Intelligent Power Scan

Training

Fuel Injection Diagnosis
It’s All About the Air

by Bernie Thompson

An engine can’t run without fuel and air. But how much fuel and how much air are needed to make it run efficiently?

A flash of sunlight reflected off the ice hammer’s head as it swung forward, breaking through the age-old ice. Normally this would have made a loud noise, but the only noise that Edmund heard was his own heart racing. The lack of oxygen had every muscle in his body aching in agony as he took his next step up the mountain. He thought to himself, Just a few more steps and I’ll be standing on top of the world. He had dreamed of the day he would reach the top of Mount Everest. On May 29, 1953, Sir Edmund Hillary and Tenzing Norgay had reached the highest point on earth, some 29,029 ft. above sea level. At this elevation there is very little oxygen in the atmosphere, and this climb had been accomplished without the aid of bottled oxygen. The amount of oxygen that’s contained in the atmosphere is important because it’s this oxygen that’s taken in by our bodies and converted chemically to give us the energy we need to do work. A similar release of energy is what powers the internal combustion engine.

In order for this combustion energy to be released, a chemical reaction must take place between oxygen and the hydrocarbons in the fuel. This chemical reaction is based on the weight mass of the two elements—oxygen and hydrocarbons—that react together. In the spark ignition internal combustion engine, this weight ratio can change from 11:1 under a power demand to 17:1 in a lean cruise condition. At both weight ratio extremes, the tailpipe emissions levels will rise considerably.

Many years ago tailpipe emissions levels were not regulated. As the concern about air quality around large cities grew, government regulations were imposed on vehicle manufacturers. For the manufacturers to meet these emissions regulations, a new technology emerged. This technology employs a method of weighing precisely the air entering the engine and then delivering the correct weight of hydrocarbons or fuel for an engine’s running condition. This technology is referred to as fuel injection.

Fuel injection can be either mechanical or electronic, or a combination of both. This discussion will center on electronic fuel injection for the spark ignition internal combustion engine. There are two basic methods of fuel injection currently used in vehicles—speed density and airflow. It’s important to know which system you’re working on. For example, an exhaust gas recirculation (EGR) valve stuck open on a speed density system produces a lower vacuum reading, which would normally indicate that the engine was under load. Under this condition additional fuel would be added, which would overfuel the engine, so the fuel trim correction would go negative and take fuel away. (More on fuel trim later.) On an airflow system with the same EGR valve problem, the airflow would be read correctly, so no fuel trim correction would be needed.

With the speed density method, an indirect calculation of air weight is made by measuring the intake pressure changes using the manifold absolute pressure (MAP) sensor. This sensor does not directly measure the intake manifold pressure; instead, it measures the displacement of a diaphragm that’s deflected by intake manifold pressure. This intake pressure change is converted by the MAP sensor to an output measurement of pressure in kilopascals (kPa). The change in intake manifold pressure can be used to calculate the load placed on an engine. The MAP sensor accomplishes this by monitoring the intake pressure; as the throttle blade is opened, it allows more air to enter the engine and, thus, changes the pressure from a negative state (vacuum) to one that’s slightly under atmospheric pressure at wide-open throttle.

The MAP sensor is desirable to use because the absolute engine working pressure (vacuum) at idle and light load is unchanged by elevation. At sea level, the barometric pressure is 101 kPa, and a good engine idle pressure is 27 kPa. Therefore, the engine vacuum is 101 kPa 2 27 kPa 5 74 kPa, or 29.9 in./Hg 2 10 in./Hg 5 19.9 in./Hg. At 5500 ft. of elevation, the barometric pressure is 84 kPa and a good engine idle pressure is 27 kPa. Therefore, the engine vacuum is 84 kPa 2 27 kPa 5 57 kPa, or 24.9 in./Hg 2 10 in./Hg 5 14.9 in./Hg.

An equation is needed to calculate the airflow into the engine, and certain values must be known: the size of the engine in liters; the intake manifold absolute pressure, as determined by the MAP sensor; and the revolutions per minute (rpm), because in a four-stroke engine, only one stroke produces incoming air. The rpm is determined by the crankshaft position sensor. This will become a factor since the air mass is what we're trying to measure. The air temperature will also become a factor because a change in temperature will cause a change in the density of the air. This is read by the intake air temperature (IAT) sensor. At an air temperature of 240°F, the air weighs 1.51 grams per liter (g/L); at an air temperature of 104°F, the air weighs 1.12 g/L—a 35% difference. The speed density base air equation is made with only three sensors and is as follows:

RPM x Liters x MAP x IAT Air Density = Mass Air in g/sec

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With the airflow method, a calculation of air weight can be made that is an indirect measurement or a direct measurement of the air entering the intake manifold, depending on which type of sensor is used. This airflow is measured with a device called a mass airflow (MAF) sensor. There are several styles of these devices, the most popular of which is the heated-element type. It's based on the hot-wire anemometer weather forecasters use for measuring wind velocity. A wire or element is electrically heated to a set temperature above the temperature of the inlet air. As the throttle blade is opened, the velocity of air increases, which transfers the heat from the element into the air. An electronic circuit is designed to keep the element at a set temperature so that as its temperature decreases, the current flow across it increases. By monitoring the current, the airflow will be known. The PCM converts this signal into air weight, which is read in g/sec.

In either of these methods—speed density or airflow—the air is the unknown quantity; therefore, the air flowing into the engine is what must be determined. Fuel injection is based on airflow, not fuel flow. The fuel delivery weight is a known factor.

One example can be seen by using a 25-lbs./hr. fuel injector. This number is based on the engine's brake-specific fuel consumption (BSFC), which indicates the engine's fuel consumption efficiency. The BSFC is usually measured in pounds of fuel used per hour for each unit of horsepower. This relationship means that horsepower multiplied by BSFC equals pounds of fuel consumed per hour.

A 25-lbs./hr. fuel injector's fuel delivery is based on a constant fuel pressure and volume equal to 255cc/min., or .00425cc/millisecond. One cubic centimeter is equal to .162 gram of gasoline. This fuel weight is a known quantity that will be delivered by the fuel injector to the engine.

Now that both the air weight entering the engine and the fuel weight being delivered can be determined, an equation can be derived that will set a precise air/fuel ratio for the engine. The equation is used to determine the air mass weight contained in each cylinder so the fuel weight can be delivered properly. If there were any problems, such as the sensors misreading or incorrect fuel delivery, the base air equation would need to be changed so that the correct air/fuel weight would be maintained. This is done with a multiplier to the base air equation that's called fuel trim (see Fig. 1 on page 30). The purpose of fuel trim is to monitor the ratio of air to fuel weight and to keep it at a predetermined target value.

An oxygen sensor is located in the exhaust system to continually measure the air/fuel ratio. It's set up in a feedback loop so it can report the air/fuel ratio to the microprocessor, which will use this information to adjust the fuel trim multiplier to keep the air/fuel ratio at the target value. This method of control is referred to as a closed-loop limit-cycle control system. One example of this type of control system is an oven. When the temperature is set to, say, 350°F, the electrical element comes on to heat the oven. The oven stays on until it reaches a temperature of 355°F, then shuts off. This temperature is sensed by a sensor in the oven. The oven then cools down until it reaches 345°F. At this point the heating element turns on, heating the oven to 355°F again. This cycle continues, to keep the oven close to the target temperature of 350°F.

This type of control system can maintain an average value very close to the command input. On an internal combustion engine, this system works in much the same way. The fuel trim works like the oven's heating element, driving the system rich or lean. The oxygen sensor works like the heat sensor in the oven, only it reports the air/fuel changes. The oxygen sensor reporting limits are set between .1 and .8 volt. The oxygen sensor in this range is stoichiometric. For this sensor to be rich it must be above .8 volt; to be lean it must be below .1 volt.

A vehicle's fuel control system under most conditions will cycle the oxygen sensor in this .1- to .8-volt range. This is usually accomplished with Short Term Fuel Trim (STFT). Since STFT drives the oxygen sensor, if the oxygen sensor response is slow, the STFT peak-to-peak value will increase. If the STFT value exceeds 8% peak-to-peak, the O2 sensor will have to be replaced (Fig. 2 on page 32). The cycling oxygen sensor will maintain the air/fuel ratio at 14.66

lbs. of dry air to 1 lb. of gasoline. This is referred to as stoichiometry, which is the ideal mixture of air and fuel that, when ignited, will completely burn all of the hydrocarbons and leave only carbon dioxide and water.

In a running engine, the air/fuel mixture will never completely burn, due in part to unvaporized fuel and hydrocarbons packing into the piston ring lands and the valve pocket areas. This air/fuel ratio is desirable for the catalytic converter to work correctly, thereby lowering the levels of tailpipe emissions.

Now that we have an understanding of the fuel injection fuel control system, let's put it to work in repairing vehicles. Since the fuel injection system is all about the air, it will be necessary to calculate the volumetric efficiency (VE) of the engine (see Mark Warren's June 2003 Driveability Corner for a concise explanation of VE). A Toyota 4Runner with a 3.0L engine was brought in because of low power. The Check Engine light came on and the driver complained of low power. The following diagnostic trouble codes (DTCs) were pulled: P0171 (system too lean), P0325 (knock sensor 1 circuit) and P0330 (knock sensor 2 circuit).

To find a diagnostic direction quickly it's necessary to calculate the VE. This can be done by collecting the parameter identifications (PIDs) that will be needed while test driving the vehicle. Once you have the information, just run the VE calculation to see whether the air going into the engine is correct. In this example (Fig. 3 on page 34), the scan tool automatically calculated the volumetric efficiency of the engine while the vehicle was being driven. The yellow trace is the MAF sensor signal that the scan tool reads as grams per second (g/sec) and the red trace is the VE reading, or theoretical airflow. When these two measurements of the air flowing into the engine are compared, it's easy to see whether a problem exists. In this case, the actual airflow reported from the MAF sensor (yellow trace) is much lower than the VE calculation (red trace). This low MAF reading shows that a problem is present in the airflow to the engine.

A low airflow reading could be associated with many problems, such as a restricted exhaust or intake, an air leak between MAF sensor and throttle, an incorrect MAF sensor calibration, incorrect camshaft timing, engine mechanical faults, etc. To identify what the problem is, it's necessary to check the fuel trim. When doing this, you must check the trim values over a range of engine load and rpm. In this fuel trim test (Fig. 4), total fuel trim readings are taken. Total fuel trim is Long Term Fuel Trim added to Short Term Fuel Trim. When checking the fuel trim chart, look at the way the fuel trims change over the load of the engine. In this example at idle, the fuel trim is taking away 229% from the base air equation. As the load and rpm change, the fuel trim starts to add +23% to the base air equation. As the load steadily increases, the fuel trim starts to add up to +49% to the base air equation. This indicates that the MAF sensor is dirty. The MAF sensor uses a heated element to measure the incoming air to the engine. When this element becomes dirty it overreads the incoming airflow at idle, so the fuel trim has to modify the base air equation to compensate.

At hot unloaded idle, the MAF sensor reading in g/sec should be very close to the liter size of the engine, so on this 3.0L Toyota, at hot idle the MAF sensor should read about 3 to 3.2 g/sec. This is a good way to see whether the MAF sensor is reading correctly at idle. If the MAF sensor reading in g/sec is higher or lower than the liter size of the engine at idle, check the fuel trim. If the fuel trim is good (610%), then the MAF sensor is reading the airflow correctly.

If the fuel trim is greater than this, it's an indication of a problem. As the engine load changes, the dirty MAF element cannot give up its heat to the air flowing over it, thus it underreads the airflow. The fuel trim has to correct this airflow reading from the MAF sensor. It does this by multiplying the base air equation by the trim value needed.

Another example of a MAF sensor reading incorrectly is if the MAF sensor's Wheatstone bridge is out of range, the actual g/sec reading would also be out of range. Since the MAF sensor reading sets the fuel delivery weight, the fuel trim would correct the airflow. This would create out-of-range fuel trims as well. However, there's a difference in the way the fuel trims load on the chart; rather than going from a negative to a positive value, the fuel trims stay linear. In other words, they stay very close to the same percentages from the bottom of the chart to the top. In this case, the MAF sensor would need to be replaced.

In another example, if the engine has a fuel delivery problem, the MAF sensor reading would be correct but the fuel trims would read out-of-range. Whether the fuel trims are positive or negative tells you which direction to go. When they're negative (taking away fuel), there's too much fuel getting to the engine. When they're positive (adding fuel), there's not enough fuel getting to the engine. If the engine has a misfire with low fuel trim values, the problem could be the ignition system or engine mechanical. If the engine has a misfire with high fuel trim values, look at a possible problem with the injectors.

Now back to our 3.0L Toyota's MAF sensor problem. The sensor was removed and cleaned, repairing not only the P0171, but the P0325 and P0330 (Figs. 5 and 6 on page 36). Rechecking the work you've done is important, as it verifies that the repair has corrected the problem. This entire diagnosis was made while on a test drive.

So the next time you go for a test drive, take your scan tool with you. It may save you hours of diagnostic time later. Also, remember the lesson of Mount Everest: In an internal combustion engine, just as in our bodies, the amount of available air determines the amount of work that can be done.