Mastering fuel injection
Diagnostic techniques that will lead you to the root cause quickly.
By: Bernie Thompson

Since the introduction of fuel injection on the internal combustion engine (ICE) more than 100 years ago, there have been many changes to this system. Early fuel injection systems were based on mechanical principals; these systems used a jerk pump that metered high pressure fuel to a mechanical injector. Later came electronic fuel injection systems that work with both mechanical and electronic principles; these systems use a microprocessor that calculates the fuel delivery needed and commands the fuel injector solenoid. With either of these systems the end result is to meter the correct amount of fuel and deliver this in an atomized format to the cylinder. This is better accomplished with the modern electronic fuel control system so this is the system used on the vast majority of newer vehicles.

These modern electronic controlled engines are high tech marvels that have more computer processing power than the space shuttle. With this type of sophistication present within the vehicle, many shops struggle when it comes to repairing the modern fuel injection system. When diagnosing electronic engine control systems, 80 percent of these types of problem are moderately easy, 13 percent of these types of problems are difficult, 5 percent of these types of problems are extremely difficult and 2 percent of these types of problem might be unable to be diagnosed by the shop. Many shops are losing all of their profits from the 80 percent that are easy by trying to fix the 20 percent that are hard. What we need are techniques to diagnose these sophisticated vehicles quickly and accurately, and do so in a way that allows the shop to make money.

Diagnosing drivability problems can, and should, be very profitable. In order to diagnose fuel injection problems fast and accurately, you must think outside the box. Fuel injection is about the fuel, right? The fuel is pressurized and delivered in a controlled manner to the cylinder. Fuel injection is part of the engine control system. This system will regulate the intake air, fuel and spark timing in order to achieve the desired performance in the form of torque or power output. The driver of the vehicle will determine the power output from the engine by depressing the accelerator pedal. This is a request to the microprocessor from the Throttle Position Sensor (TPS) or from the Accelerator Pedal Position Sensor (APPS). These sensors convey the driver intent in the form of voltage.

As with all sensors, the TPS and APPS take a physical quantity and convert this quantity to an electrical output signal (voltage). The microprocessor then uses a circuit to change the sensor voltage into a binary code (1s and 0s). This binary code allows the microprocessor to read the voltage change produced from the sensor. In order for the microprocessor to use this voltage, a programmer will program a look up table, otherwise known as a transfer function table. This transfer function table takes the voltage and converts it to a physical quantity. One example of a transfer function table would be used for a Mass Air Flow (MAF) sensor. This sensor may produce an analog voltage that will need to be converted into air weight (grams per second). The transfer function table will have all of the voltage readings that can be produced from the MAF sensor on a particular engine and will provide an actual air weight for each of the voltage readings. In this way the voltage can be used to represent the actual air weight.

![Fig. 1](image)

So what is the fuel injection system doing as the engine is running? It is calculating the amount of air entering the engine and commanding the fuel injector on-time, the fuel injector sequence, the ignition spark timing and the
ignition spark sequence, as well as other functions. We think of fuel injection as being about the fuel; however fuel injection is about the air. You must think outside the box because before the microprocessor can do any control function, it must first calculate the air weight entering the engine.

The fuel weight is a known factor; the air weight is the unknown factor. The fuel injector flow rate is known and is rated based on the restriction size of the discharge orifice and the fuel system pressure. This orifice size is rated by what is known as the Injector Slope or the Injector Flow Rate. This flow rate is the weight of fuel the injector can deliver in a set amount of time. As seen in Figure 1, the fuel weight delivered in a set amount of time can be calculated.

The air flow into the engine is an UNKNOWN factor and must be calculated. This air weight calculation can be made using different methods; the two most common methods are Speed Density and Mass Air Flow. Both Speed Density and Mass Air Flow calculations will provide the actual Air Weight entering the engine. This air weight can be displayed in Grams Per Second (GPS). However, these Air Weight calculations are derived differently. Speed Density measures the vacuum in the manifold to calculate the air weight. This is an indirect or inferred method that uses look up tables based on engine vacuum (engine load) and the engine rotational speed (rpm).

Mass Air Flow is a method of measuring the air weight directly. With this method, the direct voltage produced from the MAF sensor is used in conjunction with the transfer function table. Once the total air entering the engine has been weighed, the air flow entering each cylinder must be calculated, as seen in Figure 2. It is important to understand that the total air entering the engine must be converted into the amount of air entering each of the cylinders. Once the air in the cylinder is known the fuel weight to the cylinder can be delivered.

Because the Engine Control Module (ECM) is calculating the air rate entering the engine in order to deliver fuel, the AIR is very important. For a quick and accurate diagnosis, it will be necessary to calculate the AIR rate into the engine. This is known as Volumetric Efficiency (VE), or the ability of the engine to pump air. The air entering the engine can be calculated with a basic mathematical equation. If the liter size is known, the barometric pressure is known, the engine rpm is known, and the air temperature is known an equation can be given for the air entering the engine, This V.E. equation can be seen in Figure 3.

So what Volumetric Efficiency would the engine that you are working on have? Volumetric Efficiency is the engine swept volume (displacement per cylinder) x the number of cylinders x rpm / intake strokes per revolution = 100
percent VE. However, other factors come into play. Air density, barometric pressure, and engine design can impact the air flow into the engine. Most naturally aspirated engines have a Volumetric Efficiency of about 86 to 89 percent at sea level. Some high performance engines have a Volumetric Efficiency of about 93 to 99 percent at sea level. Since the Volumetric Efficiency is not truly an efficiency, the engine can have a V.E. greater than 100 percent.

So how do you use VE to fix your vehicles? By calculating the VE of the engine and comparing it to the actual Mass Air Flow sensor reading, you can determine whether or not the airflow to the engine is correct. To accomplish this, take your scan tool and set it up to make a recording. Drive the vehicle from a stop in first gear and accelerate under Wide Open Throttle (WOT). Once the vehicle has pulled through first gear, take the recorded data, calculate the VE (there are a number of manual VE calculators available on line) and compare the calculated VE against the actual MAF grams per second.

The Esca scan tool by ATS automatically does this VE calculation for you as seen in Figure 4. The yellow trace is the actual MAF sensor reading in Grams Per Second and the red trace is the calculated VE. When these graphs are overlaid it is quite easy to see any differences between them. The table to the right shows the percentage difference between the actual MAF and the calculated VE.

![Fig. 4](image)

The ECM is weighing the air and then controlling the fuel delivery (fuel weight) into the engine. This is a feed forward system. With a feed forward system there is no way to correct it if anything is wrong. What is needed is a way to change the base air equation so the fuel delivery can be modified. This will allow the fuel weight to match the air weight keeping it stoichiometric for a complete reaction. This is accomplished by the use of an oxygen sensor or Wide Range Air Fuel sensor. The ECM then uses this data to make changes to the fuel injector on-time. The ECM calculates the air weight and then delivers the fuel weight (this is feed forward). The oxygen sensor then weighs the air/fuel ratio and sends this data to the ECM where it is used to change the air/fuel ratio (this is feedback). The fuel trim is the control of the feedback system. If anything is incorrect with the feed forward system, the fuel trim will modify the base air equation so that the fuel weight to air weight can be corrected.

The air weight calculation is made, the fuel weight is delivered, the oxygen sensor weighs the air/fuel that was delivered, the ECM calculates if the fuel delivery needs to be changed and uses a modifier in percent called fuel trim in order to change the air/fuel weight. Now that this sequence is understood it will be easy to see that the VE will be used in conjunction with the fuel trim to diagnose the fuel injection system. If either the VE or the fuel trim is used separately, this data will not provide you with the information required to diagnose the system. However, when VE and fuel trim are used together it becomes magic.

Now that we have the winning formula let us diagnose a few problem vehicles. The first is a 2003 KIA Sorento. This KIA was driven while the scan tool recorded the data. In Figure 5, the calculated VE is shown in red and the actual MAF air weight is shown in yellow. It is clear that these two traces do not follow each other. The calculated VE is 37 percent higher than the actual MAF air weight. With only the VE data you would not be able to determine what the problem is, but only that the engine’s pumping ability is low (restricted exhaust, restricted induction, camshaft
So what is the fuel injection system doing as the engine is running? It is calculating the amount of air entering the engine, which needs to be converted into air weight (grams per second). The transfer function table will have all of the voltage readings that the system needs to perform its calculations. This table would be used for a Mass Air Flow (MAF) sensor. This sensor may produce an analog voltage that will be read by the microprocessor. The binary code allows the microprocessor to read the voltage change produced from the sensor. In order for the microprocessor to use this information, it must change the sensor voltage into a binary code (1s and 0s). This allows the microprocessor to interpret the data accurately.

Fuel injection is part of the engine control system. This system will regulate the intake air, fuel, and spark timing in order to achieve the desired performance in the form of torque or horsepower. The fuel is delivered in a controlled manner to the cylinder. Fuel injection is used in conjunction with the fuel trim to diagnose the fuel injection system. If either the VE or the fuel trim is used the system will calculate if the fuel delivery needs to be changed and use a modifier in percent called fuel trim.

Since the introduction of fuel injection on the internal combustion engine (ICE) more than 100 years ago, there have been systems that work with both mechanical and electronic principles; these systems use a microprocessor that calculates the fuel weight. The fuel weight is a known factor; the air weight is the unknown factor. The fuel injector flow rate is known and is what is known as the Injector Slope or the Injector Flow Rate. This flow rate is the weight of fuel the injector can deliver in a controlled manner.

Now let the magic begin! We will compare the VE and fuel trim charts together. First we will analyze the VE chart. This chart shows that the VE at 2100 rpm is 25 percent different and at 4500 rpm is 37 percent different. Now let us analyze the fuel trim chart. At 2100 rpm the fuel trim is +24 percent and at 4500 rpm the fuel trim is +36 percent. It now becomes clear that the air weight was misread by the MAF sensor and the fuel was delivered for this incorrect air weight (feed forward). The oxygen sensor then reads the incorrect air/fuel weight and the ECM corrects the low air weight (feedback).

It is important to note the air rate difference provided with the VE matches the positive fuel trim numbers, this shows that the MAF sensor is misreading the air weight. The reason that the air weight matches the fuel trim is that the fuel trim is a multiplier to the base equation. In other words the base equation is mainly based on the air weight so when the fuel trim is used as a multiplier it is increasing or decreasing the air weight. Yes, the fuel trim is about the AIR weight. As the air weight is changed the fuel weight will be changed to match the air weight, thus keeping the air/fuel ratio at stoichiometric. On this 2003 KIA Sorento the MAF sensor is bad. Before any sensor is replaced always test the circuit, it takes a good power and ground to make sensors function correctly.

The second problem vehicle is a 2005 Subaru Forester. First we will analyze the V.E. as seen in Figure 7. The calculated VE (red trace) and the actual MAF air weight (yellow trace) follow each other quite closely; this indicates that the air weight was read correctly. Now we will analyze the total fuel trim chart as seen in Figure 8. By analyzing the fuel trim
chart it is clear that at low engine loads there is no problem present. However, as the engine load is increased the fuel trims are indicating problems. By looking at the VE chart, it is clear that this problem is in the fuel delivery side of the system. By using both the VE and fuel trim you can divide the system into the air side and the fuel side. Since the air was read correctly the problem is on the fuel side. Now it is necessary to look at how the fuel trim changes occur under the dynamic load of the engine.

When diagnosing fuel trim problems never look at the fuel trim in only one load state. It will be important to run the engine through its entire load range and analyze how these fuel trims change. On this Subaru, the fuel trims are good at low engine load, low fuel consumption conditions. As the engine load is slightly increased the fuel trims become negative (taking away fuel). Then, as the engine load is further increased the fuel trims become positive (adding fuel) under high fuel consumption conditions. Under load these fuel trims are adding up to +38 percent, which is a large fuel trim correction.

So what is this chart showing us? It is indicating that the fuel delivery cannot keep up with the fuel needed to produce power under load. But what about the negative fuel trims? Since these negative fuel trims are right at the point the fuel pressure is failing, the fuel pressure at this load point is both good and bad. The negative fuel trims at this load point are caused as the fuel pressure drops and then returns back to high pressure. As the engine load is increased the fuel pressure continues to drop, thus the fuel trim is increased to compensate for the lower fuel pressure. On this Subaru Forester a restricted fuel line is the cause of this problem. In order to find this type of problem an amp clamp on the fuel pump is used with an oscilloscope. This will provide the fuel pumps current draw and RPM.

The VE and fuel trim technique is just magical and it is important to just use this technique regardless of what scan tool you have. The more you become familiar with this technique, the faster your diagnostic routine will become. Soon you will be able to diagnose problem vehicles on your initial test drive.