10 | 74.43 | 74.55 | 253 |
| 33.1 | 3.91 | 8.09 | 12.93 | 18.30 | 24.86 | 32.22 | 38.99 | 47.21 | 53.71 | 60.34 | 64.91 | 69.22 | 71.54 | 74.26 | 74.59 | 74.79 | 74.39 | 74.00 | 74.33 | 74.26 | 73.80 | 74.39 | 74.73 | 74.79 | 74.59 | 74.13 | 228 |
| 31.2 | 3.62 | 7.50 | 12.00 | 17.00 | 23.12 | 30.00 | 36.31 | 44.00 | 50.06 | 56.25 | 61.87 | 66.75 | 70.69 | 72.62 | 75.00 | 75.00 | 74.37 | 74.25 | 74.81 | 75.00 | 74.81 | 74.25 | 74.75 | 75.00 | 75.00 | 74.75 | 215 |
| 29.4 | 3.36 | 6.95 | 11.13 | 15.55 | 21.50 | 27.56 | 33.39 | 40.52 | 47.17 | 52.41 | 58.30 | 62.90 | 67.37 | 70.91 | 73.32 | 74.44 | 74.09 | 74.20 | 74.97 | 74.20 | 74.20 | 73.85 | 74.50 | 74.91 | 74.35 | 73.50 | 203 |
| 27.6 | 3.10 | 6.30 | 10.12 | 14.37 | 19.90 | 25.54 | 30.96 | 37.60 | 43.79 | 48.65 | 53.52 | 59.05 | 63.25 | 67.34 | 71.32 | 73.42 | 74.25 | 74.64 | 74.58 | 74.08 | 74.31 | 74.20 | 73.75 | 74.31 | 74.64 | 74.75 | 190 |
| 25.7 | 2.83 | 5.77 | 9.27 | 13.18 | 18.02 | 23.48 | 28.83 | 34.60 | 39.85 | 44.27 | 49.27 | 54.36 | 58.89 | 63.42 | 67.18 | 70.84 | 71.76 | 74.13 | 74.34 | 74.13 | 74.60 | 74.75 | 74.60 | 74.13 | 74.65 | 74.96 | 177 |
| 23.9 | 2.59 | 5.36 | 8.33 | 12.06 | 16.52 | 21.54 | 26.48 | 31.41 | 36.62 | 40.69 | 45.29 | 49.98 | 54.77 | 58.98 | 63.91 | 67.41 | 68.37 | 71.53 | 74.59 | 74.69 | 74.40 | 74.78 | 74.88 | 74.69 | 74.21 | 74.69 | 165 |
| 22.0 | 2.34 | 4.85 | 7.54 | 10.93 | 14.98 | 19.30 | 23.75 | 28.56 | 33.32 | 37.46 | 41.20 | 45.48 | 49.84 | 54.29 | 58.83 | 62.75 | 65.18 | 68.22 | 70.33 | 74.92 | 74.96 | 74.65 | 73.99 | 74.04 | 74.92 | 74.48 | 152 |
| 20.2 | 2.06 | 4.37 | 6.80 | 9.71 | 13.56 | 17.48 | 21.53 | 25.90 | 29.86 | 33.99 | 37.39 | 41.76 | 45.76 | 49.28 | 53.41 | 56.97 | 61.22 | 63.37 | 65.35 | 68.79 | 69.68 | 74.78 | 74.45 | 74.78 | 74.86 | 74.70 | 139 |
| 18.4 | 1.84 | 3.83 | 6.08 | 8.70 | 11.79 | 15.70 | 19.09 | 23.00 | 26.87 | 30.59 | 33.65 | 37.60 | 41.21 | 44.89 | 48.10 | 51.31 | 55.14 | 58.38 | 60.93 | 62.66 | 64.24 | 67.30 | 67.82 | 68.11 | 68.19 | 69.00 | 127 |
| 16.5 | 1.59 | 3.31 | 5.26 | 7.67 | 10.25 | 13.49 | 16.66 | 20.10 | 23.50 | 26.77 | 29.81 | 33.32 | 36.95 | 39.79 | 42.64 | 45.48 | 48.88 | 52.35 | 54.01 | 55.53 | 57.61 | 59.63 | 60.06 | 61.08 | 60.32 | 61.87 | 114 |
| 14.7 | 1.35 | 2.83 | 4.59 | 6.60 | 8.83 | 11.66 | 14.22 | 16.96 | 20.41 | 23.26 | 25.91 | 29.33 | 32.16 | 34.63 | 37.54 | 40.05 | 43.05 | 45.58 | 47.56 | 48.88 | 50.71 | 52.47 | 53.50 | 53.71 | 53.00 | 55.12 | 101 |
| 12.9 | 1.14 | 2.43 | 3.95 | 5.68 | 7.11 | 9.46 | 11.58 | 14.26 | 17.21 | 20.16 | 22.46 | 25.12 | 27.55 | 30.03 | 32.56 | 34.73 | 36.90 | 39.54 | 41.24 | 42.38 | 43.96 | 45.48 | 46.36 | 46.51 | 46.51 | 47.03 | 89 |
| 11.0 | 0.93 | 2.03 | 3.24 | 4.50 | 5.73 | 7.67 | 9.25 | 11.63 | 14.08 | 16.53 | 18.42 | 20.62 | 23.20 | 25.30 | 28.09 | 29.26 | 31.09 | 33.32 | 34.75 | 35.26 | 36.56 | 38.30 | 39.02 | 39.13 | 39.11 | 39.53 | 76 |
| 9.2 | 0.74 | 1.66 | 2.65 | 3.61 | 4.61 | 6.08 | 7.22 | 8.70 | 11.28 | 13.27 | 15.00 | 16.81 | 18.93 | 20.64 | 22.39 | 24.18 | 25.69 | 27.20 | 28.36 | 29.12 | 30.19 | 31.22 | 31.37 | 31.85 | 32.25 | 33.06 | 63 |
| 7.3 | 0.57 | 1.29 | 2.02 | 2.75 | 3.44 | 4.47 | 5.53 | 6.67 | 8.42 | 10.09 | 11.26 | 12.99 | 14.45 | 15.97 | 17.55 | 18.72 | 19.89 | 21.06 | 21.95 | 22.52 | 23.34 | 23.81 | 24.22 | 24.92 | 25.22 | 25.85 | 50 |
| 5.5 | 0.42 | 0.93 | 1.42 | 1.94 | 2.48 | 3.17 | 4.01 | 4.76 | 5.85 | 7.05 | 8.24 | 9.52 | 10.46 | 11.41 | 12.56 | 13.40 | 14.23 | 15.07 | 15.70 | 16.31 | 16.66 | 17.21 | 17.74 | 18.24 | 18.73 | 18.91 | 38 |
| 3.7 | 0.28 | 0.59 | 0.91 | 1.25 | 1.59 | 2.05 | 2.59 | 3.02 | 3.74 | 4.37 | 5.30 | 5.96 | 6.55 | 7.16 | 7.89 | 8.66 | 9.20 | 9.74 | 10.14 | 10.52 | 10.90 | 11.25 | 11.76 | 12.10 | 12.41 | 12.53 | 26 |
| 1.8 | 0.14 | 0.29 | 0.44 | 0.59 | 0.78 | 0.97 | 1.19 | 1.38 | 1.69 | 2.06 | 2.34 | 2.60 | 2.95 | 3.33 | 3.68 | 4.04 | 4.35 | 4.67 | 4.86 | 5.05 | 5.15 | 5.39 | 5.56 | 5.71 | 5.86 | 6.00 | 12 |
| 0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0 |

Figure 26 - Corrected Airflow Table (g/s)

Next, the goal air/fuel ratio table was created. Its purpose was to derive fuel mass flow from the mass airflow tables above. The airflow values in each cell would simply be divided by the corresponding AFR cell, which would yield the fuel flow. 'Figure 27' shows the air/fuel ratio table. 'Figure 28' shows the corrected fuel flow table populated using the corrected airflow table and the AFR table.

| Load (MAP) vs. RPMs - Gasoline-Equivalent Air/Fuel Ratio | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Load (PSIA) | 500 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 | 6500 | 7000 | 7500 | 8000 | 8500 | 9000 | 9500 | 10000 | 10500 | 11000 | 11500 | 12000 | 12500 | 13000 | Load (kPa) |
| 40.4 | 12.2 | 12.3 | 12.2 | 12.0 | 11.8 | 11.6 | 11.4 | 11.2 | 11.0 | 10.8 | 10.8 | 10.8 | 10.9 | 10.9 | 10.9 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 279 |
| 36.7 | 12.4 | 12.4 | 12.3 | 12.2 | 12.0 | 11.8 | 11.6 | 11.4 | 11.2 | 11.0 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 253 |
| 33.1 | 12.5 | 12.5 | 12.4 | 12.3 | 12.2 | 12.0 | 11.9 | 11.7 | 11.5 | 11.3 | 11.1 | 11.0 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 228 |
| 31.2 | 12.6 | 12.5 | 12.5 | 12.4 | 12.3 | 12.1 | 12.0 | 11.9 | 11.7 | 11.5 | 11.3 | 11.2 | 11.0 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 215 |
| 29.4 | 12.6 | 12.6 | 12.6 | 12.4 | 12.4 | 12.3 | 12.2 | 12.0 | 11.3 | 11.3 | 11.3 | 11.3 | 11.1 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 203 |
| 27.6 | 12.6 | 12.6 | 12.6 | 12.5 | 12.5 | 12.4 | 12.2 | 12.1 | 12.0 | 11.6 | 11.6 | 11.6 | 11.3 | 11.0 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 190 |
| 25.7 | 12.7 | 12.6 | 12.6 | 12.6 | 12.5 | 12.5 | 12.4 | 12.3 | 12.0 | 11.9 | 11.7 | 11.5 | 11.3 | 11.1 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 177 |
| 23.9 | 12.8 | 12.7 | 12.7 | 12.6 | 12.6 | 12.6 | 12.5 | 12.4 | 12.2 | 12.0 | 11.8 | 11.6 | 11.4 | 11.2 | 11.0 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 165 |
| 22.0 | 12.9 | 12.7 | 12.7 | 12.6 | 12.6 | 12.6 | 12.6 | 12.4 | 12.3 | 12.2 | 12.0 | 11.9 | 11.6 | 11.3 | 11.1 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 152 |
| 20.2 | 13.0 | 12.8 | 12.7 | 12.6 | 12.8 | 12.8 | 12.8 | 12.5 | 12.4 | 12.3 | 12.2 | 12.1 | 11.8 | 11.6 | 11.3 | 11.0 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 139 |
| 18.4 | 13.1 | 13.0 | 12.9 | 12.6 | 13.0 | 13.0 | 13.0 | 12.8 | 12.4 | 12.4 | 12.3 | 12.2 | 11.9 | 11.5 | 11.3 | 11.1 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 127 |
| 16.5 | 13.2 | 13.2 | 13.0 | 12.6 | 13.3 | 13.3 | 13.3 | 13.0 | 12.8 | 12.8 | 12.5 | 12.3 | 12.1 | 11.9 | 11.6 | 11.3 | 11.0 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 114 |
| 14.7 | 13.3 | 13.4 | 13.6 | 13.6 | 13.6 | 13.6 | 13.5 | 13.2 | 13.0 | 12.9 | 12.8 | 12.5 | 12.3 | 12.0 | 11.7 | 11.4 | 11.2 | 11.0 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 101 |
| 12.9 | 13.4 | 13.6 | 13.8 | 13.9 | 13.9 | 13.9 | 13.9 | 13.6 | 13.3 | 13.2 | 13.0 | 12.7 | 12.5 | 12.3 | 12.1 | 11.9 | 11.6 | 11.3 | 11.0 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 89 |
| 11.0 | 13.5 | 13.8 | 14.1 | 14.2 | 14.2 | 14.1 | 14.1 | 13.8 | 13.7 | 13.7 | 13.3 | 13.2 | 13.2 | 12.6 | 12.3 | 12.1 | 11.9 | 11.6 | 11.3 | 11.1 | 11.0 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 76 |
| 9.2 | 13.6 | 14.0 | 14.2 | 14.4 | 14.4 | 14.4 | 14.3 | 14.2 | 14.1 | 14.0 | 13.7 | 13.5 | 13.3 | 13.0 | 12.7 | 12.4 | 12.3 | 12.0 | 11.8 | 11.5 | 11.3 | 11.1 | 11.0 | 10.8 | 10.8 | 10.8 | 63 |
| 7.3 | 13.6 | 14.2 | 14.3 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.3 | 14.0 | 13.7 | 13.5 | 13.3 | 13.0 | 12.8 | 12.6 | 12.4 | 12.3 | 12.1 | 11.9 | 11.6 | 11.3 | 11.1 | 11.0 | 10.8 | 50 |
| 5.5 | 13.9 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.3 | 14.0 | 13.8 | 13.6 | 13.4 | 13.2 | 12.9 | 12.6 | 12.5 | 12.0 | 12.0 | 11.6 | 11.6 | 11.3 | 11.3 | 11.0 | 38 |
| 3.7 | 14.1 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.3 | 14.0 | 13.8 | 13.6 | 13.4 | 13.2 | 13.0 | 12.8 | 12.5 | 12.2 | 12.0 | 12.0 | 11.6 | 11.6 | 11.3 | 26 |
| 1.8 | 14.3 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.3 | 14.0 | 13.8 | 13.6 | 13.4 | 13.2 | 12.9 | 12.6 | 12.5 | 12.3 | 12.2 | 12.0 | 12.0 | 11.6 | 12 |
| 0.0 | 14.5 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.3 | 14.0 | 13.8 | 13.6 | 13.3 | 13.0 | 12.8 | 12.6 | 12.5 | 12.4 | 12.3 | 12.1 | 12.0 | 0 |

Figure 27 - Air/Fuel Ratio Table

| Load (MAP) vs. RPMs - Corrected Total Fuel System Flow in cc/min | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Load (PSIA) | 500 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 | 6500 | 7000 | 7500 | 8000 | 8500 | 9000 | 9500 | 10000 | 10500 | 11000 | 11500 | 12000 | 12500 | 13000 | Load (kPa) |
| 40.4 | 45 | 96 | 151 | 218 | 300 | 395 | 491 | 591 | 662 | 732 | 787 | 787 | 779 | 779 | 772 | 776 | 782 | 782 | 776 | 783 | 787 | 787 | 783 | 776 | 787 | 775 | 279 |
| 36.7 | 40 | 84 | 134 | 192 | 264 | 348 | 433 | 522 | 611 | 676 | 740 | 770 | 784 | 785 | 789 | 780 | 789 | 780 | 779 | 789 | 780 | 783 | 783 | 780 | 783 | 784 | 253 |
| 33.1 | 36 | 74 | 118 | 169 | 232 | 305 | 372 | 458 | 531 | 607 | 664 | 715 | 753 | 781 | 785 | 787 | 783 | 778 | 782 | 781 | 776 | 783 | 786 | 787 | 785 | 780 | 228 |
| 31.2 | 33 | 68 | 109 | 156 | 214 | 282 | 344 | 420 | 486 | 556 | 622 | 677 | 730 | 764 | 789 | 789 | 782 | 781 | 787 | 789 | 787 | 781 | 786 | 789 | 789 | 786 | 215 |
| 29.4 | 30 | 63 | 100 | 142 | 197 | 255 | 311 | 384 | 474 | 527 | 586 | 632 | 677 | 746 | 771 | 783 | 779 | 781 | 789 | 781 | 781 | 777 | 784 | 788 | 782 | 773 | 203 |
| 27.6 | 28 | 57 | 91 | 131 | 181 | 234 | 288 | 353 | 415 | 477 | 524 | 578 | 636 | 695 | 750 | 772 | 781 | 785 | 785 | 779 | 782 | 780 | 776 | 782 | 785 | 786 | 190 |
| 25.7 | 25 | 52 | 84 | 119 | 164 | 213 | 264 | 320 | 377 | 423 | 478 | 537 | 592 | 649 | 707 | 745 | 755 | 780 | 782 | 780 | 785 | 786 | 785 | 780 | 785 | 789 | 177 |
| 23.9 | 23 | 48 | 75 | 109 | 149 | 194 | 241 | 288 | 341 | 385 | 436 | 490 | 546 | 598 | 660 | 709 | 719 | 752 | 785 | 786 | 783 | 787 | 788 | 786 | 781 | 786 | 165 |
| 22.0 | 21 | 43 | 67 | 99 | 135 | 174 | 214 | 262 | 308 | 349 | 390 | 434 | 488 | 546 | 602 | 660 | 686 | 718 | 740 | 788 | 789 | 785 | 778 | 779 | 788 | 783 | 152 |
| 20.2 | 18 | 39 | 61 | 88 | 120 | 155 | 191 | 235 | 274 | 314 | 348 | 392 | 441 | 483 | 537 | 588 | 644 | 667 | 687 | 724 | 733 | 787 | 783 | 787 | 787 | 786 | 139 |
| 18.4 | 16 | 33 | 54 | 78 | 103 | 137 | 167 | 204 | 246 | 280 | 311 | 350 | 393 | 444 | 484 | 525 | 580 | 614 | 641 | 659 | 676 | 708 | 713 | 717 | 717 | 726 | 127 |
| 16.5 | 14 | 28 | 46 | 69 | 88 | 115 | 142 | 176 | 209 | 238 | 271 | 308 | 347 | 380 | 418 | 457 | 505 | 551 | 568 | 584 | 606 | 627 | 632 | 643 | 635 | 651 | 114 |
| 14.7 | 12 | 24 | 38 | 55 | 74 | 97 | 120 | 146 | 178 | 205 | 230 | 267 | 297 | 328 | 365 | 399 | 437 | 471 | 500 | 514 | 533 | 552 | 563 | 565 | 558 | 580 | 101 |
| 12.9 | 10 | 20 | 33 | 46 | 58 | 77 | 95 | 119 | 147 | 173 | 196 | 225 | 250 | 277 | 306 | 332 | 361 | 397 | 426 | 446 | 462 | 478 | 488 | 489 | 489 | 495 | 89 |
| 11.0 | 8 | 17 | 26 | 36 | 46 | 62 | 75 | 96 | 117 | 137 | 157 | 178 | 200 | 228 | 259 | 275 | 297 | 326 | 349 | 361 | 378 | 403 | 411 | 412 | 411 | 416 | 76 |
| 9.2 | 6 | 13 | 21 | 28 | 36 | 48 | 57 | 70 | 91 | 108 | 124 | 141 | 162 | 180 | 200 | 222 | 237 | 258 | 273 | 288 | 303 | 320 | 324 | 335 | 339 | 348 | 63 |
| 7.3 | 5 | 10 | 16 | 21 | 27 | 35 | 43 | 52 | 65 | 80 | 91 | 108 | 122 | 136 | 153 | 166 | 179 | 193 | 203 | 211 | 223 | 233 | 243 | 255 | 261 | 272 | 50 |
| 5.5 | 3 | 7 | 11 | 15 | 19 | 25 | 31 | 37 | 45 | 54 | 65 | 77 | 86 | 95 | 106 | 115 | 125 | 136 | 143 | 154 | 158 | 169 | 174 | 183 | 188 | 195 | 38 |
| 3.7 | 2 | 5 | 7 | 10 | 12 | 16 | 20 | 23 | 29 | 34 | 41 | 47 | 53 | 59 | 66 | 73 | 79 | 85 | 90 | 96 | 101 | 107 | 111 | 118 | 122 | 126 | 26 |
| 1.8 | 1 | 2 | 3 | 5 | 6 | 8 | 9 | 11 | 13 | 16 | 18 | 20 | 23 | 27 | 30 | 34 | 37 | 40 | 43 | 46 | 47 | 50 | 52 | 54 | 55 | 59 | 12 |
| 0.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Figure 28 - Corrected Fuel Flow Table

It is important to point out that the air/fuel ratio table included above uses ratios based on the gasoline stoichiometric ratio of 14.68:1. Oxygen sensors read lambda values and usually display the air/fuel ratios in gasoline equivalent scale, so even though the table above uses this scale, in reality the AFRs are much lower. 'Figure 29' below shows the actual goal AFRs when E85 is in use. The gasoline equivalent table though is the one, which was used with the Haltech EMS.

| Load (MAP) vs. RPMs - Actual Air/Fuel Ratio | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Load (PSIA) | 500 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 | 6500 | 7000 | 7500 | 8000 | 8500 | 9000 | 9500 | 10000 | 10500 | 11000 | 11500 | 12000 | 12500 | 13000 | Load (kPa) |
| 40.4 | 8.19 | 8.26 | 8.19 | 8.06 | 7.92 | 7.79 | 7.66 | 7.52 | 7.39 | 7.25 | 7.25 | 7.25 | 7.32 | 7.32 | 7.32 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 279 |
| 36.7 | 8.33 | 8.33 | 8.26 | 8.19 | 8.06 | 7.92 | 7.79 | 7.66 | 7.52 | 7.39 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 253 |
| 33.1 | 8.39 | 8.39 | 8.33 | 8.26 | 8.19 | 8.06 | 7.99 | 7.86 | 7.72 | 7.59 | 7.45 | 7.39 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 228 |
| 31.2 | 8.46 | 8.39 | 8.39 | 8.33 | 8.26 | 8.13 | 8.06 | 7.99 | 7.86 | 7.72 | 7.59 | 7.52 | 7.39 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 215 |
| 29.4 | 8.46 | 8.46 | 8.46 | 8.33 | 8.33 | 8.26 | 8.19 | 8.06 | 7.59 | 7.59 | 7.59 | 7.59 | 7.59 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 203 |
| 27.6 | 8.46 | 8.46 | 8.46 | 8.39 | 8.39 | 8.33 | 8.19 | 8.13 | 8.06 | 7.79 | 7.79 | 7.79 | 7.59 | 7.39 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 190 |
| 25.7 | 8.53 | 8.46 | 8.46 | 8.46 | 8.39 | 8.39 | 8.33 | 8.26 | 8.06 | 7.99 | 7.86 | 7.72 | 7.59 | 7.45 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 177 |
| 23.9 | 8.60 | 8.53 | 8.53 | 8.46 | 8.46 | 8.46 | 8.39 | 8.33 | 8.19 | 8.06 | 7.92 | 7.79 | 7.66 | 7.52 | 7.39 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 165 |
| 22.0 | 8.66 | 8.53 | 8.53 | 8.46 | 8.46 | 8.46 | 8.46 | 8.33 | 8.26 | 8.19 | 8.06 | 7.99 | 7.79 | 7.59 | 7.45 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 152 |
| 20.2 | 8.73 | 8.60 | 8.53 | 8.46 | 8.60 | 8.60 | 8.60 | 8.39 | 8.33 | 8.26 | 8.19 | 8.13 | 7.92 | 7.79 | 7.59 | 7.39 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 139 |
| 18.4 | 8.80 | 8.73 | 8.66 | 8.46 | 8.73 | 8.73 | 8.73 | 8.60 | 8.33 | 8.33 | 8.26 | 8.19 | 7.99 | 7.72 | 7.59 | 7.45 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 127 |
| 16.5 | 8.86 | 8.86 | 8.73 | 8.46 | 8.93 | 8.93 | 8.93 | 8.73 | 8.60 | 8.60 | 8.39 | 8.26 | 8.13 | 7.99 | 7.79 | 7.59 | 7.39 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 114 |
| 14.7 | 8.93 | 9.00 | 9.13 | 9.13 | 9.13 | 9.13 | 9.07 | 8.86 | 8.73 | 8.66 | 8.60 | 8.39 | 8.26 | 8.06 | 7.86 | 7.66 | 7.52 | 7.39 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 101 |
| 12.9 | 9.00 | 9.13 | 9.27 | 9.33 | 9.33 | 9.33 | 9.33 | 9.13 | 8.93 | 8.86 | 8.73 | 8.53 | 8.39 | 8.26 | 8.13 | 7.99 | 7.79 | 7.59 | 7.39 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 89 |
| 11.0 | 9.07 | 9.27 | 9.47 | 9.54 | 9.54 | 9.47 | 9.47 | 9.27 | 9.20 | 9.20 | 8.93 | 8.86 | 8.86 | 8.46 | 8.26 | 8.13 | 7.99 | 7.79 | 7.59 | 7.45 | 7.39 | 7.25 | 7.25 | 7.25 | 7.25 | 7.25 | 76 |
| 9.2 | 9.13 | 9.40 | 9.54 | 9.67 | 9.67 | 9.67 | 9.60 | 9.54 | 9.47 | 9.40 | 9.20 | 9.07 | 8.93 | 8.73 | 8.53 | 8.33 | 8.26 | 8.06 | 7.92 | 7.72 | 7.59 | 7.45 | 7.39 | 7.25 | 7.25 | 7.25 | 63 |
| 7.3 | 9.13 | 9.54 | 9.60 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.60 | 9.40 | 9.20 | 9.07 | 8.93 | 8.73 | 8.60 | 8.46 | 8.33 | 8.26 | 8.13 | 7.99 | 7.79 | 7.59 | 7.45 | 7.39 | 7.25 | 50 |
| 5.5 | 9.33 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.60 | 9.40 | 9.27 | 9.13 | 9.00 | 8.86 | 8.66 | 8.46 | 8.39 | 8.06 | 8.06 | 7.79 | 7.79 | 7.59 | 7.59 | 7.39 | 38 |
| 3.7 | 9.47 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.60 | 9.40 | 9.27 | 9.13 | 9.00 | 8.86 | 8.73 | 8.60 | 8.39 | 8.19 | 8.06 | 8.06 | 7.79 | 7.79 | 7.59 | 26 |
| 1.8 | 9.60 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.60 | 9.40 | 9.27 | 9.13 | 9.00 | 8.86 | 8.66 | 8.46 | 8.39 | 8.26 | 8.19 | 8.06 | 8.06 | 7.79 | 12 |
| 0.0 | 9.74 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.87 | 9.60 | 9.40 | 9.27 | 9.13 | 8.93 | 8.73 | 8.60 | 8.46 | 8.39 | 8.33 | 8.26 | 8.13 | 8.06 | 0 |

Figure 29 - Actual Air/Fuel Ratio Table

Based on the baseline pressure in the fuel system and the injectors used (260cc), the injector duty cycle and Injector pulse width (IPW) tables were populated. Those can be seen below in 'Figures 30 and 31'. IPW signifies the time in milliseconds for which the injector stays open. This is the way the ECU controls fuel delivery.

| Load (MAP) vs. RPMs - Injector Duty Cycle in % | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Load (PSIA) | 500 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 | 6500 | 7000 | 7500 | 8000 | 8500 | 9000 | 9500 | 10000 | 10500 | 11000 | 11500 | 12000 | 12500 | 13000 | Load (kPa) |
| 40.4 | 5 | 10 | 15 | 22 | 30 | 40 | 50 | 60 | 67 | 74 | 79 | 79 | 78 | 79 | 78 | 78 | 79 | 79 | 78 | 79 | 79 | 79 | 79 | 78 | 79 | 78 | 279 |
| 36.7 | 4 | 8 | 14 | 19 | 27 | 35 | 44 | 53 | 62 | 68 | 75 | 78 | 79 | 79 | 80 | 79 | 80 | 79 | 79 | 80 | 79 | 79 | 79 | 79 | 79 | 79 | 253 |
| 33.1 | 4 | 7 | 12 | 17 | 23 | 31 | 38 | 46 | 53 | 61 | 67 | 72 | 76 | 79 | 79 | 79 | 79 | 78 | 79 | 79 | 78 | 79 | 79 | 79 | 79 | 79 | 228 |
| 31.2 | 3 | 7 | 11 | 16 | 22 | 28 | 35 | 42 | 49 | 56 | 63 | 68 | 74 | 77 | 80 | 80 | 79 | 79 | 79 | 80 | 79 | 79 | 79 | 80 | 80 | 79 | 215 |
| 29.4 | 3 | 6 | 10 | 14 | 20 | 26 | 31 | 39 | 48 | 53 | 59 | 64 | 68 | 75 | 78 | 79 | 79 | 79 | 80 | 79 | 79 | 78 | 79 | 79 | 79 | 78 | 203 |
| 27.6 | 3 | 6 | 9 | 13 | 18 | 24 | 29 | 36 | 42 | 48 | 53 | 58 | 64 | 70 | 76 | 78 | 79 | 79 | 79 | 79 | 79 | 79 | 78 | 79 | 79 | 79 | 190 |
| 25.7 | 3 | 5 | 8 | 12 | 17 | 22 | 27 | 32 | 38 | 43 | 48 | 54 | 60 | 65 | 71 | 75 | 76 | 79 | 79 | 79 | 79 | 79 | 79 | 79 | 79 | 79 | 177 |
| 23.9 | 2 | 5 | 8 | 11 | 15 | 20 | 24 | 29 | 34 | 39 | 44 | 49 | 55 | 60 | 67 | 71 | 72 | 76 | 79 | 79 | 79 | 79 | 79 | 79 | 79 | 79 | 165 |
| 22.0 | 2 | 4 | 7 | 10 | 14 | 18 | 22 | 26 | 31 | 35 | 39 | 44 | 49 | 55 | 61 | 67 | 69 | 72 | 75 | 79 | 79 | 79 | 78 | 79 | 79 | 79 | 152 |
| 20.2 | 2 | 4 | 6 | 9 | 12 | 16 | 19 | 24 | 28 | 32 | 35 | 40 | 44 | 49 | 54 | 59 | 65 | 67 | 69 | 73 | 74 | 79 | 79 | 79 | 79 | 79 | 139 |
| 18.4 | 2 | 3 | 5 | 8 | 10 | 14 | 17 | 21 | 25 | 28 | 31 | 35 | 40 | 45 | 49 | 53 | 58 | 62 | 65 | 66 | 68 | 71 | 72 | 72 | 72 | 73 | 127 |
| 16.5 | 1 | 3 | 5 | 7 | 9 | 12 | 14 | 18 | 21 | 24 | 27 | 31 | 35 | 38 | 42 | 46 | 51 | 56 | 57 | 59 | 61 | 63 | 64 | 65 | 64 | 66 | 114 |
| 14.7 | 1 | 2 | 4 | 6 | 7 | 10 | 12 | 15 | 18 | 21 | 23 | 27 | 30 | 33 | 37 | 40 | 44 | 47 | 50 | 52 | 54 | 56 | 57 | 57 | 56 | 58 | 101 |
| 12.9 | 1 | 2 | 3 | 5 | 6 | 8 | 10 | 12 | 15 | 17 | 20 | 23 | 25 | 28 | 31 | 33 | 36 | 40 | 43 | 45 | 47 | 48 | 49 | 49 | 49 | 50 | 89 |
| 11.0 | 1 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 23 | 26 | 28 | 30 | 33 | 35 | 36 | 38 | 41 | 41 | 41 | 41 | 42 | 76 |
| 9.2 | 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 9 | 11 | 13 | 14 | 16 | 18 | 20 | 22 | 24 | 26 | 28 | 29 | 31 | 32 | 33 | 34 | 34 | 35 | 63 |
| 7.3 | 0 | 1 | 2 | 2 | 3 | 3 | 4 | 5 | 7 | 8 | 9 | 11 | 12 | 14 | 15 | 17 | 18 | 19 | 20 | 21 | 22 | 24 | 25 | 26 | 26 | 27 | 50 |
| 5.5 | 0 | 1 | 1 | 2 | 2 | 2 | 3 | 4 | 5 | 5 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 14 | 16 | 16 | 17 | 18 | 18 | 19 | 20 | 38 |
| 3.7 | 0 | 0 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 | 4 | 5 | 5 | 6 | 7 | 7 | 8 | 9 | 9 | 10 | 10 | 11 | 11 | 12 | 12 | 13 | 26 |
| 1.8 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 6 | 6 | 12 |
| 0.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Figure 30 - Injector Duty Cycle Table

| Load (MAP) vs. RPMs - Injector Pulse Width in ms | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Load (PSIA) | 500 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 | 6500 | 7000 | 7500 | 8000 | 8500 | 9000 | 9500 | 10000 | 10500 | 11000 | 11500 | 12000 | 12500 | 13000 | Load (kPa) |
| 40.4 | 10.9 | 11.6 | 12.2 | 13.2 | 14.5 | 15.9 | 17.0 | 17.9 | 17.8 | 17.7 | 17.3 | 15.9 | 14.5 | 13.5 | 12.4 | 11.7 | 11.1 | 10.5 | 9.9 | 9.5 | 9.1 | 8.7 | 8.2 | 7.8 | 7.6 | 7.2 | 279 |
| 36.7 | 9.8 | 10.1 | 10.8 | 11.6 | 12.8 | 14.0 | 15.0 | 15.8 | 16.4 | 16.3 | 16.3 | 15.5 | 14.6 | 13.6 | 12.7 | 11.8 | 11.2 | 10.5 | 9.9 | 9.5 | 9.0 | 8.6 | 8.2 | 7.9 | 7.6 | 7.3 | 253 |
| 33.1 | 8.6 | 8.9 | 9.6 | 10.2 | 11.2 | 12.3 | 12.9 | 13.9 | 14.3 | 14.7 | 14.6 | 14.4 | 14.0 | 13.5 | 12.7 | 11.9 | 11.1 | 10.5 | 10.0 | 9.4 | 8.9 | 8.6 | 8.3 | 7.9 | 7.6 | 7.3 | 228 |
| 31.2 | 7.9 | 8.2 | 8.8 | 9.4 | 10.3 | 11.4 | 11.9 | 12.7 | 13.1 | 13.4 | 13.7 | 13.7 | 13.6 | 13.2 | 12.7 | 11.9 | 11.1 | 10.5 | 10.0 | 9.5 | 9.1 | 8.6 | 8.3 | 8.0 | 7.6 | 7.3 | 215 |
| 29.4 | 7.3 | 7.6 | 8.1 | 8.6 | 9.5 | 10.3 | 10.7 | 11.6 | 12.7 | 12.7 | 12.9 | 12.7 | 12.6 | 12.9 | 12.4 | 11.8 | 11.1 | 10.5 | 10.0 | 9.4 | 9.0 | 8.5 | 8.2 | 7.9 | 7.6 | 7.2 | 203 |
| 27.6 | 6.8 | 6.9 | 7.4 | 7.9 | 8.8 | 9.4 | 10.0 | 10.7 | 11.1 | 11.5 | 11.5 | 11.7 | 11.8 | 12.0 | 12.1 | 11.7 | 11.1 | 10.6 | 10.0 | 9.4 | 9.0 | 8.6 | 8.2 | 7.9 | 7.6 | 7.3 | 190 |
| 25.7 | 6.1 | 6.3 | 6.7 | 7.2 | 7.9 | 8.6 | 9.1 | 9.7 | 10.1 | 10.2 | 10.5 | 10.8 | 11.0 | 11.2 | 11.4 | 11.3 | 10.7 | 10.5 | 10.0 | 9.4 | 9.0 | 8.6 | 8.3 | 7.9 | 7.6 | 7.3 | 177 |
| 23.9 | 5.6 | 5.8 | 6.0 | 6.6 | 7.2 | 7.8 | 8.3 | 8.7 | 9.2 | 9.3 | 9.6 | 9.9 | 10.2 | 10.3 | 10.6 | 10.7 | 10.2 | 10.1 | 10.0 | 9.5 | 9.0 | 8.7 | 8.3 | 7.9 | 7.6 | 7.3 | 165 |
| 22.0 | 5.0 | 5.2 | 5.4 | 6.0 | 6.5 | 7.0 | 7.4 | 7.9 | 8.3 | 8.4 | 8.6 | 8.8 | 9.1 | 9.4 | 9.7 | 10.0 | 9.8 | 9.6 | 9.4 | 9.5 | 9.1 | 8.6 | 8.2 | 7.9 | 7.6 | 7.3 | 152 |
| 20.2 | 4.4 | 4.7 | 4.9 | 5.3 | 5.8 | 6.3 | 6.6 | 7.1 | 7.4 | 7.6 | 7.7 | 7.9 | 8.2 | 8.3 | 8.7 | 8.9 | 9.2 | 9.0 | 8.8 | 8.8 | 8.4 | 8.7 | 8.2 | 7.9 | 7.6 | 7.3 | 139 |
| 18.4 | 3.9 | 4.1 | 4.3 | 4.7 | 5.0 | 5.5 | 5.8 | 6.2 | 6.6 | 6.8 | 6.8 | 7.1 | 7.3 | 7.7 | 7.8 | 7.9 | 8.3 | 8.3 | 8.2 | 8.0 | 7.8 | 7.8 | 7.5 | 7.2 | 6.9 | 6.8 | 127 |
| 16.5 | 3.3 | 3.4 | 3.7 | 4.2 | 4.2 | 4.6 | 4.9 | 5.3 | 5.6 | 5.7 | 6.0 | 6.2 | 6.5 | 6.6 | 6.7 | 6.9 | 7.2 | 7.4 | 7.2 | 7.1 | 7.0 | 6.9 | 6.6 | 6.5 | 6.1 | 6.1 | 114 |
| 14.7 | 2.8 | 2.9 | 3.1 | 3.3 | 3.6 | 3.9 | 4.1 | 4.4 | 4.8 | 5.0 | 5.1 | 5.4 | 5.5 | 5.7 | 5.9 | 6.0 | 6.2 | 6.3 | 6.4 | 6.2 | 6.1 | 6.1 | 5.9 | 5.7 | 5.4 | 5.4 | 101 |
| 12.9 | 2.3 | 2.5 | 2.6 | 2.8 | 2.8 | 3.1 | 3.3 | 3.6 | 4.0 | 4.2 | 4.3 | 4.5 | 4.7 | 4.8 | 4.9 | 5.0 | 5.1 | 5.3 | 5.4 | 5.4 | 5.3 | 5.3 | 5.1 | 4.9 | 4.7 | 4.6 | 89 |
| 11.0 | 1.9 | 2.0 | 2.1 | 2.2 | 2.2 | 2.5 | 2.6 | 2.9 | 3.1 | 3.3 | 3.5 | 3.6 | 3.7 | 3.9 | 4.2 | 4.2 | 4.2 | 4.4 | 4.4 | 4.4 | 4.3 | 4.4 | 4.3 | 4.1 | 4.0 | 3.9 | 76 |
| 9.2 | 1.5 | 1.6 | 1.7 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.4 | 2.6 | 2.7 | 2.9 | 3.0 | 3.1 | 3.2 | 3.3 | 3.4 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.4 | 3.4 | 3.3 | 3.2 | 63 |
| 7.3 | 1.2 | 1.2 | 1.3 | 1.3 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.9 | 2.0 | 2.2 | 2.3 | 2.4 | 2.5 | 2.5 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.5 | 2.5 | 50 |
| 5.5 | 0.8 | 0.9 | 0.9 | 0.9 | 0.9 | 1.0 | 1.1 | 1.1 | 1.2 | 1.3 | 1.4 | 1.6 | 1.6 | 1.6 | 1.7 | 1.7 | 1.8 | 1.8 | 1.8 | 1.9 | 1.8 | 1.9 | 1.8 | 1.8 | 1.8 | 1.8 | 38 |
| 3.7 | 0.5 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.7 | 0.7 | 0.8 | 0.8 | 0.9 | 1.0 | 1.0 | 1.0 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 26 |
| 1.8 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.6 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 12 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0 |

Figure 31 - Injector Pulse Width Table

### 4.6.2 Data Acquisition Process

The total sensors used to acquire the input data for the ECU maps were five. First, a Haltech 3-bar manifold absolute pressure (MAP) sensor was attached very close to the intake manifold, to minimize the measurement latency. It provides the vacuum/pressure reading necessary to run speed density. The MAP sensor was also set up to be used for data-logging, so the team could find out exactly how much pressure the turbocharger was generating. The 3-bar nomenclature refers to the maximum absolute pressure the sensor is able to measure. This allows a range for this sensor between 29.4inHg and 28.8psi (0-5V). These are the values called upon in the Haltech MAP sensor setup window, which calibrate the function of the sensor.

A Haltech intake air temperature (IAT) sensor was also used. It was threaded directly into the intake manifold and it provided the temperature readings necessary for the ECU to run speed density accurately. The IAT could also be used to log the temperature increase associated with the increase in the pressure ratio through the turbocharger.

A Haltech coolant temperature sensor (CTS) was also utilized in this system, both for temperature-based fuel enrichment, as well as for coolant temperature logging through the ECU.

Furthermore, an Innovate wideband O2 sensor was used to monitor the air/fuel ratios that the engine produces. This sensor acts as a feedback to the ECU, which adjusts the fuel offset based on these readings, in order to obtain the requested air/fuel ratio. It is also imperative to use this sensor in order to dial-in the VE table correctly. The settings necessary for the ECU to read the output of this sensor are 7.4:1 at 0V and 22:1 at 5V.

Finally, the throttle position sensor, designed to be used with the purchased intake pipe, was added to the system. Haltech is able to manually set the voltages representative of 0% throttle and 100% throttle. This is how the TPS was calibrated and this very calibration is critical, since most of the maps used by the EMS are selected based on throttle position.

### 4.6.3 EMS Configuration

Since the engine was originally carbureted, it does not have a camshaft angle sensor. Due to its design, it is virtually impossible to insert one such sensor, so the entire piston position information is generated by a low-resolution, hall-effect crank angle sensor. Therefore, the trigger type used to provide information to the EMS is a 'No Home' type. This means that the injectors have to fire twice, during the intake and the power strokes. This is inevitable since the EMS only knows that cylinders #1 and #4 are at top dead center (TDC) but it does not know which part of the 4 stroke cycle they are in. This fueling mode is called Batch fire and is inferior to the alternatives possible with a homing signal coming from the camshaft angle sensor. The trigger angle of that specific sensor is 40 degrees and the trigger edge type is 'Falling'.

Furthermore, the injectors used in this project would have been an appropriate size if Batch mode wasn't used. Due to the fact that the injectors fire twice, the pulse width was divided by two. This takes an already short IPW at idle and cuts it in half. What resulted was a requested pulse width that was impossible to be executed by the injectors, since every injector has a certain IPW minimum that it can execute. At the instances when the value went lower than the minimum IPW, the cylinder no longer received fuel and the car stalled out. Lowering the system fuel pressure would effectively downsize the injector, which would increase the required IPW. Therefore, the FSAE vehicle was set up with a baseline fuel pressure of 25psig (instead of 43.5psig). This pressure can be adjusted using the adjustable fuel pressure regulator, which was mounted onto the fuel rail. Dropping fuel pressure to very low values can bring about problems, since the injector flow profile will change. Therefore, it is not recommended that a baseline pressure lower than 25psig is used. Even through lowering the fuel pressure, the car could only remain idling at 2500RPM, under a very rich idle air/fuel ratio. The rich idle is usually responsible for idle 'surging' and that was also observed in this project.

Due to the lack of a camshaft angle sensor, the EMS also could not predict the location of cylinders #2 and #3. Therefore, it was necessary to install an external ignition module, which utilized a secondary to the system, built-in loop, through which the position of the middle two cylinders could be determined. This is the only way spark could be produced in both ignition coils without either using a camshaft angle sensor or modifying the crank sensor to have dual, opposite in charge magnets. Although functional and somewhat tunable, the ignition management of the external module was far inferior to the tuning capabilities through the ECU, so the team lost a valuable tuning tool when the decision to use the external module was made.

## 4.7 Final Steps

Once the car was entirely assembled (as seen in 'Appendix 2: Turbo-System Schematics') and the EMS was configured well enough that the car could start up and rev freely, the vehicle was towed back to 'New England Dyno & Tune' for some tuning time at realistic engine loads. This was where wide-open throttle (WOT) tuning was performed so that the maximum, safe power and torque could be extracted from the vehicle. Once this was done, the 'before' and 'after' results were compiled and compared to each other. At this point, the tuning part of the project was considered completed although the car was not entirely tuned for drivability. The issues that became evident at the dyno were corrected, so that the car would operate as designed.

# Chapter 5: Project Results

## 5.1 Results Overview

When the car was taken to the dynamometer to obtain new readings, the timing was set to a conservative 18 degrees maximum advance. In addition, the turbocharger was run at 3psig, which is the minimum possible pressure that the compressor could output at full load. It was decided that for safety reasons the car should slowly be revved higher and higher, based on 1000-2000 RPM increments, starting at 5000RPM. In this manner, the car was retuned step by step until it produced 72 horsepower and 40 lb*ft of torque at a 9,500 RPM peak. 'Figure 32' below shows the 'before' and 'after' graphs inserted into a common plot:

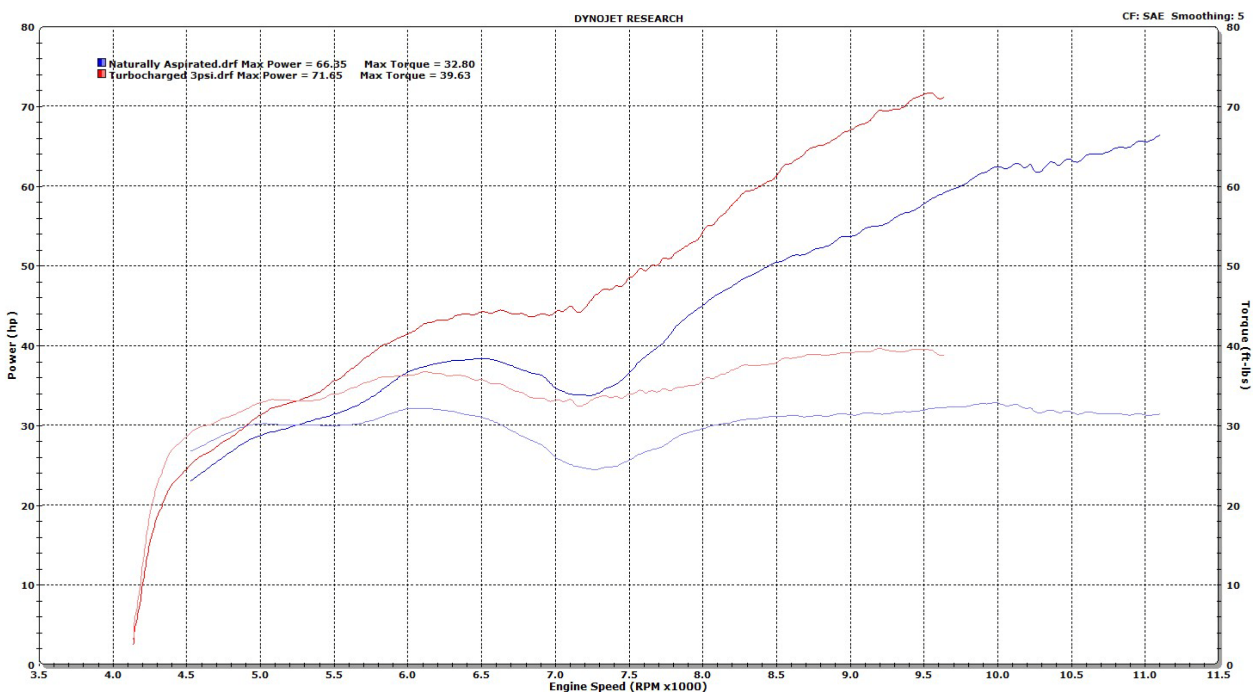



Figure 32 - Dynamometer Results

The red lines represent the performance output with the added turbocharger, while the blue lines represent the car in its naturally aspirated configuration. If the peak values are compared (72whp, 40wtq vs. 66whp, 33wtq), a power gain of 10% and a torque gain of 20% are concluded. This is not an accurate comparison though, since the horsepower peak depends on the maximum RPM reached by the engine. Since the turbocharged setup was only revved to

9,500 RPM, while the naturally aspirated setup was revved to 11,000 RPM, it is only fair to compare the values at the same RPM instance. Based on the trend seen in the graph, it is estimated that the turbocharged setup would make near 80 horsepower if it were revved to 11,000 RPM. This is theoretical though, so for best results, horsepower and torque readings must be compared at the same RPM value. At 9,500 RPM, the torque increase and the power increase are roughly 20%. This value (20%) remains fairly constant throughout the RPM range and should therefore be used as the overall gain value.

The weight added by the turbo-system was estimated to be roughly 30 pounds. The car was weighed after the turbo-system was installed and the resulting weight was 520 pounds. This suggests that in its naturally aspirated configuration, the vehicle weighed roughly 490 pounds. Therefore, the turbo-system increased the weight of the racecar by roughly 6%.

When cost is considered, it can be concluded that adding a turbocharger system to a naturally aspirated engine is not unreasonably costly. The most expensive part of this project was the engine management system, which is required regardless of whether or not the vehicle is turbocharged. The project budget can be seen in 'Appendix 7: Project Budget'.

In conclusion, a 20% increase in power and torque in a vehicle which has a severe airflow restriction should render the project successful regardless of other factors. If weight gains and cost were considered though, it still appears that adding a turbocharger to a naturally aspirated engine outweighs the downsides associated with doing so. Therefore, the team considers this project a total success!

## 5.2 Detailed Powerband Analysis

A powerband of an engine is its primary operating range. The minimum and maximum engine speeds are typically determined by engine geometry such as bore/stroke ratio and overall configuration. The powerband is designed around the intended use of the vehicle. A vehicle can be used for towing, commuting, racing, etc. Each design scenario will have different parameters, which will be altered. The powerband of an engine can be tweaked through changing the maximum engine speed (redline), through cam selection, through intake and exhaust manifold design, and through turbocharger sizing. A city transportation bus will have different requirements than a motorcycle designed for track use.

The basic laws of motion govern the motion of a vehicle. The acceleration is proportional to the force and inversely proportional to the mass. For a racecar, the acceleration should be optimized by increasing the force as much as reasonably possible and reducing unnecessary mass. 'Eq. 19' below shows the interaction between force, mass, and acceleration:

$$Force = Mass * Acceleration \quad [Eq. 19]$$

The two primary ways to characterize and engine's performance are the power and torque that they produce. These two characteristics are linked by engine speed, as seen below in 'Eq. 20':

$$Power\ (watts) = Torque\ (N * m) * Engine\ Speed\ \left(\frac{radians}{\text{sec}}\right) \quad [Eq. 20]$$

In order to increase the power of a vehicle, there needs to be an increase in the torque and/or engine speed. Power plays a crucial role in the dynamics of a vehicle. The power output required to sustain a certain force (mainly drag) at a certain velocity is:

$$Power = Force * Velocity \quad [Eq. 21]$$

The force from an engine is calculated from the engine torque after drivetrain losses, multiplied by the various gear ratios for that selected gear and divided by the wheel radius. This can be seen below in 'Eq. 22':

$$Force\ from\ Engine = \frac{Engine\ Torque\ after\ losess * Gear\ Ratios}{Wheel\ Radius} \quad [Eq. 22]$$

where

$$Torque = Force * Radius \quad [Eq. 23]$$

The power of an engine can be estimated by the heat of combustion of the fuel, the fuel mass flow rate, and the energy conversion efficiency. This relationship is shown below in 'Eq. 24':

$$Power\ Ouput = Conversion\ Efficiency * Heat\ of\ Combustion * Fuel\ Mass\ Flow\ Rate \quad [Eq. 24]$$

The conversion efficiency is the product of the various efficiencies affecting the process of converting chemical energy to mechanical energy. This can include anything from combustion efficiency, thermal efficiencies (heat losses to cylinder walls, exhaust to atmosphere, etc.), and mechanical efficiencies (spark timing, compression ratio, etc.). This conversion efficiency value is typically between 25% and 35%, depending on various factors. Several ways to improve this percentage are increasing the compression ratio (mechanical), optimizing ignition timing (mechanical), and optimizing the combustion process through better fuel injection techniques.

The next variable in the equation is the heat of combustion for the given fuel. This is a chemical value, which cannot be modified without mixing fuels. A table containing the heat of combustion values of common fuels is shown below in 'Table 3':

| Fuel | kJ/g | BTU/lb |
|---|---|---|
| Hydrogen | 141.9 | 61000 |
| Gasoline | 47 | 20000 |
| Diesel | 45 | 19300 |
| Ethanol | 29.8 | 12000 |
| Propane | 49.9 | 21000 |
| Butane | 49.2 | 21200 |
| Wood | 15 | 6000 |
| Coal (Lignite) | 15 | 8000 |
| Coal (Anthracite) | 27 | 14000 |
| Natural Gas | 54 | 23000 |

Table 3 - Fuel Type vs. Heat of Combustion

The final, and most alterable variable in the equation for power is the fuel mass flow rate. This rate is dependent on the air mass flow rate, combined with the air/fuel ratio. The AFR is dependent on the engine loading requirements, factored onto the stoichiometric values for the combustion reaction. The air mass flow rate is dependent on the volumetric flow rate of the engine, the volumetric efficiency, and the charge of the density. The density of the charge is dependent on the pressure and temperature. The use of a turbocharger increases the density of the charge and therefore the air mass flow rate. This consequently increases the fuel mass flow rate, which results in a higher amount of power output at the same engine speed, for a given displacement.

### Understanding a Dynamometer Graph:

A dynamometer graph is a set of data that describes the performance of an internal combustion engine throughout its RPM range. These graphs plot the engine power and torque (y-axis) over the usable powerband of that engine (engine speed in x-axis). For the goals associated with a motorcycle, an engine that can achieve high RPMs and power will provide the best match for highest performance. Below, once again, is the dyno graph for the FSAE car before and after the turbo-system addition. With a fairly steady torque curve, the power climbs with engine speed.

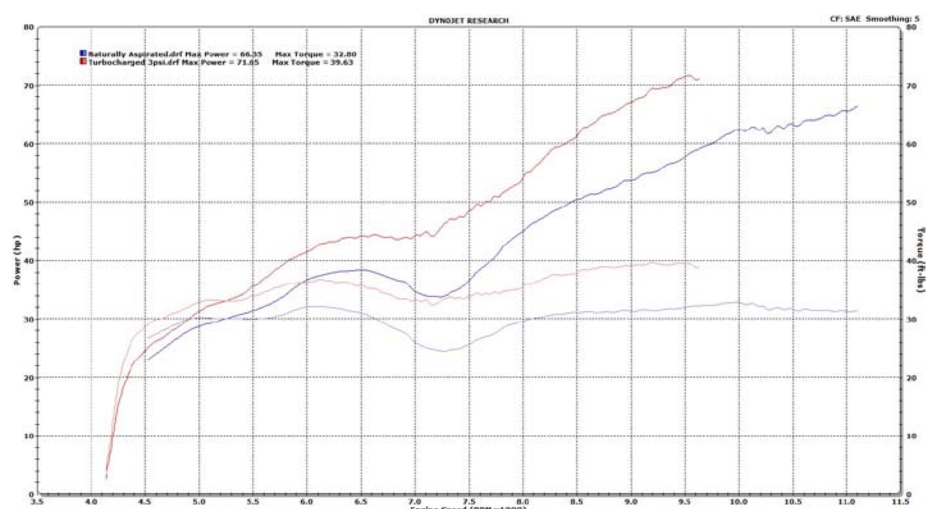



Figure 33 - Dynamometer Results

### Vehicle Propulsion Dynamics:

With the data available from the dynamometer testing, as well as the gear ratios and tire diameter, an accurately estimated acceleration analysis can be performed. The propulsive force from a vehicle is provided by the engine through the torque multiplications of the drivetrain. This relationship is show in 'Eq. 25'.

$$Propulsive\ Force = \frac{Engine\ Torque\ (after\ losses) * Transmission\ Ratio * Transfer\ Case\ Ratio * Final\ Drive}{Wheel\ Radius}$$

$$[Eq. 25]$$

Below are the gear ratios for the Honda F3 gear set. The final drive is the product of the final reduction from the gearbox multiplied by the ratio of the teeth on the sprockets. From the equation above, the momentary propulsive force can be increased by increasing the engine torque, having a numerically higher transmission and final drive ratio, or a smaller wheel radius.

| Gear | Honda F3 |
|---|---|
| 1 | 2.928 |
| 2 | 2.062 |
| 3 | 1.647 |
| 4 | 1.368 |
| 5 | 1.200 |
| 6 | 1.086 |
| **Final** | 5.988 |

Table 4 - Honda F3 Gear Ratios

The portion of the worksheet that incorporates the predicted vehicle acceleration for a given road speed can be seen below in 'Figure 34':

| | A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **Engine Speed (rpm)** | **4500** | **5000** | **5500** | **6000** | **6500** | **7000** | **7500** | **8000** | **8500** | **9000** | **9500** | **10000** |
| 2 | **Power (hp)** | 23.27 | 28.73 | 31.34 | 36.62 | 38.36 | 34.7 | 36.51 | 44.99 | 50.36 | 53.63 | 57.72 | 62.55 |
| 3 | **Torque (ft-lb)** | 26.87 | 30.18 | 29.93 | 32.05 | 31 | 26.04 | 25.57 | 29.54 | 31.12 | 31.29 | 31.91 | 32.8 |
| 4 | **1st Gear Accel (m/s^2)** | 8.78 | 9.86 | 9.77 | 10.45 | 10.09 | 8.45 | 8.28 | 9.57 | 10.07 | 10.11 | 10.29 | 10.56 |
| 5 | **1st Gear Speed (mph)** | 14.5 | 16.1 | 17.7 | 19.3 | 21.0 | 22.6 | 24.2 | 25.8 | 27.4 | 29.0 | 30.6 | 32.2 |
| 6 | **1st Gear Drag (N)** | 12.6 | 15.6 | 18.8 | 22.4 | 26.3 | 30.5 | 35.0 | 39.9 | 45.0 | 50.5 | 56.2 | 62.3 |
| 7 | **2nd Gear Accel** | 6.13 | 6.87 | 6.80 | 7.26 | 6.99 | 5.82 | 5.68 | 6.56 | 6.89 | 6.90 | 7.00 | 7.17 |
| 8 | **2nd Gear Speed (mph)** | 20.6 | 22.9 | 25.2 | 27.5 | 29.8 | 32.0 | 34.3 | 36.6 | 38.9 | 41.2 | 43.5 | 45.8 |
| 9 | **2nd Gear Drag (N)** | 25.4 | 31.4 | 38.0 | 45.2 | 53.1 | 61.5 | 70.7 | 80.4 | 90.8 | 101.7 | 113.4 | 125.6 |
| 10 | **3rd Gear Accel** | 4.83 | 5.41 | 5.33 | 5.68 | 5.45 | 4.49 | 4.35 | 5.04 | 5.27 | 5.25 | 5.30 | 5.40 |
| 11 | **3rd Gear Speed (mph)** | 25.8 | 28.7 | 31.5 | 34.4 | 37.3 | 40.1 | 43.0 | 45.8 | 48.7 | 51.6 | 54.4 | 57.3 |
| 12 | **3rd Gear Drag (N)** | 39.9 | 49.2 | 59.6 | 70.9 | 83.2 | 96.5 | 110.7 | 126.0 | 142.2 | 159.5 | 177.7 | 196.9 |
| 13 | **4th Gear Accel** | 3.93 | 4.39 | 4.30 | 4.57 | 4.35 | 3.53 | 3.39 | 3.92 | 4.09 | 4.03 | 4.04 | 4.08 |
| 14 | **4th Gear Speed (mph)** | 31.0 | 34.5 | 37.9 | 41.4 | 44.8 | 48.3 | 51.7 | 55.2 | 58.6 | 62.1 | 65.5 | 69.0 |
| 15 | **4th Gear Drag (N)** | 57.8 | 71.3 | 86.3 | 102.7 | 120.6 | 139.8 | 160.5 | 182.6 | 206.2 | 231.2 | 257.6 | 285.4 |
| 16 | **5th Gear Accel** | 3.37 | 3.75 | 3.65 | 3.87 | 3.65 | 2.90 | 2.75 | 3.18 | 3.30 | 3.21 | 3.18 | 3.18 |
| 17 | **5th Gear Speed (mph)** | 35.4 | 39.3 | 43.3 | 47.2 | 51.1 | 55.1 | 59.0 | 62.9 | 66.9 | 70.8 | 74.7 | 78.7 |
| 18 | **5th Gear Drag (N)** | 75.1 | 92.7 | 112.2 | 133.5 | 156.7 | 181.7 | 208.6 | 237.4 | 268.0 | 300.4 | 334.7 | 370.9 |
| 19 | **6th Gear Accel** | 2.97 | 3.30 | 3.19 | 3.36 | 3.14 | 2.43 | 2.27 | 2.63 | 2.70 | 2.59 | 2.52 | 2.49 |
| 20 | **6th Gear Speed (mph)** | 39.1 | 43.5 | 47.8 | 52.1 | 56.5 | 60.8 | 65.2 | 69.5 | 73.9 | 78.2 | 82.6 | 86.9 |
| 21 | **6th Gear Drag (N)** | 91.7 | 113.2 | 137.0 | 163.0 | 191.3 | 221.9 | 254.7 | 289.8 | 327.2 | 366.8 | 408.7 | 452.8 |

Figure 34 - Naturally Aspirated - Vehicle Acceleration vs. Road Speed Table

The road speed value is determined by the wheel radius, the gear ratios, and the engine speed:

$$Road\ Speed = \frac{Engine\ RPM}{Trans\ Ratio * Final\ Drive\ Ratio} * Tire\ Diameter \quad [Eq. 26]$$

The spreadsheet is set up to show the road speeds for each gear at each engine speed. Accordingly, the acceleration is predicted using simple physics (the propulsive force/mass equation) for those engine speeds. The resulting acceleration vs. road speed chart is produced from this data. This chart can be seen below in 'Figure 35':

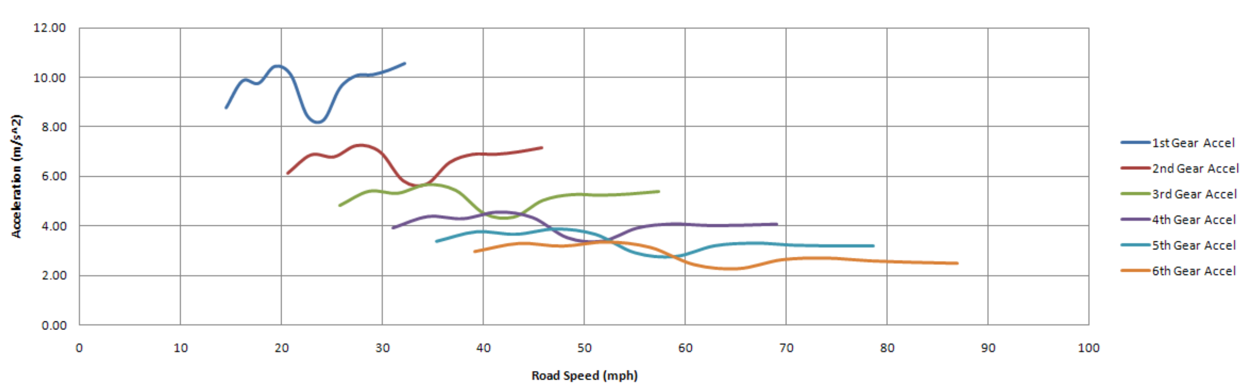



Figure 35 - Naturally Aspirated - Acceleration vs. Road Speed

From the chart above, it becomes apparent that as the road speed increases, the vehicle acceleration decreases. This is due to the fact that as the engine speed increases, the torque will have to decrease for a given power. Of course, just with any other type of theoretical analysis, error can and will occur. There are assumptions that may be voided under certain off-design scenarios and conditions. The modeling of the $1^{st}$ gear acceleration is rather difficult due to factors such turbocharger spool time, wheel spin, and clutch slip. These factors as well as human error can change the acceleration numbers.

As a continuation to the powerband and acceleration analysis, the data was further used in predicting the times that it would take to accelerate from a stop to maximum speed. This process can be seen below in 'Figure 36':

| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 1 | Time (sec) | Acceleration (m/s^2) | Speed (m/s) | Speed (mph) | Distance (m) | Distance (feet) | |
| 2 | 0 | 8 | 0 | 0.0 | 0.0 | 0 | |
| 3 | 0.1 | 8 | 0.8 | 1.8 | 0.1 | 0 | |
| 4 | 0.2 | 8 | 1.6 | 3.6 | 0.3 | 1 | |
| 5 | 0.3 | 8 | 2.4 | 5.4 | 0.6 | 2 | |
| 6 | 0.4 | 8 | 3.2 | 7.2 | 1.0 | 3 | |
| 7 | 0.5 | 8 | 4 | 9.0 | 1.4 | 5 | |
| 8 | 0.6 | 8 | 4.8 | 10.7 | 1.9 | 6 | |
| 9 | 0.7 | 8 | 5.6 | 12.5 | 2.5 | 8 | |
| 10 | 0.8 | 8 | 6.4 | 14.3 | 3.2 | 10 | |
| 11 | 0.9 | 8 | 7.2 | 16.1 | 4.0 | 13 | |
| 12 | 1 | 8 | 8 | 17.9 | 4.8 | 16 | |
| 13 | 1.1 | 8 | 8.8 | 19.7 | 5.7 | 19 | |
| 14 | 1.2 | 8 | 9.6 | 21.5 | 6.7 | 22 | |
| 15 | 1.3 | 8 | 10.4 | 23.3 | 7.8 | 26 | |
| 16 | 1.4 | 8 | 11.2 | 25.1 | 9.0 | 29 | |
| 17 | 1.5 | 8.5 | 12.05 | 27.0 | 10.2 | 33 | |
| 18 | 1.6 | 9 | 12.95 | 29.0 | 11.5 | 38 | |
| 19 | 1.7 | 9.5 | 13.9 | 31.1 | 13.0 | 43 | |
| 20 | 1.8 | 10 | 14.9 | 33.3 | 14.5 | 48 | |
| 21 | 1.9 | 0 | 14.9 | 33.3 | 16.0 | 53 | 1-2 shift |
| 22 | 2 | 0 | 14.9 | 33.3 | 17.5 | 57 | 1-2 shift |
| 23 | 2.1 | 0 | 14.9 | 33.3 | 19.0 | 62 | 1-2 shift |
| 24 | 2.2 | 0 | 14.9 | 33.3 | 20.5 | 67 | 1-2 shift |
| 25 | 2.3 | 6 | 15.5 | 34.7 | 22.1 | 72 | |
| 26 | 2.4 | 6 | 16.1 | 36.0 | 23.7 | 78 | |

Figure 36 - Acceleration to Speed Analysis

The first column in 'Figure 36' shows time in steps of 0.1 seconds, which was considered to be a fairly large resolution. As previously stated, the acceleration for first gear is difficult to model, but based on personal experience and basic test data, it was approximated to be $8\frac{m}{s^2}$. This should account for basic wheel spin and turbocharger spool. The speed is derived from the following equation:

$$Velocity\ Final = Velocity\ Initial + Accleration * \Delta t \quad [Eq. 27]$$

The initial velocity is the value that was generated at the previous time step. The acceleration is chosen either from test data (1st gear) or from the acceleration chart (every following gear). The distance from the starting line is derived from the following equation:

$$Distance\ Final = Distance\ initial + Velocity * \Delta T + \frac{1}{2} * Accel * (\Delta T)^2 \quad [Eq. 28]$$

After manually inputting the data points for the acceleration for each gear, excel completes the rest. The red lines in 'Figure 37' below represent an up-shift and show how the acceleration decreases with a numerically higher gear. An up-shift was modeled as 0 acceleration for 0.4 seconds.

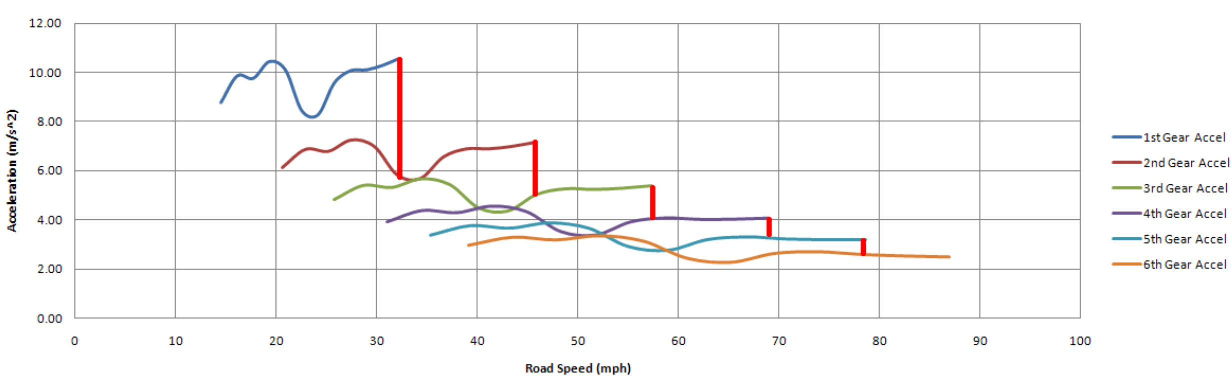



Figure 37 - Naturally Aspirated - Acceleration vs. Road Speed w/ Shift Points

'Figures 38 and 39' show the velocity vs. time and speed vs. time charts for the naturally aspirated configuration:

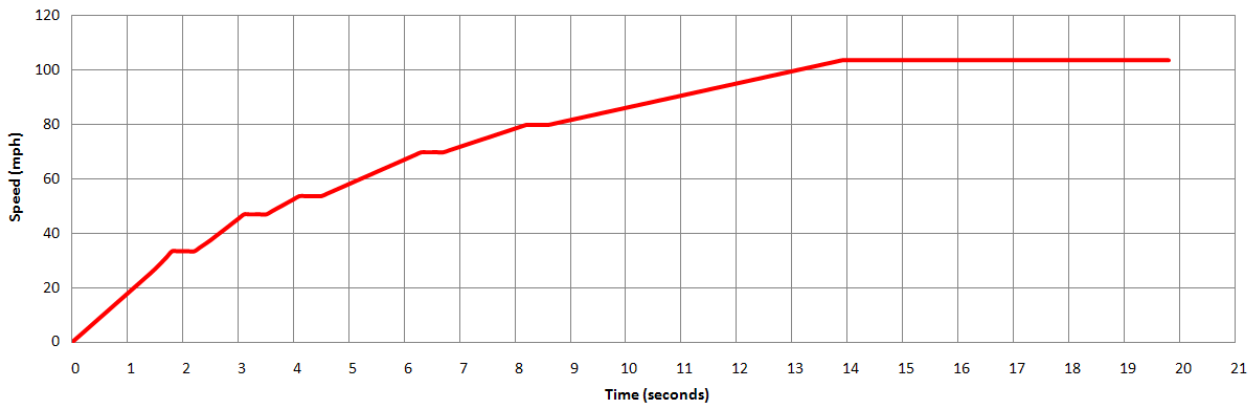



Figure 38 - Naturally Aspirated - Time vs. Speed

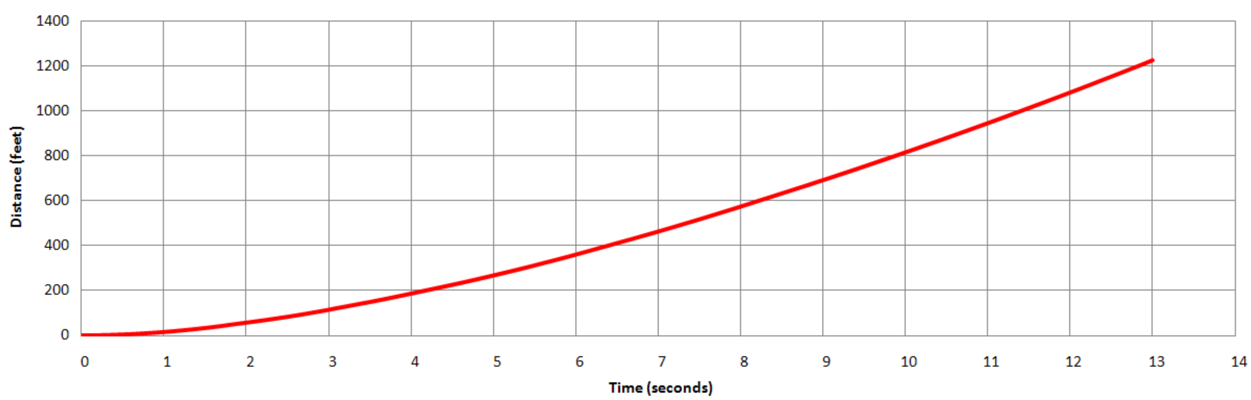



Figure 39 - Naturally Aspirated - Time vs. Distance

When this analysis is performed using the turbocharged data, the following charts are obtained:

- Figure 40 - Turbocharged - Acceleration vs. Road Speed
- Figure 41 - Turbocharged - Time vs. Speed
- Figure 42 - Turbocharged - Time vs. Distance

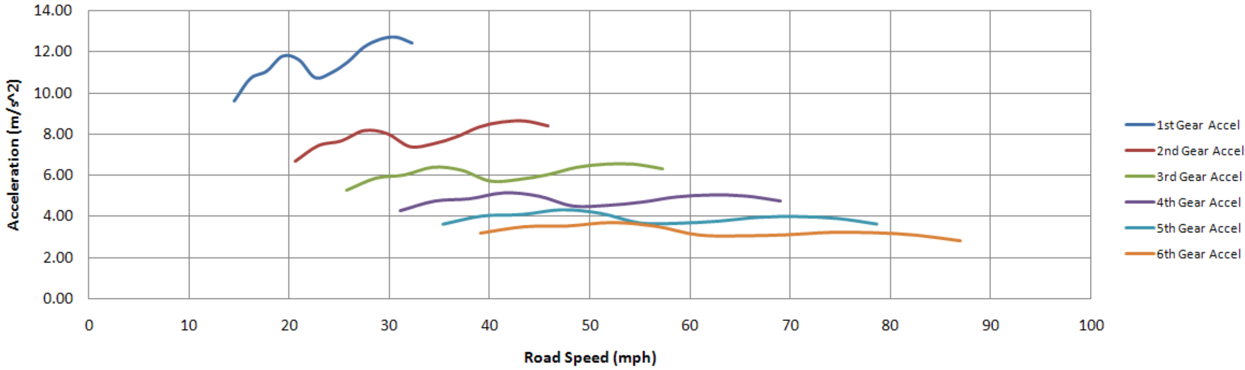



Figure 40 - Turbocharged - Acceleration vs. Road Speed

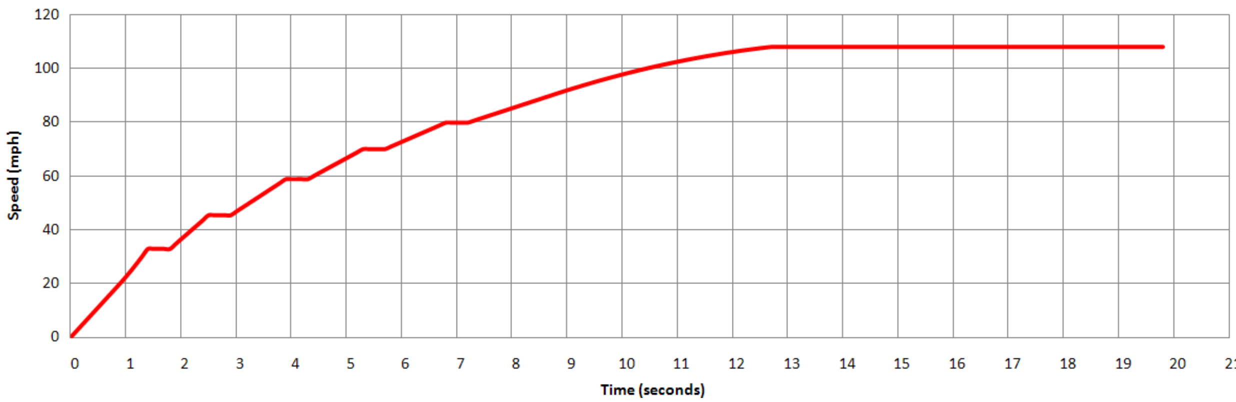



Figure 41 - Turbocharged - Time vs. Speed

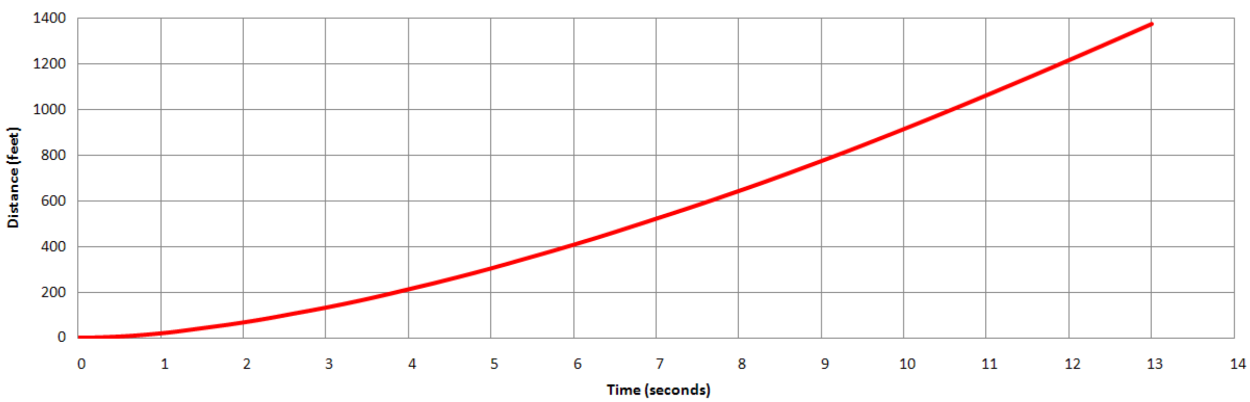



Figure 42 - Turbocharged - Time vs. Distance

The following graphs ('Figures 43 and 44') combine the naturally aspirated and the turbocharged data. There is consistently an increased distance travelled and vehicle speed attained in the same amount of time for the turbocharged vehicle vs. the naturally aspirated counterpart. These results would be exacerbated if the turbocharged setup was further optimized, which is certainly a possibility.

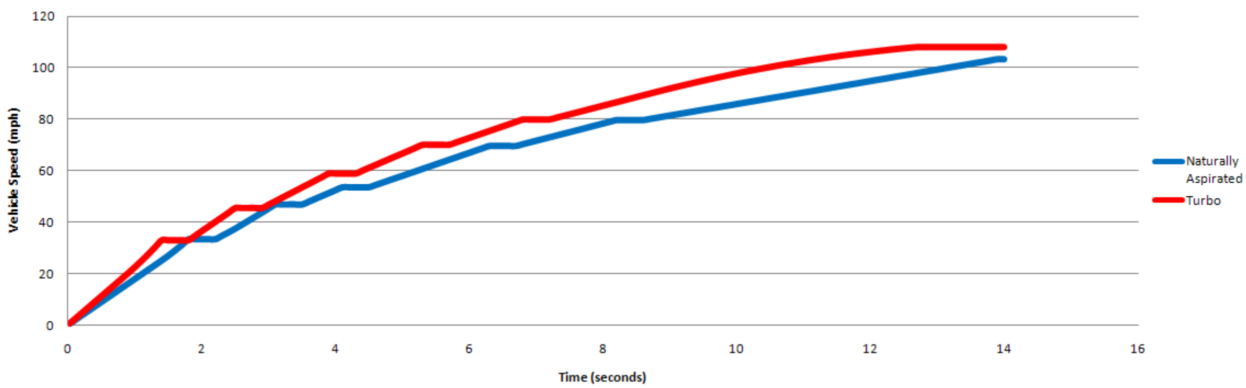



Figure 43 - Naturally Aspirated vs. Turbocharged - Time vs. Velocity

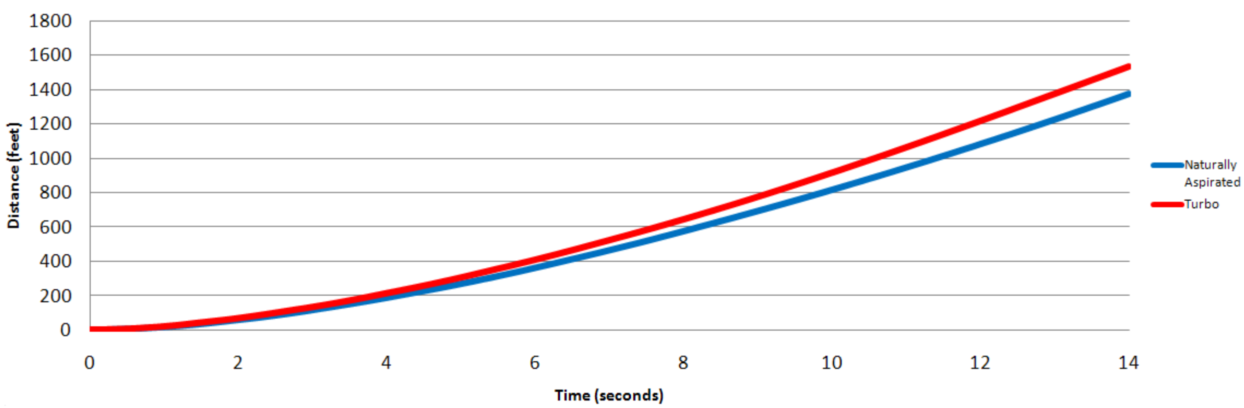



Figure 44 - Naturally Aspirated vs. Turbocharged - Time vs. Distance

As a final note, perhaps the greatest benefit of turbocharging an FSAE car is the ability to keep the vehicle in a higher gear for longer. This is due to the larger and wider powerband provided by the turbocharger. The greater area under the torque curve, as seen below in 'Figure 45', is noted by the diagonal black lines. This extra area results in greater acceleration. Due to the wider powerband, the driver can retain 3rd gear throughout a turn instead of having to rapidly downshift to 2nd gear into the corner and up-shift back into 3rd gear after the corner. Shifting is time lost (approximated at 0.4 seconds), which should be minimized in order to maximize performance. Vehicle wear is also lowered if shifting is avoided due to less stress experienced from shifts and potential driver error.

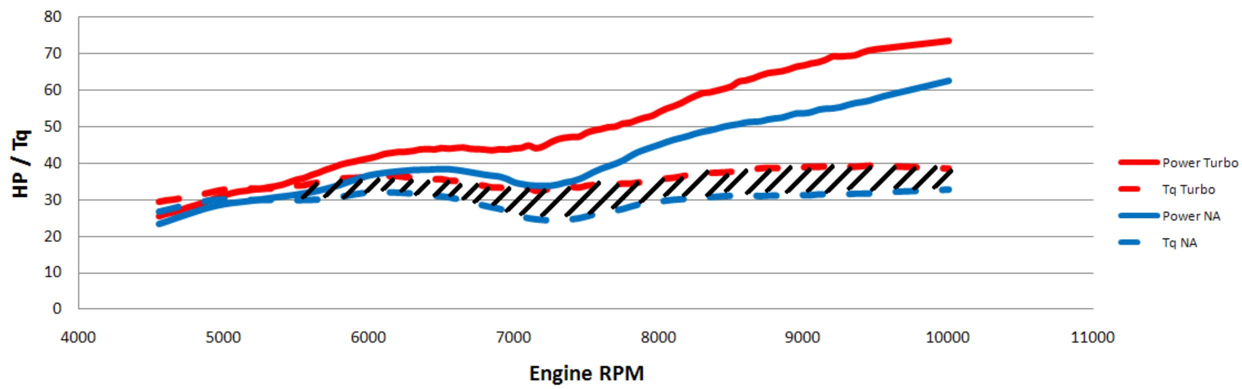



Figure 45 - Gained Area Under The Curve w/ Turbocharger

# Chapter 6: Project Summary

To summarize, the team was given the task to add a turbocharger and all other supporting components onto an old FSAE race car, which was used in competition in 2001. The team had to analyze the system, select a turbocharger, design the turbo-system around the turbocharger selection, select and configure an engine management system, and finally tune the engine management system, so that the maximum, safe amount of horsepower and torque could be extracted from the setup. In this process, custom parts had to be designed and manufactured, so that the turbocharger system could be adapted to the naturally aspirated vehicle. Also, automotive theory had to be explored to find solutions to critical problems, which could threaten the success of the project, as well as the lifespan of the system.

The team produced power and torque gains of roughly 20% throughout the RPM range. The cost of the parts associated with the project was rather low due to several sponsorships and the weight gains were not comparable to the performance gains associated with this project. Therefore, if this specific system is reused in the future and the race car is designed with the consideration of operating with a turbocharger, the team believes that adding a turbocharger would produce a result similar or better to the one obtained in this project, which can be considered very successful.

# Chapter 7: Future Recommendations

### Restrictor / Throttle Body Design:

The team will most certainly benefit from placing the throttle body in a location separate from the restrictor. Currently, the throttle body is placed at the restrictor and therefore, the 19mm diameter, associated with the cross-sectional area, is effectively minimized due to the throttle body shaft and the throttle body plate. Moving the throttle body upstream or downstream of the restrictor can potentially produce notable gains.

### Intake Manifold Design:

Although the original intake manifold provides a decent design, the intake manifold can be redesigned for the turbocharger system. This can produce higher peak numbers and a more favorable powerband (through increasing VE), which would further optimize the system.

### Intake Piping Design:

This project employed several separate aluminum pipes, which were attached to each other using silicone couplers and metal clamps. Ideally, the charge piping will be one piece, in order for the pumping losses to be minimized. Therefore, it would be best if the charge piping was made of a lightweight material (such as carbon fiber), which would vary in shape and diameter, so all of the different system components can be connected to it without using separate adapters.

### Exhaust Manifold Design:

Although the current exhaust manifold works fairly well with the turbo-system, the exhaust manifold can also be redesigned, in order to maximize the pressure gradient and the temperature gradient associated with the turbine. Ideally, the turbocharger will be mounted as close to the cylinder head as possible but since the firewall is a major constraint, this will require some engineering time.

### Engine Selection:

There are modernized versions of the 4 cylinder 600cc engine that was used in this project. An engine that is fuel injected from the factory will contain a camshaft angle sensor, which would provide the homing signal needed for the ECU to function properly. This will increase tuning capabilities, which in terms will allow for a higher resolution of tuning. A higher resolution usually allows for more power to be produced.

### Knock Sensor Feedback:

Knock sensors are very important when optimizing a tune safely is the goal. Tuning without a knock sensor provides no detonation feedback to the tuner and to the engine management system, and this can result in total engine failure. Therefore, a knock sensor should be used so that the tuner can determine when the tuning has reached its limits. This would allow for the tune to be finalized in a way that would produce the maximum amount of power and torque safely.

### Turbocharger Oil Consumption Fix:

In this project, the turbocharger inlet was connected to the crankcase, with the idea of bringing down the absolute pressure inside the crankcase, so that it matches the vacuum that is created before the compressor at certain operating conditions. This method allows for the pressure differential between the two to be minimized or even removed, so that the pre-compressor inlet vacuum is no longer large enough to pull oil through the bearing seals of the turbocharger. This is not a perfect fix but it certainly minimizes the problem. In order for this solution to satisfy FSAE rules, the point of this connection on the restrictor end must be placed before the restrictor. In addition, a catch can should be placed in-line with the line connecting the restrictor and the crankcase, so oil does not flow from the crankcase into the restrictor. This can be seen below in 'Figure 46':

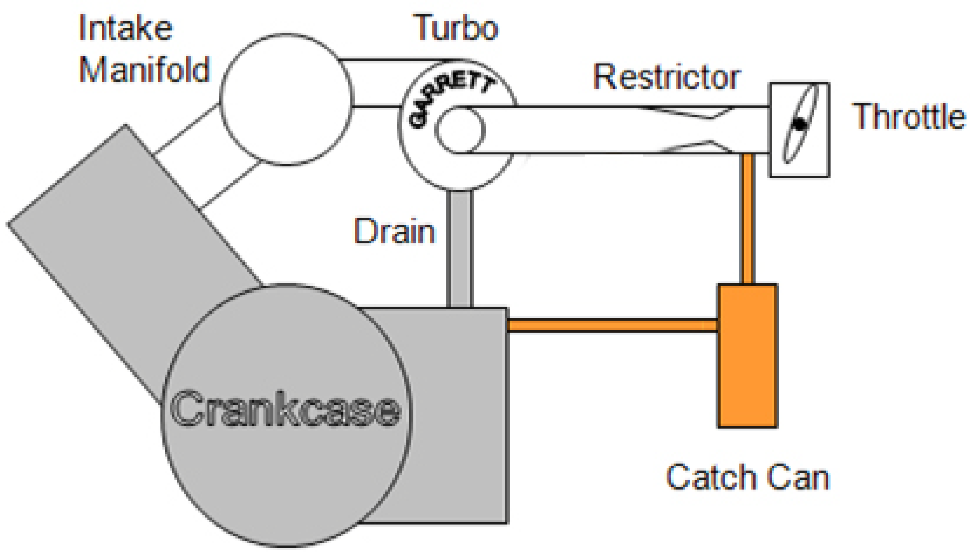



Figure 46 - Oil Consumption Solution

# References

"About Formula SAE." SAE International. Web. 28 Apr. 2010. http://students.sae.org/competitions/formulaseries/about.htm.

Curran, David, David Lamoureux, and JohnPaul Piccolomini. FSAE Turbocharger Design and Implementation. Worcester Polytechnic Institute. April 24, 2008.

Jahnke, Caitlin, Kevin Locke, and Russel Shuman. Turbocharging the Formula SAE Race Car. Worcester Polytechnic Institute.

"SAE Convergence: Convergence History." SAE International. Web. 28 Apr. 2010 http://www.sae.org/events/convergence/history.htm.

"SAE Number (Motor Oil)." Encyclopædia Britannica. Web. 28 Apr. 2010. http://www.britannica.com/EBchecked/topic/665787/SAE-number.

# Appendix 1: Applicable 2010 FSAE Rules (Excerpts)

**B8.6 Intake System Restrictor**

B8.6.1 In order to limit the power capability from the engine, a single circular restrictor must be placed in the intake system between the throttle and the engine and all engine airflow must pass through the restrictor.

B8.6.2 Any device that has the ability to throttle the engine downstream of the restrictor is prohibited.

B8.6.3 The maximum restrictor diameters are:
- Gasoline fueled cars - 20.0 mm (0.7874 inch)
- E-85 fueled cars – 19.0 mm (0.7480 inch)

B8.6.4 The restrictor must be located to facilitate measurement during the inspection process.

B8.6.5 The circular restricting cross section may NOT be movable or flexible in any way, e.g. the restrictor may not be part of the movable portion of a barrel throttle body.

B8.6.6 If more than one engine is used, the intake air for all engines must pass through the one restrictor.

**B8.7 Turbochargers & Superchargers**

B8.7.1 Turbochargers or superchargers are allowed if the competition team designs the application. Engines that have been designed for and originally come equipped with a turbocharger are not allowed to compete with the turbo installed.

B8.7.2 The restrictor must be placed upstream of the compressor but after the carburetor or throttle valve. Thus, the only sequence allowed is throttle, restrictor, compressor, engine.

B8.7.3 The intake air may be cooled with an intercooler (a charge air cooler). Only ambient air may be used to remove heat from the intercooler system. Air-to-air and water-to air intercoolers are permitted. The coolant of a water-to-air intercooler system must comply with Rule B.8.10.

**ARTICLE 10: EXHAUST SYSTEM AND NOISE CONTROL**

**B10.1 Exhaust System General**

The car must be equipped with a muffler in the exhaust system to reduce the noise to an acceptable level.

B10.1.1 Exhaust Outlet

The exhaust must be routed so that the driver is not subjected to fumes at any speed considering the draft of the car.

*B10.1.2 The exhaust outlet(s) must not extend more than 45 cm (17.7 inches) behind the centerline* of the rear axle, and shall be no more than 60 cm (23.6 inches) above the ground.

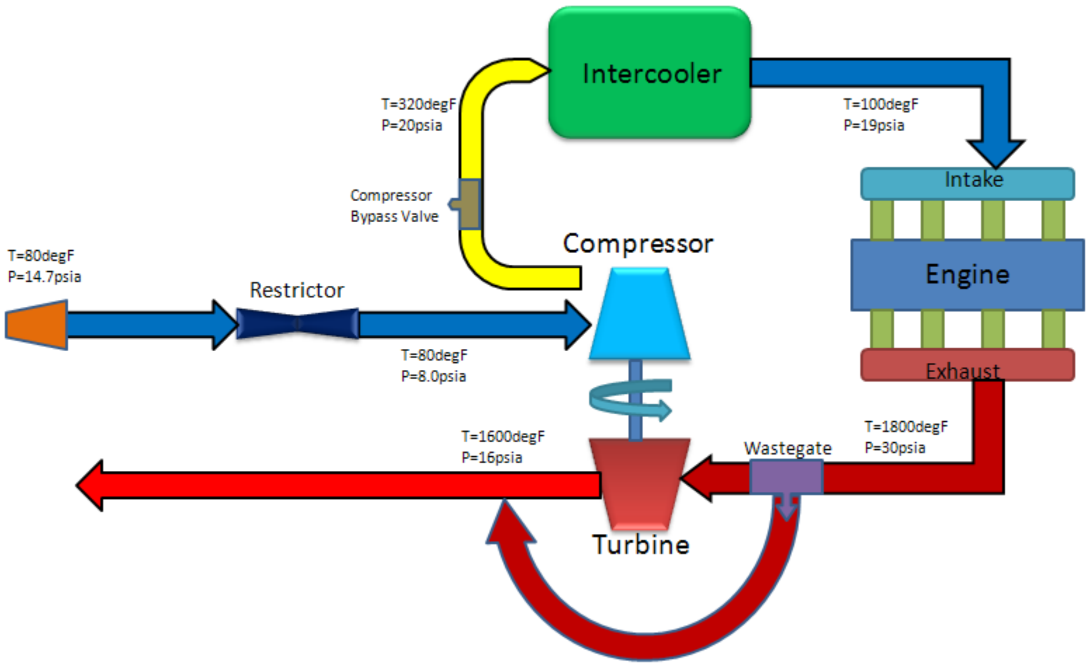
B10.1.3 Any exhaust components (headers, mufflers, etc.) that protrude from the side of the body in front of the main roll hoop must be shielded to prevent contact by persons approaching the car or a driver exiting the car.

**B10.3 Maximum Sound Level**

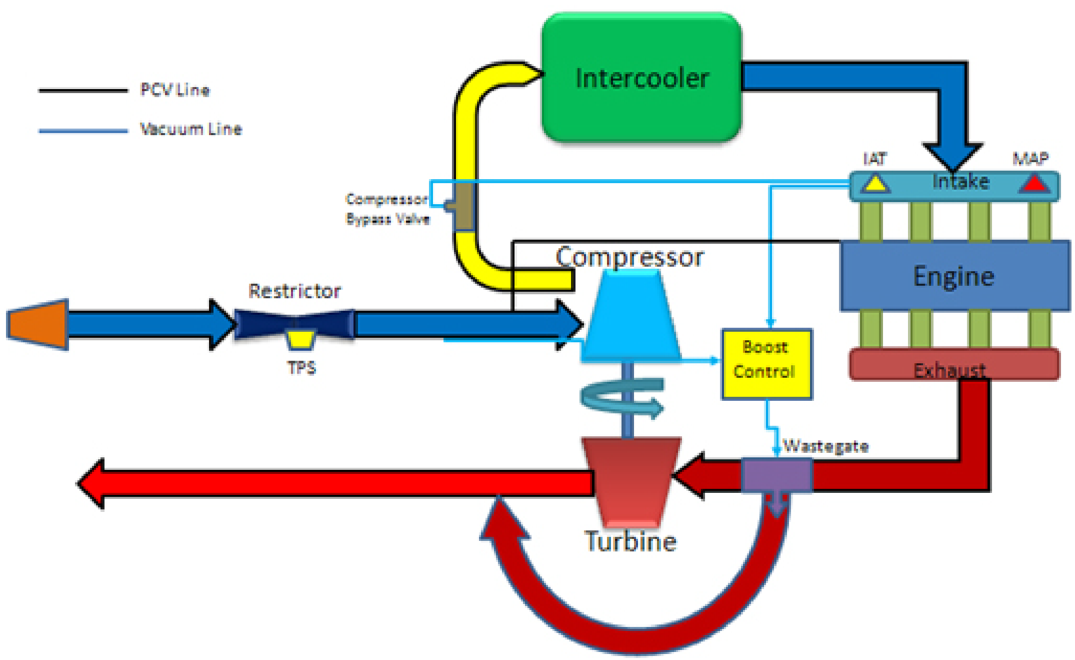
The maximum permitted sound level is 110 dBA, fast weighting.

# Appendix 2: Turbo-System Schematics

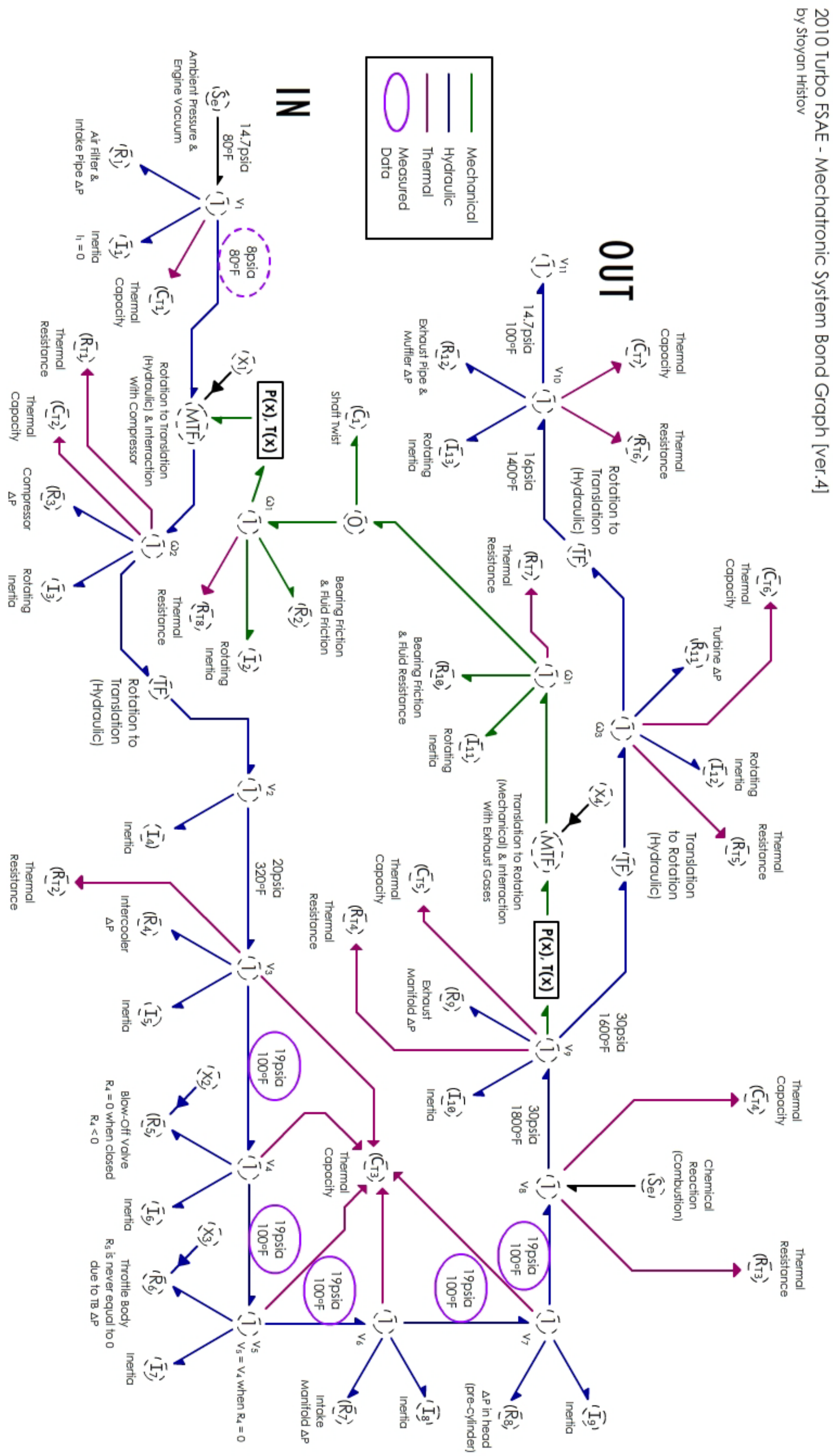
## Overall Schematic - Temperature and Pressure Points:




## Overall Schematic - Input/Output:

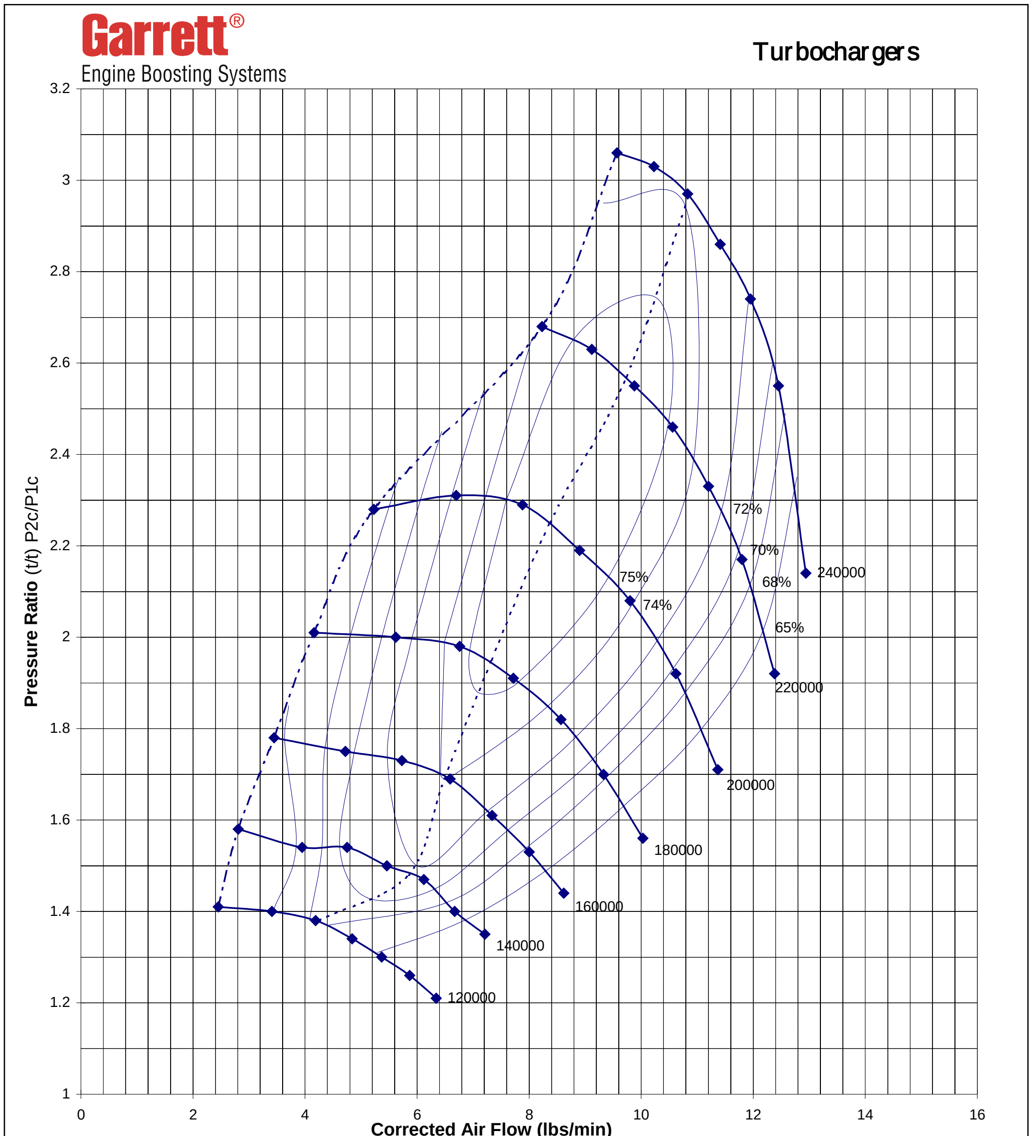


## Mechatronic Analysis:



# Appendix 3: Turbocharger Selection - Compressor Maps

## GT12:




TITLE: **GT12 C101D(41) 50 TRIM 0.33 A/R D=1.94**

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$$\eta_c = \frac{T_1 (P_r^{\frac{\gamma-1}{\gamma}} - 1)}{T_2 - T_1} \qquad N_c = \frac{N_{phy}}{\sqrt{T_{1c} / 545}} \qquad W^* = \frac{W\sqrt{T_{1c}/545}}{P_{1c}/28.4}$$

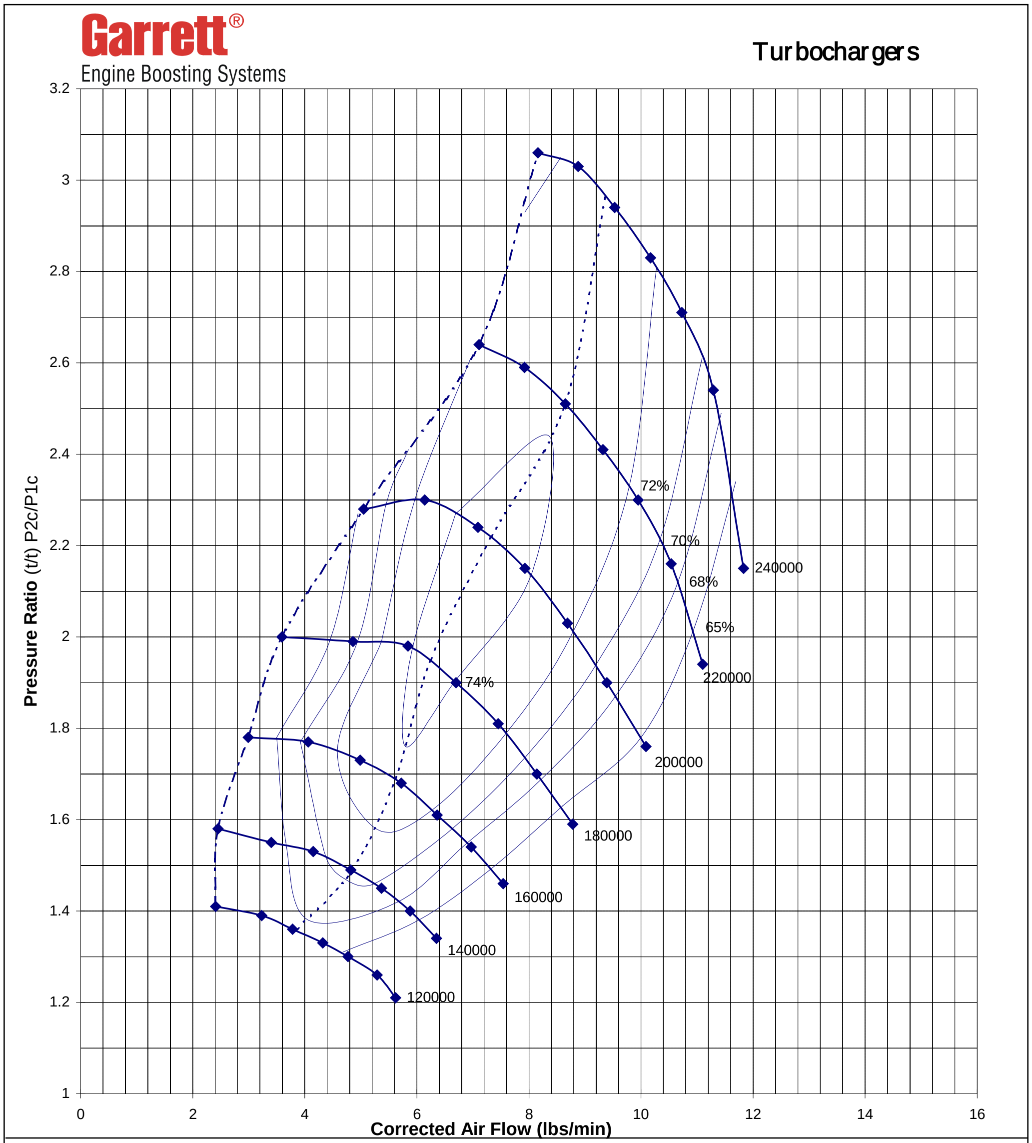
COMMENTS:

Engineer:

TEST No: 98030204
DATE: 1/25/1999
CELL No: 1
REF: 01

**Garrett Engine Boosting Systems: Torrance, California U.S.A.** **68.** **REV:**

## GT15VNT:




TITLE: **GT14 C101D(41) 45 TRIM 0.33 A/R D=1.72**

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$\eta_c = \frac{T_1(P_r^{\frac{\gamma-1}{\gamma}} - 1)}{T_2 - T_1}$ $N_c = \frac{N_{phy}}{\sqrt{T_{1c}/545}}$ $W^* = \frac{W\sqrt{T_{1c}/545}}{P_{1c}/28.4}$

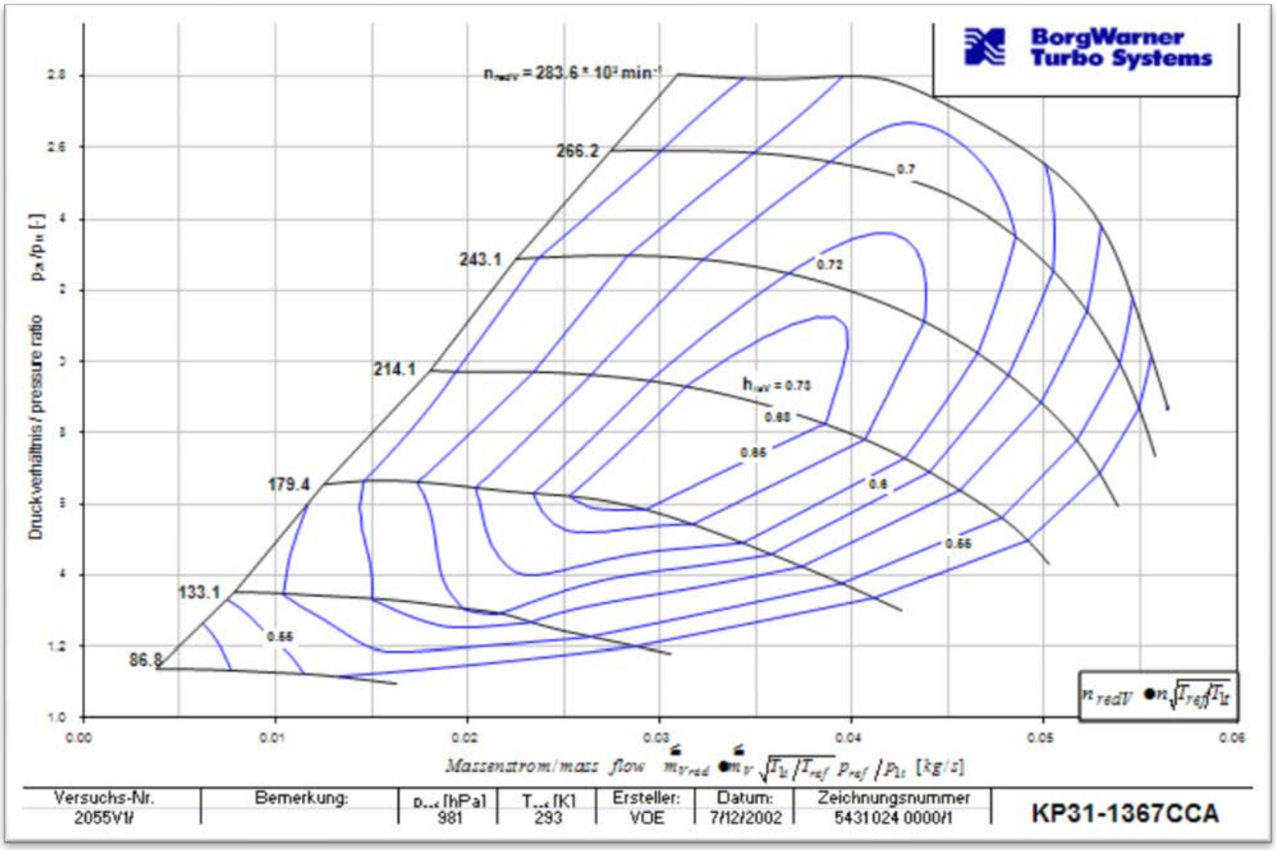
COMMENTS:

Engineer:

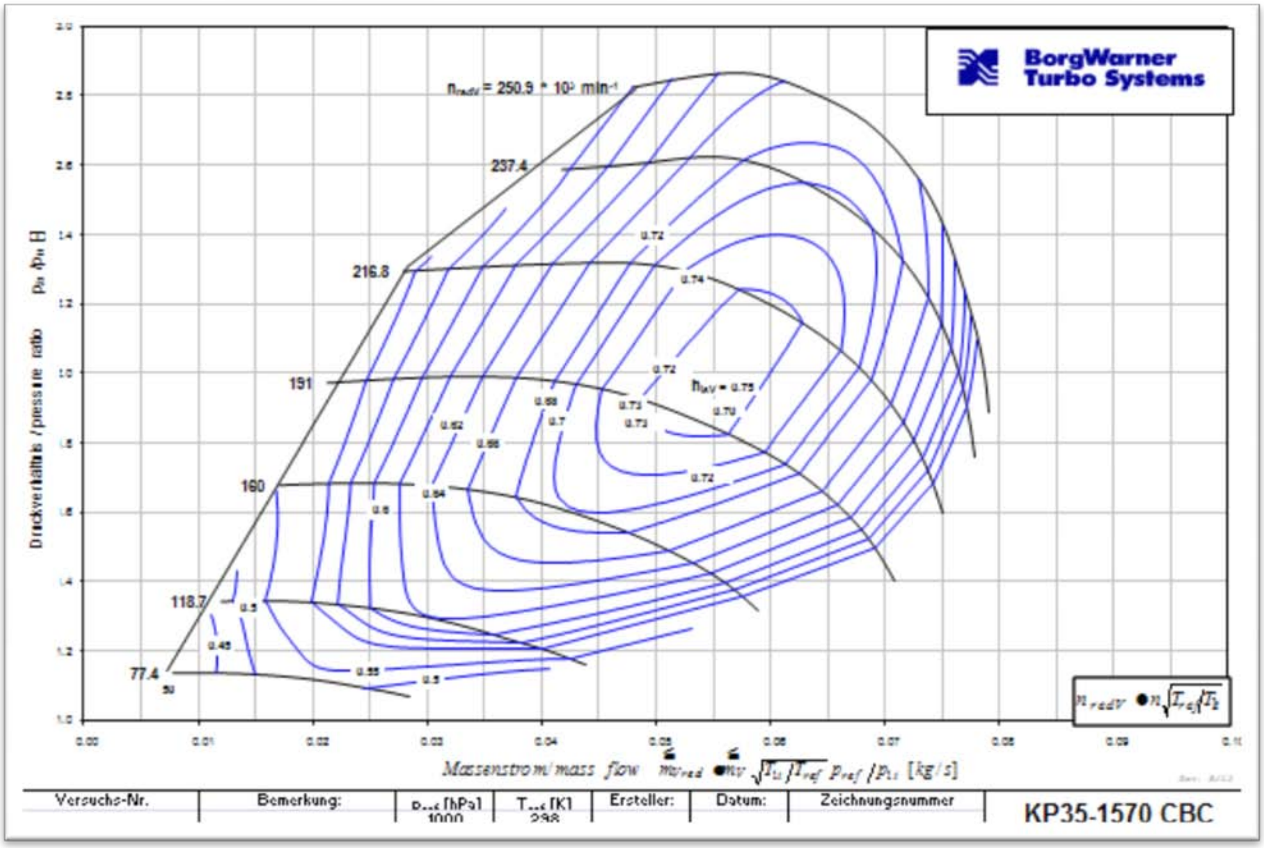
TEST No: 98030305
DATE: 12/ 7/1998
CELL No: 1
REF: 01

**Garrett Engine Boosting Systems: Torrance, California U.S.A.** **68.** **REV:**

## KP31:


BorgWarner Turbo Systems
Druckverhältnis / pressure ratio
Massenstrom/mass flow
266.2
243.1
214.1
179.4
133.1
86.8
0.7
0.72
0.68
0.66
0.6
0.65
0.55
Versuchs-Nr.
2055V1/
Bemerkung:
981
293
Ersteller:
VOE
Datum:
7/12/2002
Zeichnungsnummer
5431024 0000/1
KP31-1367CCA

## KP35:

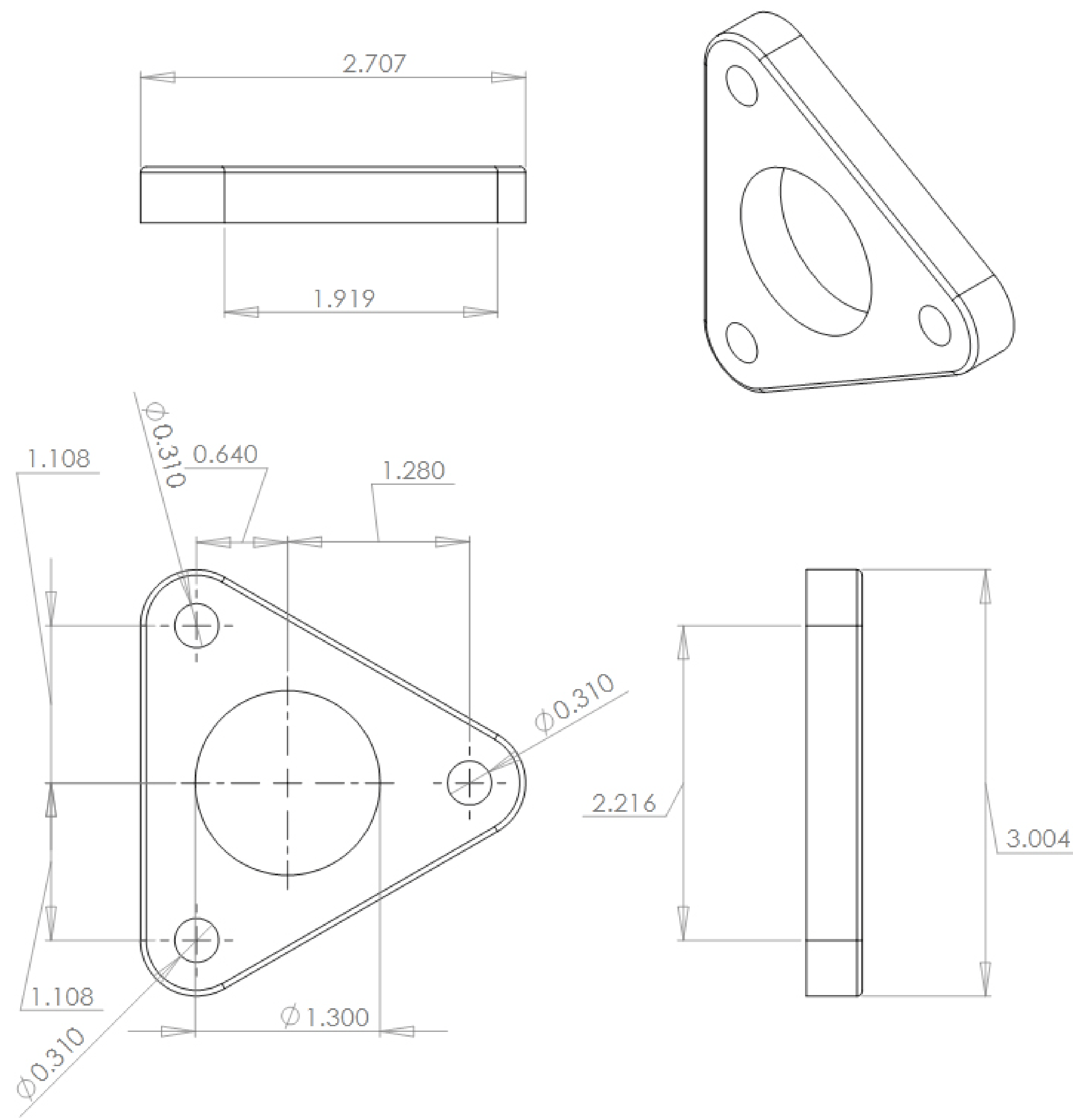

BorgWarner
Turbo Systems
250.9
237.4
216.8
191
160
118.7
77.4
Druckverhältnis / pressure ratio
Massenstrom/mass flow
Versuchs-Nr.
Bemerkung:
Ersteller:
Datum:
Zeichnungsnummer
KP35-1570 CBC

# Appendix 4: Engine Management System Comparison Table

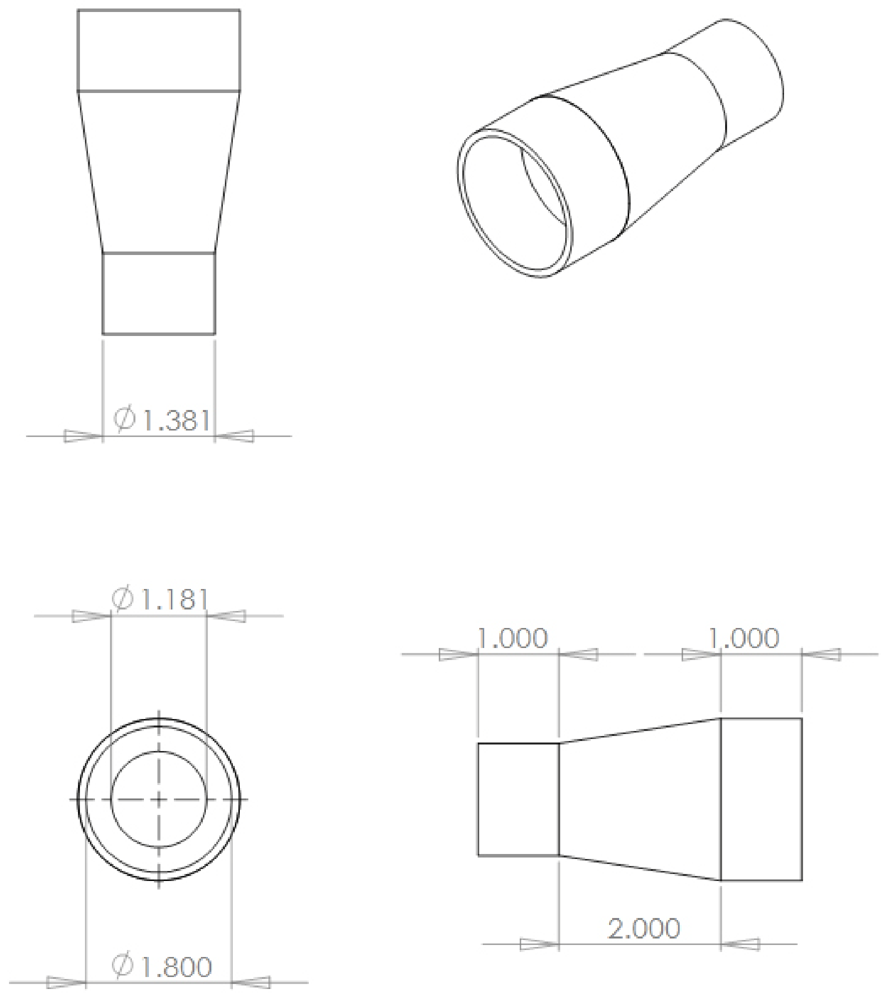
| - | Haltech | AEM |
|---|---|---|
| Fuel Map Sites | 32x32 (1024) | 21x17 (357) |
| Ignition Map Sites | 32x32 (1024) | 21x17 (357) |
| Injector Driver | 4 | 10 |
| Ignition Drivers | 4 | 5 |
| Direct Ignition Driver? | No | Yes |
| Closed Loop Support | Wideband (x2) Narrowband (x2) | Wideband (x2) |
| Auto tune (fuel) | Yes | Yes |
| Knock Control | No | Yes |
| Launch Control | Yes | Yes |
| Traction Control | Yes | Yes |
| Flatshift | Yes | Yes |
| Analog Inputs | 8 | 7 |
| Digital Outputs | 9 | 6 |
| Rev Limiter | Soft or Hard | Soft |
| MAP | Onboard 2.5 bar, or external up to 10 bar | External up to 10 bar |
| TPS | x1 | x1 |
| MAF | no | yes |
| EGT Fuel Correction | Yes (x4) | Yes (x4) |
| Boost Control | Yes (open or close loop) | Yes |
| Fan Control | Yes | Yes |
| Switch on the fly fuel/ignition/boos t maps? | Yes (x2) | Yes (x2) |
| Programmable Tach Output | Yes | Yes |
| Antilag | Yes | Yes |
| Onboard DAQ | 512mb | 512mb |
| Scalable Sensors | Yes | No |
| CAN Output Support | Yes | Yes |
| Wheel Speed Inputs | 4 | 1 |

# Appendix 5: Custom Part Drawings

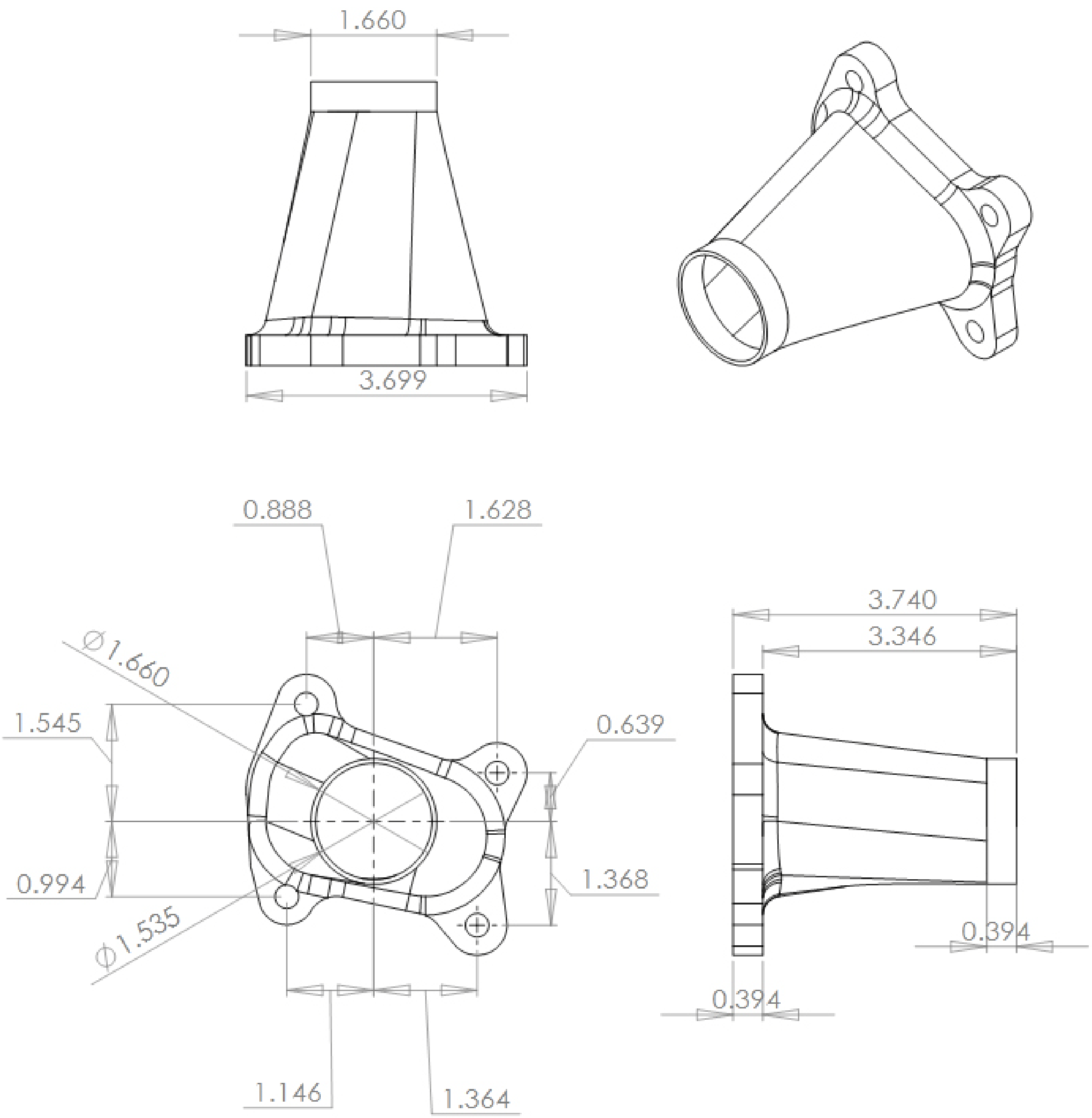
## Turbine Inlet Flange:



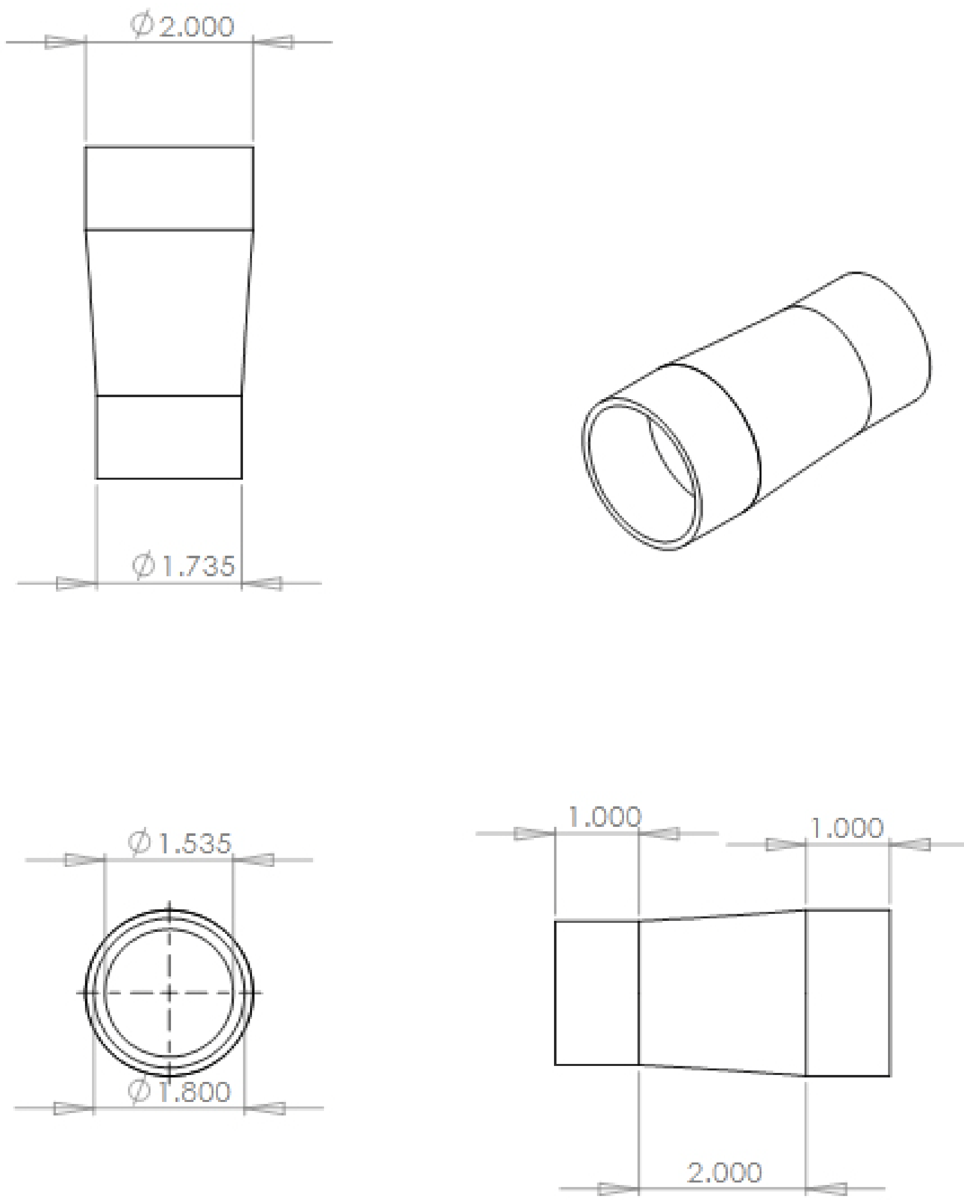
**Turbine Inlet Reducer:**



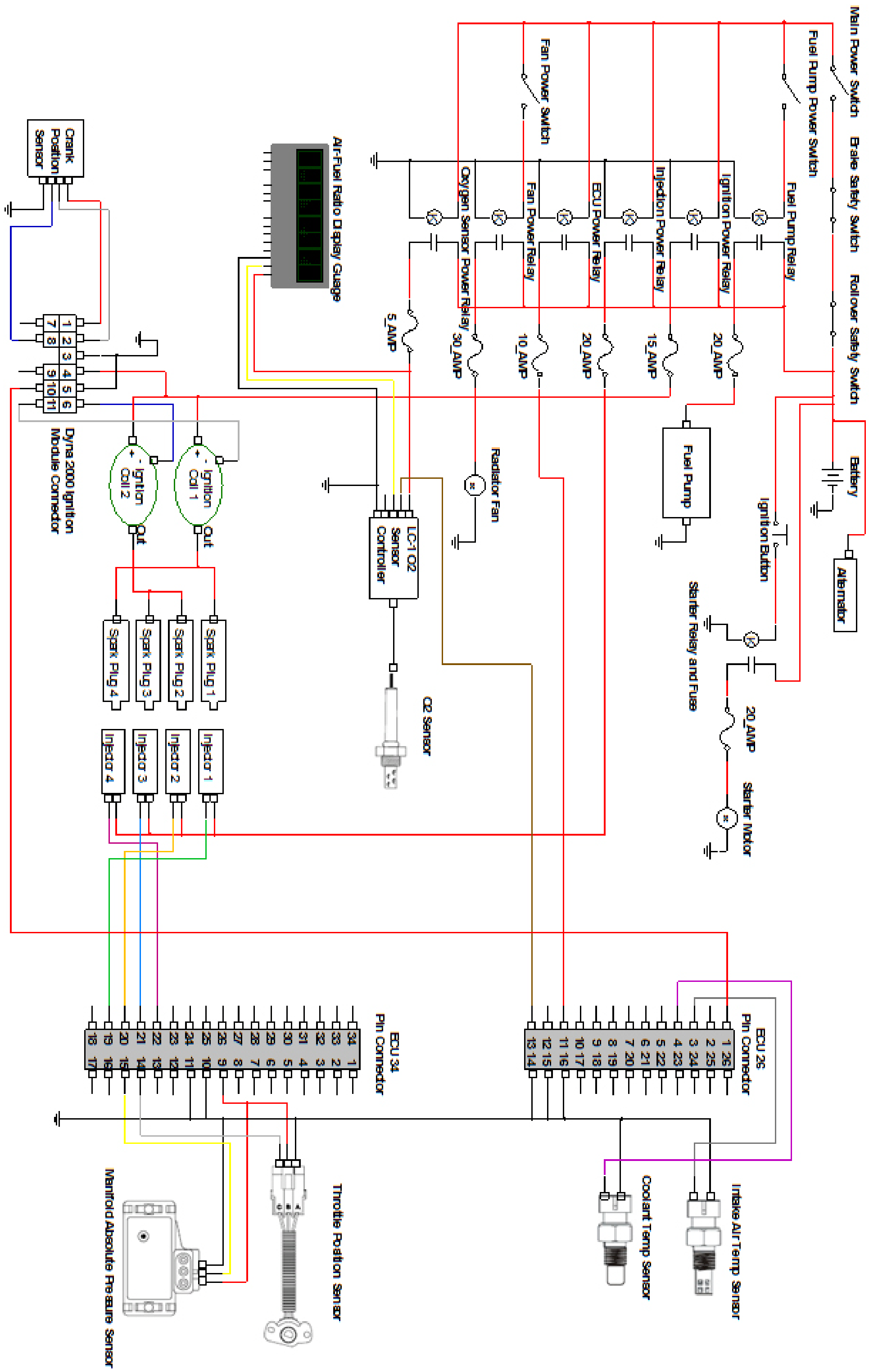
## Turbine Outlet Collector:



**Turbine Outlet Expander:**



# Appendix 6: Electrical System Schematic



# Appendix 7: Project Budget

| Category | Price |
|---|---|
| Miscellaneous Maintenance Items | $400 |
| Engine Management System and Other Electrical Parts | $2000 |
| Raw Materials | $75 |
| Intake System | $775 |
| Exhaust System | $150.00 |
| Oil/Fuel System | $300 |
| Turbocharger | $0 (Sponsored) |
| **Total** | **$3700** |