Drawing a Line in the Mixture —

Honda Linear O_2 Sensors

Honda's Linear Air/Fuel Sensor lets the engine sometimes run on extremely lean air-fuel mixtures for fuel economy. But how does it work, and how did they avoid the emissions problem of NO_x?

Above: The first sensors had one wire, the output signal. Later versions had heater circuits and dedicated grounds to allow the system to bias the signal output voltage. A linear air/fuel sensor has to have a minimum of five wires to do its work.

In an odd way, they're the oldest of the 'new' oxygen sensors. Honda used a special "linear air/fuel sensor" from 1992 to 1995 on certain Civics and on some other cars and model years. A major reason Honda installed this sensor was to allow those vehicles to run at air/fuel ratios much leaner than the emissions-stoichiometric 14.7:1. While *stoichiometric* means *in the ideal ratio*, the real question is: Ideal for what? As *Import Service* readers already know, that famous ratio selects not the best mixture for power nor the best mixture for range or fuel economy or engine life, but the best mixture for the catalytic converter, the mixture that makes its exhaust cleanup job easier. In private moments, this has to strike a combustion engineer as madness, as if the law construed a car as primarily a machine to mass-produce clean exhaust, with powerful or efficient or merely functional transportation as an intermittent, almost incidental byproduct of the exhaust production.

Tuning for maximum power is not the problem you might think: The emissions laws don't apply to a vehicle at WOT, so you can profit from a hundred years of racing experience. Just richen the mixture to about 12:1 and bounce the ignition timing off the knock sensor. Then shape the runners and exhaust pipes for good breathing, use springs and rods that can take big revs, hollow out the block for cubes, and you've done most of the work. However, people in the real (i.e., non-racetrack) world rarely hold a car at WOT for even a full minute. Tuning for fuel economy is considerably harder, in part because the car has to sustain lean mixture settings for hours to show any benefit: Fuel economy is about distance, and distance is speed times *time*. Whatever you do for fuel economy or range, you have to do over the long term and under a wide variety of driving conditions.

Going Lean and NO_x

By expanding the effective range of their oxygen sensor, Honda could accurately measure air/fuel ratios as high as 23:1, and once you can measure that, you can control for it, maximizing fuel economy. But the emissions problem with a fuel-efficient, lean mixture, of course, is NO_x, the name given to the several chemical combinations of nitrogen and oxygen that sometimes form at high temperatures, over 2500 degrees F., such as can occur in combustion chambers with lean mixtures and sustained loads. A rich mixture leaves high levels of carbon monoxide or, at the extreme, of unburned fuel (hydrocarbons) in the exhaust; and it cokes up the engine with deposits. But a lean mixture looks like it slams against the brick wall of legally unacceptable quantities of NO_x.

Fortunately, combustion temperatures don't rise indefinitely as the mixture gets leaner; eventually there's just no more fuel to make more heat. In the same way adding exhaust to the intake mixture through the EGR system effectively cools the burn by inclusion of an inert gas, adding extra air in the form of an extremely lean mixture can also cool the combustion burn, provided there isn't enough residual fuel in the cylinder to combine with all that extra oxygen. The air's not inert, of course, but there can't be any residual oxygen reaction with the fuel if all the fuel has already combined with some of the intaken oxygen, if there *isn't* any residual fuel.

Why *Lean* Means *Long*

There's a mechanical reason why a lean-burning engine runs more fuel-efficiently, too, a reason conflicting with some of our expectations in an interesting way. You can lean a mixture by either reducing the fuel or by increasing the air proportionately. Of course, in practice both happen. The linear air-fuel sensor, obviously, enables the computer to reduce the injection pulsewidth. During extended cruise, however, either the driver by foot or the cruise control system must open the throttle more during superlean mixture conditions than would otherwise be the case. We ordinarily think that opening the throttle (or equivalently, increasing the intake manifold pressure) increases the amount of fuel burned. But in superlean cruise we already have the fuel delivery reduced; so opening the throttle has as one of its effects the reduction of pumping losses through the engine. Ordinarily, that is at all partial-throttle settings, the engine must expend energy pulling each piston down against manifold vacuum during the intake stroke. If the superlean cruise works by opening the throttle more, that reduces the intake manifold vacuum (or increases the MAP — same phenomenon, different description) and the consequent wasted energy overcoming the vacuum.

This advantage, you probably recall, is shared by Diesel engines, already running at superlean conditions most of the time. That wider throttle at superlean cruise, however, also means a higher load, the second condition predisposing the combustion chamber toward producing NO_x. So mixture control becomes even more important.

A lean mixture has a second economy trick: It burns more slowly. That allows more of the power stroke pressure developed to apply to the top of the piston when the piston has moved farther down the cylinder, where the angles between connecting rod and crankshaft throw afford a better mechanical advantage.

Knocking Down NO_x

So back to the NO_x puzzle. It turns out that combustion temperatures start to drop back down once the mixture goes well above the emissions-stoichiometric ratio, after the air-to-fuel ratio passes 16 or 18 to one. So why doesn't everybody go lean, get great fuel economy and forget about EGR? Because of the problem of igniting such a lean mixture dependably.

The hard combustion problem with lean mixtures is not, as we have seen, that they necessarily produce NO_x because of the high combustion temperature, but that it is much harder to light them afire every time for every power stroke. Only slightly leaner than the 23:1 upper reaches the linear air-fuel sensor controls, and you don't have enough fuel to burn at all; or in plain words, you don't have a combustible mixture, and you get lean misfire. And misfire, besides losing all the benefits of fuel economy by wasting the missed cylinder's charge of fuel, puffs that same raw fuel out the exhaust as unburned hydrocarbons, undoubted toxic emissions in anybody's book.

So, besides some sort of lean-ratio sensor and the right sort of computer controls to drive the mixture lean but not so lean as to miss, any vehicle designed to run on these lean mixtures also needs an ignition system with a sufficiently long burn-time to dependably light the combustion fire for every power stroke. There is no particular need for higher maximum secondary voltage (an *overrich* mixture requires that, since fuel has insulating properties that increase the ionization-resistance between the spark plug's electrodes, and more fuel insulates more), but there is need for higher reserve energy in the coil's electromagnetic field. The spark has to hang in there long enough to find some fuel and oxygen molecules to torch. We need, in other words, a longer spark burn-time. But that's another subject for another article.... Here and now, we're after Honda's lean mixture sensor, how it works and how it fails.

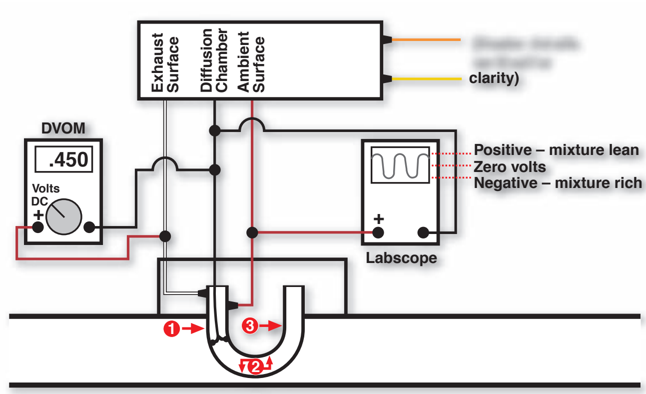
The Magic Thimble

You'll recall how a traditional oxygen sensor works: There's a difference in the concentration of oxygen on either side of the sensor's zirconium thimble because the engine has burned a good deal of the oxygen that came through the intake manifold with the fuel. Combustion engineers call this difference of oxygen concentration on either side of the sensor thimble the "oxygen pressure." It's not real pressure, of course. Exhaust backpressure is always higher than the ambient air's, but oxygen always 'wants' to move from an area of high concentration to one of low concentration, even 'uphill,' against greater psi., a molecular disposition very like pressure.

Zirconium doped with just the right proportions of just the right rare-earth minerals has the odd property (once above a threshold temperature of 600 degrees F.) of becoming relatively porous to oxygen while still blocking transit by everything else. Most oxygen sensors include an electric heater, otherwise unconnected to the sensor's information business, to get them to operating condition quickly. I'll say no more about the sensor heater since you already know how it works.

The difference in oxygen concentration between the ambient air and the exhaust (the "oxygen pressure") drives oxygen from the outside (reference) air, where oxygen is plentiful, through the ceramic and into the exhaust, where oxygen is rare. As the oxygen transits the zirconium from the oxygen-rich side to the oxygen-lean side, the superthin platinum catalyst on the ambient surface splits each O_2 molecule into individual, elemental oxygen atoms — O_1, you might say, though the subscript-1 is understood and thus conventionally omitted. But let's keep it here. Better clear than rhetorically fashionable.

Because the two elemental oxygen atoms (O_1) shared two of their electrons when they were joined as electrically-neutral, atmospheric molecular O_2, once the catalyst splits them, each is then down one electron and thus carries a net positive charge. As each elemental oxygen O_1 atom begins to travel through the ceramic, it grabs an extra electron from the conductive catalyst surface to neutralize its net positive charge, drawing these electrons down the sensor's signal output wire, making that wire positive. When the elemental oxygen atoms (O_1) emerge on the exhaust side, the platinum catalyst there recombines them into molecular O_2, and they dump their just-filched electrons on that catalytic surface (grounded to the exhaust system) and continue their way down and out the exhaust pipe. That movement of electrons through the ceramic, forced by the "oxygen pressure," the difference in oxygen saturation on either side, *is* electrical flow; and the volume and 'force' (the relative number of electrons/electron holes on either side of the thimble) of the travel *is* the voltage signal.



1 Exhaust Surface 2 Diffusion Chamber Surface 3 Ambient Surface

Tandem Thimbles

The Honda Linear Air-Fuel (LAF) sensor works by the same zirconium-oxygen-transport and platinum-catalytic principles, but in a still more complicated way. It is, in a sense, an oxygen sensor within an oxygen sensor, a double-thimble with a sealed, inbetween "diffusion chamber" where the computer can electrically vary the amount of oxygen present. But this is where things get a bit tricky! The surface that surrounds the closed diffusion chamber also has surrounding, conductive catalytic surface (electrically insulated from everything else except a single wire from the computer). None of the three conductive catalytic surfaces — exhaust, diffusion chamber or ambient reference — grounds to the exhaust system or to battery negative or to battery positive; they all connect by individual wires to the computer alone.

The arrangement makes use of the electrical reversibility of the traditional oxygen sensor. Just as a difference of oxygen saturation ("pressure") between two gases separated by the sensor's zirconium thimble can generate a voltage between the two platinum-catalyst surfaces of the ceramic, a sufficient positive voltage at one or the other surface can drive oxygen atoms from that surface (ionizing them into O_1 by the same catalytic mechanism), through the zirconium ceramic and into the other chamber. It's almost as though you could create gasoline by forcibly turning the wheels of a car against the engine's deceleration, and it's exactly the way you could recharge an electric car's batteries by hand-pushing the car down the road against the load of the regenerative braking system (in a fanciful future world where there *are* such electric cars!). To be sure, this is not an energy-efficient way to charge batteries or to bottle oxygen — nobody's going to fill welding tanks using reversed-polarity O_2 sensors – but it works well enough to generate a reliable signal for the linear air-fuel sensor.

With the diffusion chamber between the exhaust and ambient atmospheric ("reference") sides of the sensor, the computer applies or removes voltage at the interconnected diffusion chamber surfaces so as to keep the exhaust-side voltage exactly 0.45 volts *above* the diffusion chamber surfaces; or to put the same thing another way, the computer keeps the diffusion chamber surfaces 0.45 volt *below* whatever voltage the exhaust side has. Yes, this means the computer is electronically forcing the sensor to draw sparse oxygen molecules from the exhaust side, push them through the diffusion chamber and out into the ambient air, against the "oxygen pressure." Yes, this means the computer will sometimes drive the diffusion chamber surface voltage *below* zero, into negative (effectively reversed-polarity) voltage. Then *finally* the computer monitors the voltage changes between the ambient reference surface and the diffusion chamber surface as the true mixture feedback signal.

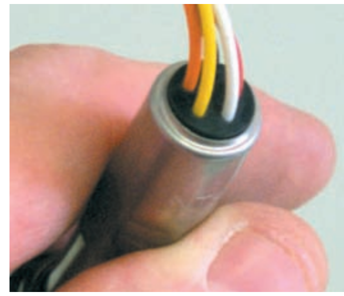
Signals in the Mirror

Because the system forces oxygen 'backwards' through the sensor, the polarity of the feedback signal is reversed. That is, *low* means *rich*; *high* means *lean*. What's more, since the system artificially fixes the exhaust voltage as a kind of electrical fulcrum by controlling the diffusion chamber voltage, the ambient reference voltage fluctuates about twice as much as its natural 'druthers. Image you moved the pivot of a seesaw to one end and then raised and lowered the middle, where the pivot used to be. Travel at the opposite end would be doubled in range. And since the control voltage to the diffusion chamber surfaces sometimes goes 'below-zero' negative, the feedback signal at the ambient surface also goes below-zero negative, even more so. In fact, the middle of the feedback oscillation trace is usually at about zero volts compared to the control voltage.

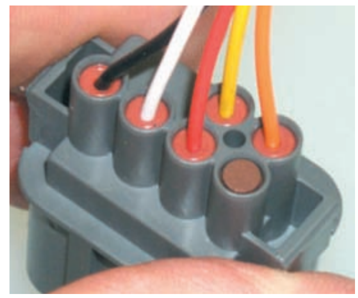
This arrangement has some unexpected consequences. If you monitor what we ordinarily look at for an O_2 sensor signal, the voltage between the ambient reference side and battery negative, you may find no readable signal at all. Ditto for the exhaust side. If you look at the diffusion chamber voltage against battery negative, you'll find an uninformative voltage flutter. If you test between the exhaust side and the diffusion chamber, you'll find a constant 0.45 volts — not very informative, either. This is what some people have seen on a scope, mistakenly concluding the sensor generated a mysterious flat voltage signal.

You have to 'see' the sensor with your voltmeter the same way the computer does, measuring the exhaust and ambient sides' voltage against the diffusion chamber's. From the exhaust side to the diffusion chamber you should find the 0.45 volts measurement above if the computer is working properly. The voltage from the atmospheric reference side to the diffusion chamber is the actual feedback signal the computer follows and trims the fuel mixture to.

Linear Sensor Connector: *The linear sensor has an eight-terminal connector, but only seven of them are occupied. Of those seven, only five are doing any work.*



Wires At Sensor



Backprobing the Connector *The linear sensor's five wires include orange and yellow wires for the heater circuit, a black wire for the diffusion chamber ground/ control, a red wire for ambient chamber and a white wire for the exhaust. Look for voltage differences as detailed in the text.*

That voltage signal will describe a scope trace ranging over 1.5 volts, about twice the usual range, but the centerpoint of the trace will be at zero volts, and in contrast to ordinary O_2 sensor signals, the lower, or more negative, the output, the richer the mixture, while the higher the signal voltage, the leaner the mixture. The signal is, in other words, of greater amplitude, and its polarity is reversed in comparison to an ordinary sensor's. Your opportunities for system misconstrual are splendid, indeed!

Guesses and Hopes

Now this next part is my conjecture, not part of the information I got from Honda. If it's preposterous rubbish, it's *my* preposterous rubbish, not theirs. It looks to me as if we have three natural variables: the voltages at the exhaust side, at the diffusion chamber and at the ambient side. By effectively fixing the exhaust side voltage at 0.45 volts above the controlled diffusion chamber surface's, the system eliminates one variable, so that disappears. The diffusion chamber's voltage becomes a command signal, not an information signal. Now the effect on the voltage monitored for the actual feedback is to multiply its variation twofold and to flip it upsidedown. The polarity reversal is weird, but not incomprehensible; you can program a computer to use it. And a doubling of the range of the signal would be just the kind of thing you'd look for to monitor and thus control a wider mixture range, particularly a leaner mixture. This is just the kind of information the computer needs to keep the mixture so lean as to deftly slip the mixture between NO_X and misfire, thus achieving high fuel economy.

Why not just bolt a linear air-fuel sensor into any car and get the fuel-economy advantages? Because the results don't come from the sensor but from the system. In the absence of the diffusion chamber control voltage, in the absence of a system that could make sense of a wider signal voltage range, in the absence of a way to deal with the reversed polarity, it couldn't work. It's a machine, not a magic talisman.

Testing the LAF Sensor

So how can you test the new sensors directly? After all, they're expensive to SWAG-test (about $150 retail). Yes, you can measure the sensor voltages against one another. You'll find five wires to the linear air-fuel sensor. The connector has eight sockets, seven of them occupied. Only five of them do anything. Two of them, the orange and yellow, go to the heater, so they're of no interest to us now unless one of them has managed to short against the information circuits. The black wire is the diffusion chamber ground/ control line; use it as your negative connection. The remaining wires go to the ambient (red) and to the exhaust (white) sides. Unfortunately, Honda wiring diagrams show a variety of other colors, including orange/blue (ambient) and white/blue (exhaust). Evidently, the color-coding varies by model and build-year. In any case, if all goes well with the sensor, you should find a steady 0.45 volt between one of the wires and the black wire and an oscillating trace above and below zero volts on the other.

Trouble codes can also flag a bad sensor. Early, pre-OBD-II systems set a single code 48 for anything amiss in the LAF circuit. With OBD-II, sensor circuit codes include P1162, P1163, P1168 and P1169, flagging shorts or opens to the several subcircuits. Remember, of course, a code fingers a circuit, not a part. You still have to test further to arrive at a diagnosis.

This has not been an easy-read, I know (nor a downhill stretch of technoscribbling, either, you should know!). So, let me both commend everyone who has slogged his or her way through it, and thank you for the effort. There are few kinds of work that require the sort of concentrated focus on learning and mastering advanced parts of every applied science than the work you and I have chosen. It is a great pleasure to know I have readers who don't wilt when the information gets a bit hairy. My regards, gentlefolk of the wrench! See you next month. ■

— By Joe Woods