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OXYGEN SENSORS 101

Oxygen Sensors....

things you should know

by Bob Freudenburger

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Ratio Reporting: Oxygen & Air/Fuel Ratio Sensors

by Bob Freudenberger

As with almost everything else automotive, the sensor that reports to the engine management computer on the state of the air/fuel ratio has evolved dramatically over the last four decades. Regardless, it remains the single most important input for allowing the closed-loop operation that reduces exhaust emissions and increases efficiency, yet many service technicians still do not understand its operation, failure modes, or diagnosis.

This is an older three-wire HEGO (Heated Exhaust Gas Oxygen) sensor. The black wire carries the signal.

Research into the idea of electronically monitoring an engine's air/fuel ratio continuously so that adjustments to the amount of gasoline delivered for combustion could be made dynamically began at Robert Bosch GmbH of Germany in the 1960s. The "Nernst cell" principle was used to generate a voltage signal from the electrical potential between ambient air and the gases in the exhaust stream. Such a signal could be interpreted by electronic logic, which would then make decisions on how much fuel should be added to the intake air to produce a near-ideal charge. In 1976, Swedish car makers Volvo and SAAB working with Bosch engineers introduced the Lambda Sond feedback system that put the principle into practice.

Computers & Catalysts

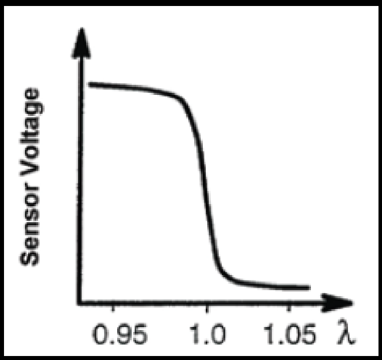
The engine management computer may be called an ECM (Electronic Control Module), an ECU (Electronic Control Unit), a PCM (Powertrain Control Module), or the ME (Motor Electronics) depending on the make of vehicle and the country you are in. No matter what the name, it is the seat of the computing power that gives us the excellent performance, efficiency, and drivability we enjoy in today's cars and light trucks. We have sometimes compared it to a country's central intelligence authority -- spies send it information, which it analyzes in order to make decisions on what it wants done, then it commands operatives in the field to do just that.

The list of "spies" (sensors) includes those for crankshaft and camshaft position, rpm, coolant and charge temperatures, mass of the air entering the intake at any given moment, detonation, vehicle speed, etc. None, however, has a more profound effect on the air/fuel mixture than those that send signals pertaining to the composition of the exhaust gases. Although two-way (meaning hydrocarbons and carbon monoxide) oxidation-type catalytic converters were already in use to cut the release of those gases into the atmosphere, getting rid of oxides of nitrogen emissions required the adoption of the three-way "reduction" catalyst (reducing NOx to harmless nitrogen and oxygen), which in turn depends on near-perfect "Lambda" (in engineering language, the Greek letter that represents the ideal stoichiometric 14.7:1 air/fuel ratio by weight) to do its job.

While "feed-back" carburetors were sometimes used early on to implement this ratio control by varying the amount of atmospheric pressure on the fuel in the bowl, that was entirely superseded by electronic fuel injection (EFI) by the late 1980s, and the systems have become more and more refined since.

Physical Evolution

The original oxygen sensor comprised a steel housing with a hex and threads, a louvered shield over the tip, and a hollow cone-shaped "thimble" made of zirconium dioxide (ZrO2), which is coated inside and out with a thin layer of micro porous platinum. The outer layer is exposed to the exhaust stream, while the inner layer is vented to the atmosphere and attached to a single wire that runs to the ECM.



In a regular oxygen sensor, output voltage changes dramatically as the air/fuel mixture crosses the Lambda line. Remember, "lean equals low."

This is essentially a galvanic cell -- the zirconium dioxide acts as the electrolyte, and the platinum layers serve as electrodes. Once the ZrO2 reaches about 300 deg. C. (600 deg. F.), it becomes electrically conductive and attracts negatively charged ions of oxygen. These ions collect on the inner and outer platinum surfaces. Naturally, there is more oxygen in plain air than in exhaust, so the inner electrode will always collect more ions than the outer electrode, and this causes an electrical potential. Electrons will flow.

When the engine is running lean, more oxygen will be present in the exhaust stream than when it is rich. That means there will be more ions on the outer electrode, a smaller electrical potential and less voltage. Just remember "L=L" for Lean=Low.

The voltage produced is small, never exceeding 1.3V (or, 1,300mV) or so, with a typical operating range being between 100 and 900mV. This is sufficient for the ECM to read, however. If it receives a sensor signal of less than about 450mV, it recognizes a lean condition, and if it gets more than that amount of voltage, it sees rich running. Either way, it instantly corrects by adjusting the injection pulse width (the length of time the injectors are energized per combustion cycle in milliseconds).

Electric Heat to Planar

The next step in the development of Lambda probes was the addition of an electrical heating element in the early 1980s. As already mentioned, the sensor has to reach 300 deg. C. (600 deg. F.) before it can generate a signal, and this heat source causes it to get to that temperature faster than it would from exposure to exhaust alone. It also prevents it from cooling off during idle, which can throw the system into open-loop.

The "planar" sensor, which appeared in the mid-1990s, was another big improvement. Instead of a heavy thimble, planar sensors have a flat ZrO2 element (less than 2mm thick) projecting into the exhaust stream. The electrodes, conductive ceramic layer, and heater are laminated into a unified strip that is smaller, lighter, and more resistant to contamination than the thimble design. The integrated heater element also requires less electrical power.

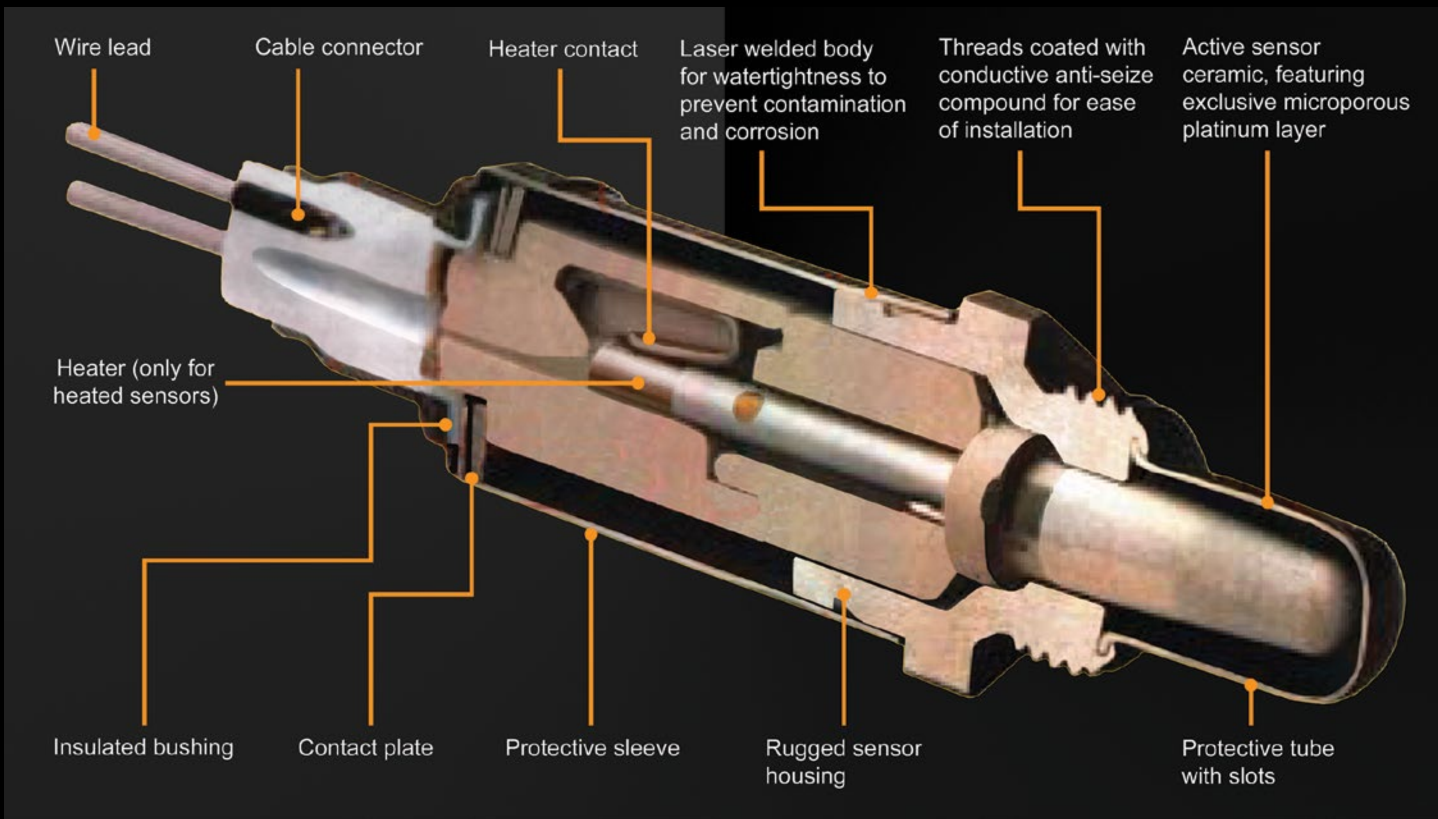
Another advantage is that planar sensors send signals to the ECM five to seven times per second for much more precision in fuel management. To put this into historical perspective, the O2 sensors used on cars with feedback carburetors sent roughly one signal per second, and those used with throttle body injection provided only two to three signals per second.

These sensors have evolved from the one-wire thimble type through planar to the AFR sensors of today

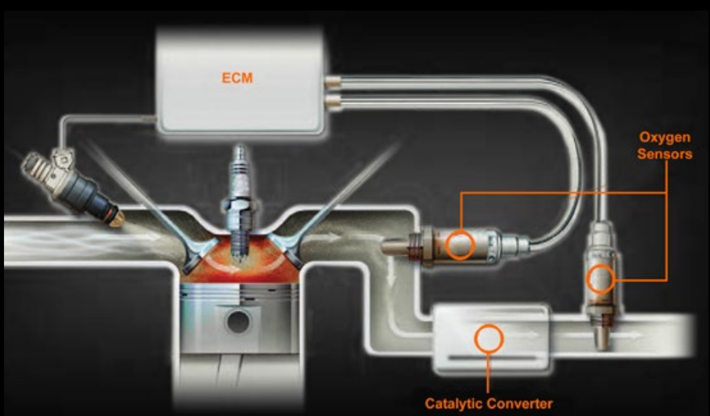
In some applications, you can upgrade an older heated thimble sensor to a planar, but you can never go downscale -- you cannot install a thimble sensor to replace a planar.

Big Departure

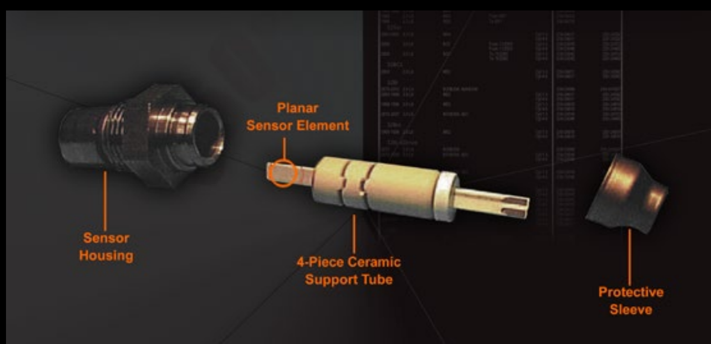
While planars are faster and better than thimble-type sensors, they still operate in basically the same manner. At stoichiometric, when the air/fuel ratio is perfectly balanced, conventional sensors have an output voltage of about 0.45V (450mV). When the fuel mixture goes even a little rich, the sensor's volt-age output does not just increase slightly. It shoots up to its maximum output of about 0.9V. When the mixture is lean, sensor output quickly drops to 0.1V. Every time the oxygen sensor's output jumps back and forth, the ECM responds by decreasing or increasing the amount of fuel delivered to the combustion chamber. The rapid flip-flopping achieves something approaching an average stoichiometric condition. But aver-ages are not good enough for optimal fuel efficiency and the latest emission control standards. More precise control over the air/fuel ratio is needed. Everything changed when the wide-range sensor (also known as an air/fuel, AFR, or lean sensor) appeared in



The ceramic thimble with its metallic coating acts as a galvanic cell. The difference in the oxygen content of the reference air to that of exhaust gas is what generates voltage (courtesy Robert Bosch).



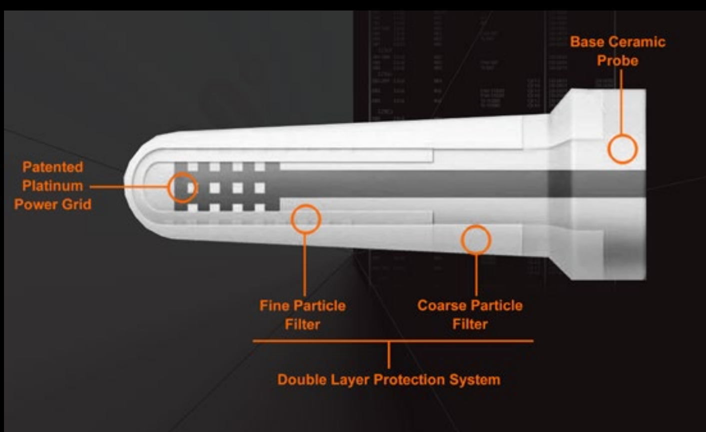
The addition of an oxygen sensor downstream of the catalytic converter makes it possible for second-generation on-board diagnostics to test the catalyst's capacity and efficiency (courtesy Robert Bosch).



The planar type uses a much lighter unified strip to produce voltage in-stead of that big thimble. With its integrated heater, it starts sending the ECM accurate signals almost immediately upon start-up (courtesy Robert Bosch).

the late-1990s, which has made lean-burn engines with stunningly efficient characteristics possible. It does not simply send a lean/rich toggle. Instead, it tells the ECM how lean or rich the mixture is by providing useable linear output over a wide range of a/f ratios. It adds an electrochemical "pumping cell" to the planar sensor's layered ceramic strip. This pumps a sample of the oxygen in the exhaust into a "diffusion" gap within the sensor. The sensor is designed so that a certain amount of current is needed to maintain a balanced oxygen level in the diffusion gap. This current is directly proportional to the oxygen level in the exhaust, and amounts to an analog input to the ECM. This is superior in speed and accuracy to simply switching rich to lean at the 450mV threshold.

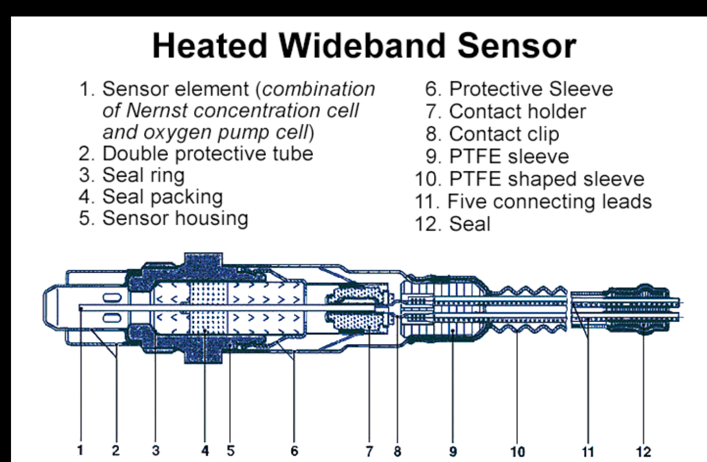
A wideband AFR sensor provides precise readings for air-fuel ratios from very rich (Lambda 0.7, or an air/fuel ratio of about 11:1) to pure air, no fuel. The sensor receives a reference voltage from the ECM and generates a signal that corresponds to the fuel mixture. It operates at a temperature about twice that of older O2 sensor designs, and it reaches this within 20 seconds after a cold start. Response time to changes in air/fuel ratios is less than 100 milliseconds, much faster than that of any previous sensor, which provides optimal mixture management. When the air/fuel mixture is perfectly balanced at 14.7:1, the sensor produces no signal. As the air/fuel mixture starts to go rich, the sensor output goes from zero to about negative 2.0 milliamps. When the mixture is lean, the sensor produces a positive current that goes from zero up to 1.5 milliamps as the exhaust gases approach pure air.



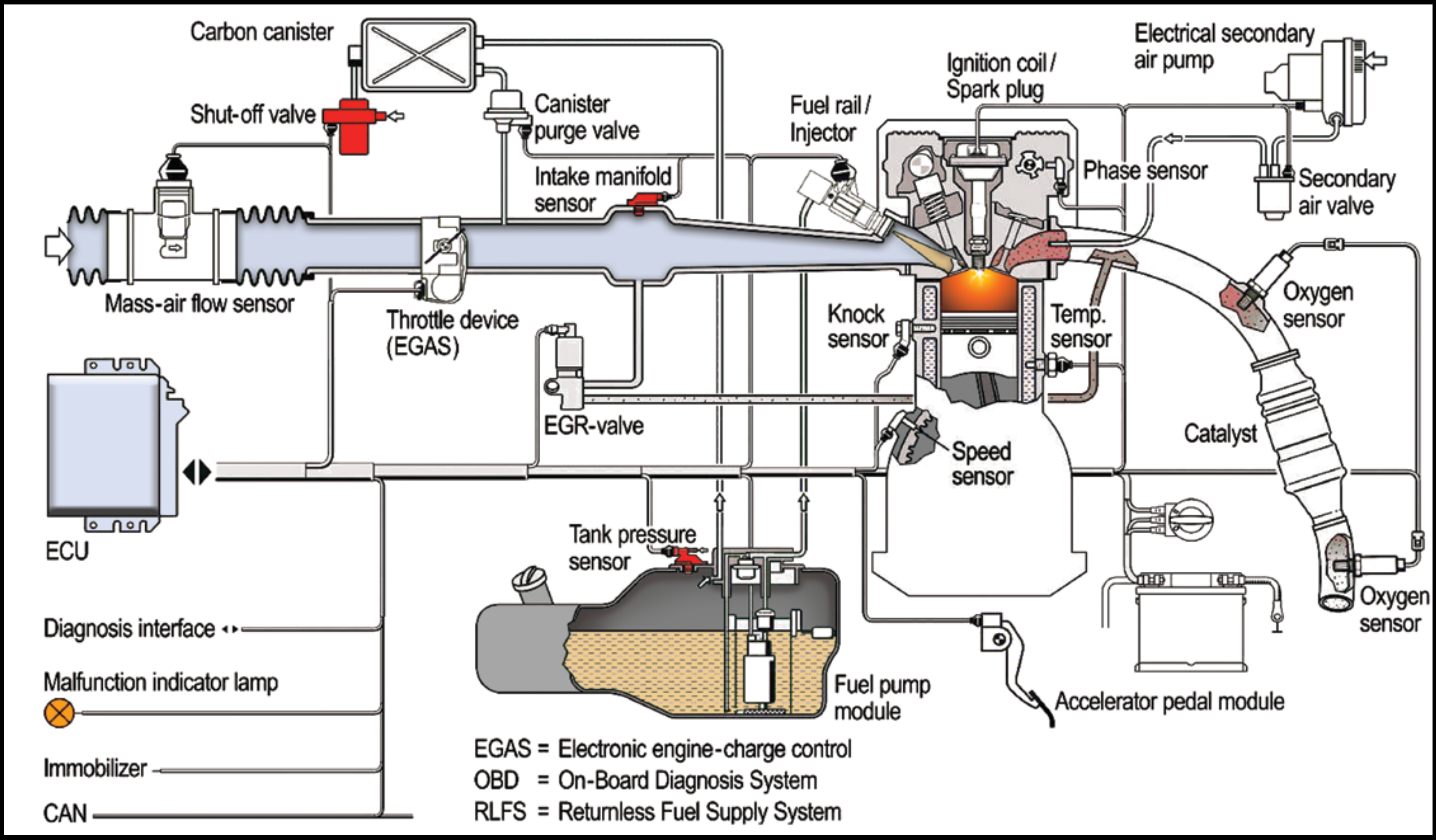
Thimble Ceramic Element
Although all oxygen sensors are carefully constructed so that harmful particles do not get through to the platinum-coated zirconium, contamination is still the biggest killer. (courtesy Robert Bosch).

You will want to use your scan tool as one of the first steps in O2 sensor evaluation.

Although it may look very similar to a planar sensor from the outside, the wide-band type sends a completely different kind of signal to the computer, which results in much more accurate mixture control than can be achieved with the "dithering" of a regular thimble or planar oxygen sensor.



If you have not yet encountered the wide-band oxygen sensor, it is time to get familiar with it. This is what it looks like inside. Note that the pumping cell allows it to produce a signal directly proportional to the air/fuel ratio, as opposed to the high and low switching of traditional oxygen sensors.



This second-generation on-board diagnostics Motronic system shows how much is involved in modern engine management. Regardless of all the recent developments, however, oxygen sensors remain the linchpin of accurate air/fuel mixture control.

TiO2

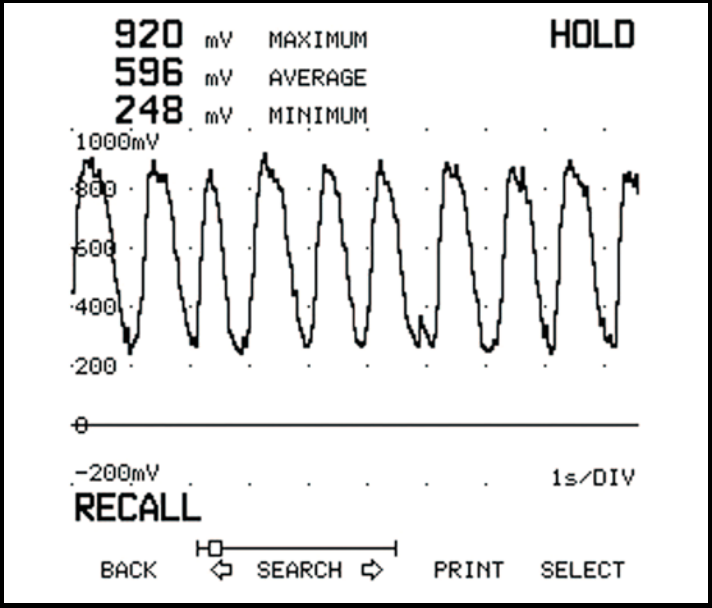
We should at least mention the only other type of oxygen sensor even though it has not been used for years, and then only in a small number of Nissan and Toyota models. Called the titanium sensor, it does not generate a voltage signal. Instead, its resistance changes dramatically when the oxygen content of the exhaust reflects stoichiometry, so it is used to modify a reference signal (typically one volt) from the computer in much the same way as a coolant temperature sensor does. The oxygen blocks the passage of electrons through the TiO2 element, and resistance rises sharply as the mixture goes lean.

If you ever encounter an oxygen sensor with 12mm threads instead of the standard 18mm, or a wire that is color-coded red, you are probably dealing with a titanium-type sensor.

Connections

While the basic first-generation sensor has only one wire, today you will see up to four on thimble and planar types. In most cases, two means it is an early unheated unit -- the extra wire just provides a more dependable ground than thread contact in the manifold or head pipe. Three leads indicate a HEGO (Heated Exhaust Gas Oxygen) sensor, one for the signal, two for the heater circuit. Although the signal wire is typically black, it can be hard to tell which of the other two is ground and which is 12V to the heating element, so a wiring diagram would be helpful. Typically, a fourth wire is a dedicated ground for the signal portion.

Wideband AFR sensors have five or six wires: two for the heating element's power and ground, one each for the pumping cell, the sensor element, and a calibration resistor, and sometimes an extra ground.



With a lab scope, you can easily see what kind of a signal the oxygen sensor is sending. This is obviously a good one.

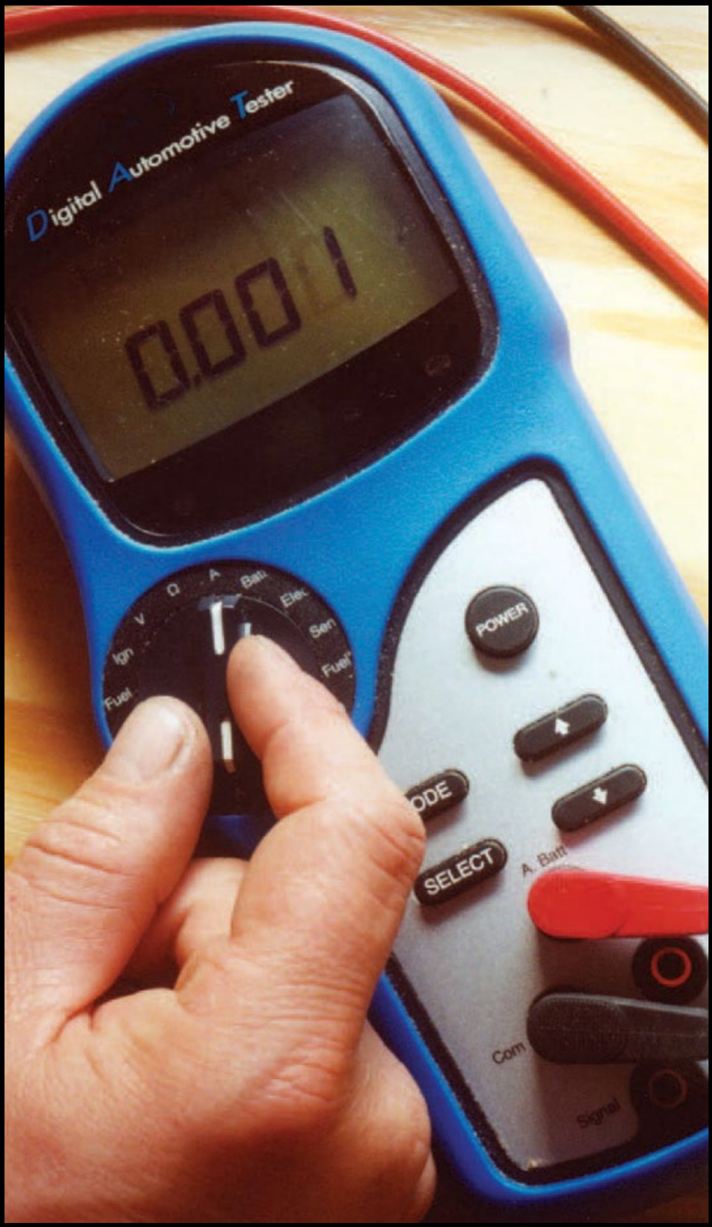
Failures

Early in the history of closed-loop engine management, oxygen sensor replacement was recommended as often as every 25,000km (15,000 miles) or 50,000 km (30,000 miles). Experience has shown that many are still working fine after several times that, and regular retirement intervals were lengthened to 100,000 km (60,000 miles), then eliminated altogether. "Many" is the key word, though. It is not uncommon for them to fail prematurely.

Oxygen sensors can be ruined by several things. Mechanical damage in the form of a broken element or wire is always a possibility, but the most common cause of failure is contamination. Lead, carbon, metals from motor oil additives, and silica (from high-volatile RTV silicone sealants or anti-freeze, expect O2 sensor problems whenever you replace a blown head gasket) in the exhaust can all coat the ZrO2 and make the unit sluggish or inoperative.

Deposits on the exhaust side of the cell increase voltage output, giving a false rich signal. This drives the system lean, perhaps resulting in performance or drivability problems. Many technicians have never considered the possibility of contamination of the electrode on the reference air side, but it is a problem nevertheless. Typically, it comes from the smoke given off during the deterioration of silicone rubber seals or insulation, or from aerosol wire-drying chemicals, cleaners, etc. used under the hood. Blocking the reference air lowers the unit's voltage potential, making it send a false lean signal that drives the mixture rich.

Symptoms of a lazy or dead oxygen sensor are surging, hesitation, poor overall performance, falling fuel mileage, rough idling, a failed emissions test, and an inefficient or clogged catalytic converter. As you are probably aware, it is an unfortunate fact that those problems can be caused by many other conditions besides a malfunctioning oxygen or AFR sensor, so proper diagnostic procedures must be followed.



Your DMM should have a voltage bar scale to make it useful in checking oxygen sensor output, but a graphing multi-meter, or a lab scope would give you better information.

Tools

Where equipment is concerned, the obvious first choice is a scan tool. Looking at O2 voltage, cross-counts (the rate of switching across the 450mV threshold), and fuel trim is essential. Of course, there are the fault codes of the on-board diagnostic system, too. Many technicians like to back up that data with direct checks, however. A quality DMM (Digital Multi-Meter) with a voltage bar scale, a graphing multi-meter, or a lab scope will work fine here, but we have also had success with dedicated O2 sensor testers.

A procedure from Robert Bosch for testing with the sensor isolated from the computer has been around for many years. Start by warming up the engine, then disconnect the sensor's pigtail from the harness and attach it directly to your meter or tester. To check rich response, hold 2,500 rpm, and add propane to the intake until speed drops by 200 rpm. Or, pull and plug the vacuum hose to the fuel pressure regulator, which will increase pressure and richen the blend. You should see the reading jump to 900 mV, or more. If reaction is slow, or that voltage is never reached, try running it at 3,000 rpm for a few minutes, then check again. No improvement means a new sensor is needed.

Then, test lean response. Introduce a small vacuum leak, say by removing an accessory hose, and watch the reading. If it drops to .2V or lower in less than one second, the sensor is okay. If it falls sluggishly, or you never see it get down to .2V, give it the 3,000 rpm treatment and try again, but it is probably time for replacement.

Reconnect the pigtail to put the sensor back in touch with the computer, then tap your meter into the signal wire, maintain 1,500 rpm, and you should see rapidly changing readings that average somewhere around half a volt as the computer keeps adjusting the blend. Deciding whether or not response is slow enough to justify replacement requires some judgment. On pre-planar sensors, a common rule of thumb for minimum activity was eight trips across the rich/lean line in ten seconds, and sometimes you can find specifications for cross counts.

Things are different with second-generation on-board diagnostics (OBD II) vehicles. Not only is there a HEGO both upstream and downstream of the catalyst, but two types of tests are run on them. One monitors the sensor's activity, and the other checks the sensor's electrical heating element.

An oxygen sensor can fail the activity monitor for a slow response rate, which is sometimes called a "big slope" for the way the wave looks on an oscilloscope. Or, it can fail for having too small a change in voltage output from rich to lean and vice versa.

Testing Wideband Sensors

Symptoms of a damaged wideband sensor are the same as those for any other oxygen sensor:

- Malfunction indicator/Check Engine lamp on or code set.
- A failed emissions test, usually with a high CO and/or HC reading.
- A damaged catalytic converter caused by prolonged exposure to an overly rich fuel mixture.
- A drop in fuel mileage attributed to a rich fuel mixture.
- Engine performance complaints such as "runs rough" or "sluggish."

Unlike earlier sensors, you cannot use an oscilloscope or DMM to diagnose an AFR sensor. A wideband sensor's output signal varies in both amplitude and direction. The only way to monitor its operation is with a scan tool attached to the onboard diagnostic link.

Thus connected, you can read the actual air/fuel ratio and check the sensor's response to changes in the ratio. For example, going to wide-open throttle typically causes a brief very lean condition, followed by a rich condition. With the wideband sensor's rapid response capability, the scan tool should show a steady air/fuel ratio if the sensor is operating properly.

You must consult the specific diagnostic steps for the model you are working on, but as a general rule your scan tool should show an oxygen sensor code if the signal is out of its normal range, if the readings do not make sense to the ECM, or if the heater circuit fails.

Even AFR sensors can be fooled if there is an air leak between the exhaust manifold and head, or by a misfire that pumps an unburned air/fuel charge into the exhaust. These situations cause a false signal that makes the ECM mistakenly adjust the mixture.

Extras

We will conclude with some miscellaneous points:

- Second-generation on-board diagnostic systems (commonly referred to as OBD II), which have been adopted in many places around the world, use an extra oxygen sensor downstream of the catalytic converter to test the catalyst's capacity and efficiency.
- An oxygen sensor is an averaging device that responds to the leanest cylinder -- it cannot differentiate among them. If one injector is inoperative or clogged, that cylinder will pump enough oxygen into the exhaust to fool the ECM into "thinking" there is an overall lean condition. So, it will richen the mixture unnecessarily.
- Sensor contamination is not always permanent. Try running the engine at 3,000 rpm for a few minutes, or take a drive, then retest. You may have burned off whatever was interfering with voltage generation. On the other hand, if silica or metal deposits get hot enough, they will melt into a coating that can never be removed.
- Whenever you replace an oxygen sensor, please make sure the threads are coated with the proper anti seize compound. Otherwise, the next person who tries to remove it may have great difficulty.
- If you are afraid you will spread your split oxygen sensor socket because the old sensor is in there so tightly you will have to apply extraordinary torque, there is a simple alternative. As long as you are replacing the sensor, just snip off the wires and use a regular deep socket.

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