Automotive Engineering: Engine Fuel Map Design

George Alexandrov
gpalexandrov@gmail.com
Kaitlin Bergin
Redhead3991@yahoo.com
Xiao Ying Zhao
xzhao@peddie.org
Rolih Ferdinand
ferdinandr@comcast.net
Jeffrey Kowalski
jmanrox91@aol.com

Abstract

In order to understand how to bring out the most power from a car’s engine, we needed to learn how an engine works. The main focus of this research was to tune the engine and create a fuel map that would allow it to run at its optimum level. We used the Win Tec-GT computer software to test the performance of a 2002 Yamaha YZFR6 engine that the Rutgers 2008 Racing Team uses in their car. To easily test the engine we connected it to a dynamometer that simulated a load on the engine, making it do work and simulate real life driving. The engine included numerous sensors that relayed information about conditions such as crank position and coolant temperature, allowing the Tec-GT to communicate with the engine and adjust parameters.

Our main areas of interest with the Tec-GT and the tuning of the engine were the ignition advance and volumetric advance tables. By changing different values on these tables we were able to adjust the amount of fuel that entered the engine as well as the time of injection. The two tables were adjusted until the engine performed at its highest potential at each possible variation of load and RPM. However, even when this map was completed some effects could not be tested without driving the car, such as acceleration changes in the engine.

1. Introduction

Modern automotive technology relies on electronically controlled devices to monitor and operate the car’s engine. An important automotive process that determines the performance of the engine is the fuel injection process. Fuel injection is the process that causes combustion in an engine by combining fuel and air. The fuel injection system was invented in the 1890s and was used in diesel engines, aircraft, and tanks starting in the 1920s through World War II; it began appearing commercially in gasoline-fueled cars in the 1950s (Mercedes Benz and Chevy both had models using fuel injection), and by the 1980s was the standard combustion system used in automobile engines in the United States and Europe [2]. In the past, internal combustion engines used carburetors to mix the fuel and air to a combustible state. As cars became more complex and government regulations related to exhaust emissions became stricter, however, carburetors have been replaced with electronic fuel injection systems, which can more precisely control the flow of fuel to the engine. The efficiency of the fuel injection system
will determine how well the engine runs and ultimately how well the car performs.

Today’s automotive engines use computer controlled systems to regulate fuel injection, allowing for precise mixing of fuel and air. This results in optimum engine performance, better fuel economy, and lower exhaust emissions. In this project, we designed, tested, and refined an engine fuel map utilizing computer controlled systems, and modified the engine in accordance with our findings in order to achieve improved engine performance. We worked with the Rutgers Formula Racing Team and their formula style race car in order to maximize the horsepower of their engine, utilizing the Tec-GT software and dyno.

2. Background Information

A car engine is a machine whose basic purpose is to convert fuel into motion. An internal combustion engine accomplishes this conversion by isolating a small amount of fuel in a contained space and igniting it, converting it to an expanding gas that releases energy. That energy gets translated into motion by the many different parts of the engine working together in a precise and continuous cycle of activity [3]. Understanding the various parts of the engine and how they work together is an important first step in being able to improve the efficiency and performance of the engine.

2.1 Parts of the Engine and What They Do

Some of the most important parts of modern automobile engines include the pistons, the crankshaft, the camshaft, the engine control unit (ECU), the injectors, the spark coil, the spark plugs and the valves (See Figure 1).

![Figure 1. Some of the Parts of a Four Stroke Piston Engine](image)


Inside the main body of the engine (the engine block) are cylinders. Modern cars have engines that have four, six or eight cylinders. Inside each cylinder is a piston that moves up and down. When fuel is injected into the cylinder, the movement of the piston controls the volume of air within the cylinder, providing space for the fuel and air to mix and then compressing it to aid in combustion. The pistons are connected to the crankshaft by a connecting rod. The crankshaft translates the up and down movement of the pistons into the rotational motion that moves the car. On the crankshaft there is a gear that attaches to the camshaft. The camshaft controls the intake and exhaust valves [4]. The camshaft has egg shaped structures on them (cams) that push the valves open and closed, allowing the fuel to enter the cylinder and expelling the products of combustion after ignition (See Figure 2).
Figure 2. The camshaft opens and closes the valves on an engine [12].

The ECU controls the processes of the engine. It first sends signals to the injectors controlling the amount of fuel going into the cylinder by indicating how long the injectors should stay open. The injectors spray the fuel drops into the cylinder. There are many different sized injectors for use with different engines. It is important to have injectors that are the correct size for the engine being used. If injectors are too large or too small the car will not perform at maximum efficiency [6].

The ECU also sends a signal to the spark coil so that it sparks at exactly the right time to ignite the fuel (when compression within the cylinder is greatest). The spark coil generates the 35,000 volts needed for the spark to initiate combustion from the 12 volt battery [7]. The spark coil is a transistor so it amplifies the voltage, causing the spark in the spark plugs, which in turn ignite the fuel-air mixture.

2.2 The Four-Stroke Combustion Cycle

Most automobile engines today operate using a four-stoke combustion cycle. A four-stroke engine goes through four distinct stages. The first stage is intake. In this stage the piston moves down, and the intake valve opens allowing the air/fuel mixture that was combined by fuel injection to be pushed though the intake valve into the cylinder. The next step is compression. In this stage the piston moves up causing the mixture that was just sprayed into the chamber to be compressed. Before top dead center is reached, the spark plug goes off. The third stage of the 4 stage cycle is combustion (or power). The air/fuel mixture ignites and the piston is forced down. For ideal torque (for the most power) the combustion should be completed when the crankshaft is 90 degrees beyond top dead center. The last step is exhaust. In this stage the piston is moving up and pushing out the products of the combustion reaction out of the car through the exhaust pipe. The cycle then starts over again [6].

© 2007 Encyclopaedia Britannica, Inc.
Figure 2. The Four-Stroke Combustion Cycle [11].
2.3 Optimizing Engine Performance Using an Electronic Fuel Injection System

Tuning the engine to achieve maximum efficiency is a huge part of getting the best performance out of the race cars. Making adjustments to the fuel injection system to change the amount and release time of fuel, changing the size or flow of fuel injectors, and utilizing the many available engine sensors to make other modifications can all have a great impact on engine horsepower and efficiency.

All of the above sensors and parameters are controlled by the car’s engine control unit, or ECU (See Figure 3). The ECU in an electronic fuel injection systems sends signals to the fuel injectors, indicating how long to remain open in order to reach the maximum efficiency. The fuel is added to the air mixture at the latest possible time (right before combustion). The ideal air to fuel ratio, called the stoichiometric value, is 14.68 parts air to one part fuel (AFR is 14.68:1 by mass). This is the ratio of air to fuel that allows the oxygen and fuel to burn completely. However, conditions are never ideal so the most efficient AFR depends on the temperature, the rotations per minute of the engine (the engine’s rpm), and the load on the engine (how much work the engine is doing) [6].

Different-sized injectors give different amounts of fuel per certain time. The amount of fuel an injector sprays is the injector flow which is measured in pounds per hour at a certain pressure. Every injector has an upper limit of fuel and a lower limit of fuel. The upper limit is when the injector stays completely open or at full throttle. The lower limit is when the time it takes for the injector to open is longer than the time the injector needs to be open for (it starts to close before it finishes opening). The size of the injector valve also has an impact on the injector flow rate. The smaller the valve opening, the less fuel will be sprayed. Pressure also affects the injector flow rate. When there is lower pressure there is less fuel sprayed into the engine than if there were higher pressure [6].

The ECU receives data in the form of voltage from many sensors in order to make small corrections so the engine’s ability is optimized. Most sensors are resistors that change resistance when there is a change in activity in the engine. Common sensors are positional, exhaust gas composition, temperature, pressure, and air-metering sensors. Positional sensors determine the position of the engine. Oxygen sensors, a type of exhaust sensor, send back signals to the ECU that tell the ECU how much oxygen is left over after combustion. The ECU then makes changes accordingly in order to reach the best AFR at the rotations per minute and load (for example, if there is too much oxygen after combustion the ECU will send data that would allow more fuel to be put into the air-fuel mixture). The many types of temperature sensors send
the ECU data about the temperature of the air, the engine, the oil, and exhaust gas. The manifold absolute pressure sensors determine the pressure in the intake manifold. This can give the ECU data as to how much air goes into the engine (so the ECU knows how much fuel should be added to mixture). Similarly Barometric pressure sensors tell the ECU the density of the surrounding air. These data can be used to find the absolute manifold pressure. Air metering sensors send back data to the ECU about the speed of the air. There are many sensors that do the same thing, but in a different way, so they can be changed depending on the surroundings and the other sensors on the car [6].

2.4 Advanced Engine-Tuning Technology

WinTec4 is the technology we used for this project. WinTec4 works by connecting to the ECU. WinTec4 allows the user to see data from the engine and make changes to the tables to achieve maximum efficiency. The program takes data from the engine and displays them for the user. This information includes data about the engine’s rpm and ignition advance. Using this data, different tables including volumetric efficiency and ignition advance can be adjusted to reach maximum horsepower. The changes made to the table are made immediately to the engine, so the user can see how the change affected the output of the engine.

All of our work on tuning the engine is with the use of a dynamometer (See Figure 4). A dynamometer, or dyno, is used to measure the torque force on the engine, the speed (rpm) of the engine, and the power of the engine. A dyno can find the torque and power of an engine by exerting a braking force on the engine while the engine is running. Using all of the sensors and different hook-ups to the engine, the dyno can determine the engine’s power output. The dyno allows different loads to be placed on the engine to test it under different conditions. The first step for using a dyno is to attach the engine and engine’s sensors to the dyno. Then the engine is turned on and tested with different loads. The dyno monitors the performance of the engine and outputs the horsepower. This is used to find the maximum horsepower of an engine [9].

Figure 4. This dynamometer is used to test an engine outside of a car by making the engine do work against the wheel.

The main table that is used in engine tuning is the volumetric efficiency table or VE table. Volumetric efficiency is a measure of how much air enters the engine compared to the maximum volume of air that can fit into a cylinder when the piston is at bottom dead center [7]. The ideal would be 100% but that cannot be reached without a pump to force more air into the cylinder. When the air is colder and therefore denser the volumetric efficiency is increased because there are
more molecules of air per area. The volumetric efficiency table represents the engine’s intake efficiency under different conditions. The VE table should not have any extreme values that do not fit with surrounding cells. The VE graph should be a smooth graph.

3. Experimental Design

An ideal fuel flow map for Rutgers’s formula racecar would achieve optimum horsepower and be volumetrically efficient. To obtain this ideal fuel flow map, the engine’s ECU must be electronically configured, tested, and observed. The engine needs to be monitored while it is running, but it can be difficult to track data if the engine is in a moving vehicle. For this reason, we used a dyno attached to a laptop in order to monitor the engine.

Once we attached the racecar’s engine to the dynamometer, the engine was started and data was recorded. Graphs could be created from volumetric efficiency and AFR tables. We adjusted values to produce a smoother transition between bordering cells in the fuel table. When the engine is not connected to the dyno, there is no load because the engine is in free revolution. Many things could be adjusted once the engine was connected to the dyno. The air-fuel meter changes as the engine heats up and calibrates. If fuel is taken away, the AFR becomes too low. While the engine is on the dynamometer, a volumetric efficiency table in the program WinTEC displays the percentage of air that is being given or taken away. A red dot shows where the computer is calculating, and the position is determined by pressure and rpm. The WinTEC program operates by interpolating values of bordering cells to calculate the optimal fuel and ignition values. While running the engine on the dynamometer, many things need to be watched closely and adjusted. Water temperature should remain around 70 degrees Celsius because if it gets much hotter, the engine will not function properly. Other necessary adjustments include the placement of the throttle blade because it changes the idle value. Also, fuel pressure should be maintained between 40 and 45 psi (pounds per square inch) because the fuel injectors are calibrated for this value. Adding or taking away fuel changes the temperature; when fuel is taken away, the combustion temperature increases.

We then took the car to the practice course and the racing team drove some laps while data was recorded. The data could then be read in WinTEC and analyzed. The way the race team set up volumetric efficiency and AFR tables optimized horse power, torque, rpm, and cylinder pressures. The engine was set to idle between 3000 and 3500 RPM. The initial advance was set to 14 degrees before top dead center. The spark is advanced to allow enough time for the fuel to burn before exhaust. If there was not a large enough advance, some unburned fuel could escape through the exhaust, lowering fuel efficiency.

The engine control unit (ECU) constantly monitors the conditions of the engine. The various sensors include position, exhaust, temperature, pressure, and knock which all report back the ECU allowing it to adjust the engine accordingly. These sensors all help to obtain the ideal AFR of 14.68:1. Any value higher is lean with more air, and any value lower than 14.68 is rich with more fuel. Traditionally when racing,
AFR is ideal because when more fuel is at hand, the fuel can get to the engine faster. Also, it is found that when the engine is cold, a richer mixture is needed because fuel does not vaporize well in the cold. These sensors control and regulate all aspects of the car.

4. Results

We used a variety of sensors on the dyno to measure the manifold absolute pressure, the AFR, the throttle position, the RPM, and the ignition advance in order to calibrate the engine to its optimal running state. The MAP sensor measures manifold absolute pressure, which is the amount of pressure in the intake manifold (Figure 7). The TPS sensor measures the throttle position (Figure 8). The RPM sensor is a magnetic pickup sensor that measures revolutions per minute (Figure 5). The ADV graph shows the ignition advance (Figure 6). We expect the throttle position to be wide open when the RPM of the engine reaches a maximum value. The graphs of TPS and RPM show corresponding peaks when the throttle position was completely open. The MAP sensor shows the presence of a vacuum (lower pressure than atmospheric) in the intake manifold immediately after peak RPM. The lower pressure, or the vacuum, helps draw air into the intake manifold. The ignition advance is at 30 degrees when the engine is at idle. The ignition advance peaks as the RPM peaks. The engine relies heavily on the sensors. The graphs of the sensors reveal how their functions are interrelated.
Figure 7. This graph shows the manifold absolute pressure in the intake manifold. At idle, when the throttle is closed, the MAP is around 71 kPa. Atmospheric pressure is, on average during the experiment, 97 kPa. When the throttle is closed, not much air can enter the intake manifold, so a vacuum is able to exist. The largest vacuum exists when the throttle is released after being wide open. The MAP increases when the throttle is initially depressed.

Figure 8. This graph shows the throttle angle position. When the engine is at idle, the throttle is not depressed. The throttle position relates directly with the RPM. As the throttle is opened, the RPM will increase. This graph measures the amount of opening of the throttle. The peak of the graph indicates that the throttle is wide open.

Figure 9. The Ignition Advance Table allows you to spark the air-fuel mixture earlier at the varying loads and rpm.
Figure 10. The graph of the Ignition Advance should rise relatively smoothly.

Figure 11. The Volumetric Efficiency Table allows you to put more or less air into the cylinders in order to reach the 14.68:1 AFR.
The ignition advance table sets the timing for the spark plug according to pressure (kPa) and RPM (Figures 9 and 10). The numbers do not change as much for the low loads and high RPM. We worked mainly with the top half of this table. The numbers indicate how many degrees before the piston hits top dead center the spark plug will spark. The optimal time for the spark is the time when the piston will generate the greatest amount of torque on the crankshaft, which is 90 degrees after top dead center.

The Volumetric Efficiency table will record the efficiency of the engine according to the AFR (Figures 11 and 12). The value 0 represents 50% efficiency; 50 represents 100% efficiency, and -50 represents 0% efficiency. As the engine runs on the dyno, a red dot on the chart will indicate the area where the engine is operating. We highlighted the cells around the red dot and changed the values according to the air/fuel sensor’s readout. We strived for a value of 14.68. If the sensor showed a higher value, meaning the mixture in the engine is lean, or too much air, we increased the highlighted values in the volumetric efficiency table to a more positive number. When the sensor showed a value lower than 14.68, we would decrease the highlighted values in the VE table to a less positive number to make the mixture leaner. Varying the load and the RPM permitted us to move the red dot everywhere on the chart. We adjusted each area of the chart until the air/fuel sensor showed a value close to 14.68. The sensor does not display a stable number; instead, it varies in a range of numbers. If the range is fairly close to 14.68, it is very well tuned. We also calculated the horse
power with the dyno. The horsepower is torque multiplied by the RPM divided by 5252. For example, 4800 RPM and 34.1 ft-lbs of torque generated a horsepower of 31.16. The dyno measured the amount of torque with a special calculator and the red dot in the chart indicated the RPM. At 11,500 RPM, our engine generated a peak torque of 37.5 ft-lbs, and the horsepower was calculated to be 82.1. To obtain higher horsepower, we would strive for an AFR of 13, a richer mixture [5]. Injecting a little bit more fuel than stoichiometric will generate a bit more power; however, injecting too much fuel will result in very poor fuel economy and reduced power.

5. Future Work

As the future comes closer the need for better engines that use less fuel will arise. In order to achieve this, there are a variety of improvements that can be made. We could have changed the ignition advance which would speed up the time it takes for the spark plug to light. When the spark plug lights it reacts the fuel and the air within the engine to provide power. By having this light faster it would be able to react to the fuel faster giving more power to the car. We could have also added a supercharger to the engine that would push more air into the combustion chamber, allowing a better and faster reaction with the fuel. Since a lot of power is lost during the exhaust stroke because of back pressure an exhaust header could have been added on to prevent this by pushing more exhaust gases out of the cylinders.

With recent developments in alternative fuels, future research could deal with maximizing the efficiency and power of an engine run by alternative fuel. This could be done in a similar way to our setup. The experiment would require finding the perfect stoichiometric ratio for that particular fuel. However, we do not expect the output of these engines to compare to gasoline powered ones.

6. Conclusions

To maximize the power of the engine we had to make sure our volumetric efficiency and ignition advance tables were tuned using WinTec4 and the dynamometer. By setting up the engine on the dyno and running it under different RPM and load, we were able to tune it to get a maximum horsepower of 82.1. This was accomplished by manipulating the amount of fuel the engine received and when it received it using a laptop attached to the ECU. There were areas of the tables that we could ignore as the engine used idled at relatively high RPM.

7. Acknowledgements

We would like to thank the following people and institutions for giving us this opportunity to work on this research project.

Dean Brown,
Blase Ur, for taking time to coordinate such an excellent program and giving us the opportunity to learn about engineering.

The Governor’s School Board of Overseers

Mark Sproul, for teaching us how automobiles (and specifically engines)
work, and for telling us countless stories about his personal racing experiences.

Jaime Ennis, for giving up his free time in order to let us work with the race car and engine, as well as spend hours setting up the dyno for us.

Alison Rankin, for driving us around and helping us with this project and paper in general.

The Rutgers Racing Team for allowing us to use their engine and car, as well as watching them test-drive the car.

Dean Ilene Rosen.

Rutgers University and the School of Engineering.

Jane Oates.

Prudential, Morgan Stanley, Rutgers University, The John and Margaret Post Foundation, John and Laura Overdeck.
8. Works Cited


