Oxygen sensor

An oxygen sensor, or lambda sensor, is an electronic device that measures the proportion of oxygen ($O_2$) in the gas or liquid being analyzed. It was developed by Robert Bosch GmbH during the late 1960s under supervision by Dr. Günter Bauman. The original sensing element is made with a thimble-shaped zirconia ceramic coated on both the exhaust and reference sides with a thin layer of platinum and comes in both heated and unheated forms. The planar-style sensor entered the market in 1998 (also pioneered by Robert Bosch GmbH) and significantly reduced the mass of the ceramic sensing element as well as incorporating the heater within the ceramic structure. This resulted in a sensor that both started operating sooner and responded faster. The most common application is to measure the exhaust gas concentration of oxygen for internal combustion engines in automobiles and other vehicles. Divers also use a similar device to measure the partial pressure of oxygen in their breathing gas.

Scientists use oxygen sensors to measure respiration or production of oxygen and use a different approach. Oxygen sensors are used in oxygen analyzers which find a lot of use in medical applications such as anesthesia monitors, respirators and oxygen concentrators.

There are many different ways of measuring oxygen and these include technologies such as zirconia, electrochemical (also known as Galvanic), infrared, ultrasonic and very recently laser. Each method has its own advantages and disadvantages.

Automotive applications

Automotive oxygen sensors, colloquially known as $O_2$ sensors, make modern electronic fuel injection and emission control possible. They help determine, in real time, if the air fuel ratio of a combustion engine is rich or lean. Since oxygen sensors are located in the exhaust stream, they do not directly measure the air or the fuel entering the engine. But when information from oxygen sensors is coupled with information from other sources, it can be used to indirectly determine the air-to-fuel ratio. Closed-loop feedback-controlled fuel injection varies the fuel injector output according to real-time sensor data rather than operating with a predetermined (open-loop) fuel map. In addition to enabling electronic fuel injection to work efficiently, this emissions control technique can reduce the amounts of both unburnt fuel and oxides of nitrogen from entering the atmosphere. Unburnt fuel is pollution in the form of air-borne hydrocarbons, while oxides of nitrogen (NOx gases) are a result of combustion chamber temperatures exceeding 1,300 kelvins due to excess air in the fuel mixture and contribute to smog and acid rain. Volvo was the first automobile manufacturer to employ this technology in the late 1970s, along with the 3-way catalyst used in the catalytic converter.

The sensor does not actually measure oxygen concentration, but rather the amount of oxygen needed to completely oxidize any remaining combustibles in the exhaust gas. Rich mixture causes an oxygen demand. This demand causes a voltage to build up, due to transportation of oxygen ions through the sensor layer. Lean mixture causes low voltage, since there is an oxygen excess.

Modern spark-ignited combustion engines use oxygen sensors and catalytic converters in order to reduce exhaust emissions. Information on oxygen concentration is sent to the engine management computer or ECU, which adjusts the amount of fuel injected into the engine to compensate for excess air or excess fuel. The ECU attempts to maintain, on average, a certain air-fuel ratio by interpreting the information it gains from the oxygen sensor. The primary goal is a compromise between power, fuel economy, and emissions, and in most cases is achieved by an...
air-fuel-ratio close to stoichiometric. For spark-ignition engines (such as those that burn gasoline, as opposed to diesel), the three types of emissions modern systems are concerned with are: hydrocarbons (which are released when the fuel is not burnt completely, such as when misfiring or running rich), carbon monoxide (which is the result of running slightly rich) and NO\(_x\) (which dominate when the mixture is lean). Failure of these sensors, either through normal aging, the use of leaded fuels, or fuel contaminated with silicones or silicates, for example, can lead to damage of an automobile's catalytic converter and expensive repairs.

Tampering with or modifying the signal that the oxygen sensor sends to the engine computer can be detrimental to emissions control and can even damage the vehicle. When the engine is under low-load conditions (such as when accelerating very gently, or maintaining a constant speed), it is operating in "closed-loop mode." This refers to a feedback loop between the ECU and the oxygen sensor(s) in which the ECU adjusts the quantity of fuel and expects to see a resulting change in the response of the oxygen sensor. This loop forces the engine to operate both slightly lean and slightly rich on successive loops, as it attempts to maintain a mostly stoichiometric ratio on average. If modifications cause the engine to run moderately lean, there will be a slight increase in fuel economy, sometimes at the expense of increased NO\(_x\) emissions, much higher exhaust gas temperatures, and sometimes a slight increase in power that can quickly turn into misfires and a drastic loss of power, as well as potential engine damage, at ultra-lean air-to-fuel ratios. If modifications cause the engine to run rich, then there will be a slight increase in power to a point (after which the engine starts flooding from too much unburned fuel), but at the cost of decreased fuel economy, and an increase in unburned hydrocarbons in the exhaust which causes overheating of the catalytic converter. Prolonged operation at rich mixtures can cause catastrophic failure of the catalytic converter (see backfire). The ECU also controls the spark engine timing along with the fuel injector pulse width, so modifications which alter the engine to operate either too lean or too rich may result in inefficient fuel consumption whenever fuel is ignited too soon or too late in the combustion cycle.

When an internal combustion engine is under high load (e.g. wide open throttle), the output of the oxygen sensor is ignored, and the ECU automatically enriches the mixture to protect the engine, as misfires under load are much more likely to cause damage. This is referred to an engine running in 'open-loop mode'. Any changes in the sensor output will be ignored in this state. In many cars (excepting some turbocharged ones), inputs from the air flow meter are also ignored, as they might otherwise lower engine performance due to the mixture being too rich or too lean, and increase the risk of engine damage due to detonation if the mixture is too lean.

**Function of a lambda probe**

Lambda probes are used to reduce vehicle emissions by ensuring that engines burn their fuel efficiently and cleanly. Robert Bosch GmbH introduced the first automotive lambda probe in 1976\(^{[1]}\), and it was first used by Volvo and Saab in that year. The sensors were introduced in the US from about 1980, and were required on all models of cars in many countries in Europe in 1993.

By measuring the proportion of oxygen in the remaining exhaust gas, and by knowing the volume and temperature of the air entering the cylinders amongst other things, an ECU can use look-up tables to determine the amount of fuel required to burn at the stoichiometric ratio (14.7:1 air:fuel by mass for gasoline) to ensure complete combustion.
The probe

The sensor element is a ceramic cylinder plated inside and out with porous platinum electrodes; the whole assembly is protected by a metal gauze. It operates by measuring the difference in oxygen between the exhaust gas and the external air, and generates a voltage or changes its resistance depending on the difference between the two.

The sensors only work effectively when heated to approximately 316 °C (600 °F), so most newer lambda probes have heating elements encased in the ceramic that bring the ceramic tip up to temperature quickly. Older probes, without heating elements, would eventually be heated by the exhaust, but there is a time lag between when the engine is started and when the components in the exhaust system come to a thermal equilibrium. This lag is due to the engine, oil, coolant, and other components' absorption of heat from the exhaust gases. The exhaust gases heat these other components, causing the gases to drop below the probe's operating temperature and therefore heat the probe slowly. The length of time required for the exhaust gases to bring the probe to temperature depend on the temperature of the ambient air and the geometry of the exhaust system. Without a heater, the process may take several minutes. There are pollution problems that are attributed to this slow start-up process, including a similar problem with the working temperature of a catalytic converter.

The probe typically has four wires attached to it: two for the lambda output, and two for the heater power, although some automakers use a common ground for the sensor element and heaters, resulting in three wires. Earlier non-electrically-heated sensors had one or two wires.

Operation of the probe

Zirconia sensor

The zirconium dioxide, or zirconia, lambda sensor is based on a solid-state electrochemical fuel cell called the Nernst cell. Its two electrodes provide an output voltage corresponding to the quantity of oxygen in the exhaust relative to that in the atmosphere. An output voltage of 0.2 V (200 mV) DC represents a "lean mixture" of fuel and oxygen, where the amount of oxygen entering the cylinder is sufficient to fully oxidize the carbon monoxide (CO), produced in burning the air and fuel, into carbon dioxide (CO₂). An output voltage of 0.8 V (800 mV) DC represents a "rich mixture", one which is high in unburned fuel and low in remaining oxygen. The ideal setpoint is approximately 0.45 V (450 mV) DC. This is where the quantities of air and fuel are in the optimum ratio, which is ~0.5% lean of the stoichiometric point, such that the exhaust output contains minimal carbon monoxide.

The voltage produced by the sensor is nonlinear with respect to oxygen concentration. The sensor is most sensitive near the stoichiometric point and less sensitive when either very lean or very rich.

The engine control unit (ECU) is a control system that uses feedback from the sensor to adjust the fuel/air mixture. As in all control systems, the time constant of the sensor is important; the ability of the ECU to control the fuel-air-ratio depends upon the response time of the sensor. An aging or fouled sensor tends to have a slower response time, which can degrade system performance. The shorter the time period, the higher the so-called "cross count"[2] and the more responsive the system.

The zirconia sensor is of the "narrow band" type, referring to the narrow range of fuel/air ratios to which it responds.

Wideband zirconia sensor

A variation on the zirconia sensor, called the "wideband" sensor, was introduced by Robert Bosch in 1994 but is (as of 2006) used in only a few vehicles. It is based on a planar zirconia element, but also incorporates an electrochemical gas pump. An electronic circuit containing a feedback loop controls the gas pump current to keep the output of the electrochemical cell constant, so that the pump current directly indicates the oxygen content of the exhaust gas. This sensor eliminates the lean-rich cycling inherent in narrow-band sensors, allowing the control unit to adjust the fuel delivery and ignition timing of the engine much more rapidly. In the automotive industry this sensor is also called a UEGO (for Universal Exhaust Gas Oxygen) sensor. UEGO sensors are also commonly used in
aftermarket dyno tuning and high-performance driver air-fuel display equipment. The wideband zirconia sensor is used in stratified fuel injection systems, and can now also be used in diesel engines to satisfy the forthcoming EURO and ULEV emission limits.

**Wideband sensors have three elements:**

- Ion Oxygen pump
- Narrowband zirconia sensor
- Heating element

The wiring diagram for the wideband sensor typically has 6 wires:

- resistive heating element (2 wires)
- sensor
- pump
- calibration resistor
- common

**Titania sensor**

A less common type of narrow-band lambda sensor has a ceramic element made of titanium dioxide (titania). This type does not generate its own voltage, but changes its electrical resistance in response to the oxygen concentration. The resistance of the titania is a function of the oxygen partial pressure and the temperature. Therefore, some sensors are used with a gas temperature sensor to compensate for the resistance change due to temperature. The resistance value at any temperature is about 1/1000th the change in oxygen concentration. Luckily, at lambda = 1, there is a large change of oxygen, so the resistance change is typically 1000 times between rich and lean, depending on the temperature.

As titania is an N-type semiconductor with a structure $\text{TiO}_2$, the $x$ defects in the crystal lattice conduct the charge. So, for fuel-rich exhaust the resistance is low, and for fuel-lean exhaust the resistance is high. The control unit feeds the sensor with a small electrical current and measures the resulting voltage across the sensor, which varies from near 0 volts to about 5 volts. Like the zirconia sensor, this type is nonlinear, such that it is sometimes simplistically described as a binary indicator, reading either "rich" or "lean". Titania sensors are more expensive than zirconia sensors, but they also respond faster.

In automotive applications the titania sensor, unlike the zirconia sensor, does not require a reference sample of atmospheric air to operate properly. This makes the sensor assembly easier to design against water contamination. While most automotive sensors are submersible, zirconia-based sensors require a very small supply of reference air from the atmosphere. In theory, the sensor wire harness and connector are sealed. Air that leaches through the wire harness to the sensor is assumed to come from an open point in the harness - usually the ECU which is housed in an enclosed space like the trunk or vehicle interior.

**Location of the probe in a system**

The probe is typically screwed into a threaded hole in the exhaust system, located after the branch manifold of the exhaust system combines, and before the catalytic converter. New vehicles are required to have a sensor before and after the exhaust catalyst to meet U.S. regulations requiring that all emissions components be monitored for failure. Pre and post-catalyst signals are monitored to determine catalyst efficiency. Additionally, some catalyst systems require brief cycles of lean (oxygen-containing) gas to load the catalyst and promote additional oxidation reduction of undesirable exhaust components.
**Sensor surveillance**

The air-fuel ratio and naturally, the status of the sensor, can be monitored by means of using an air-fuel ratio meter that displays the read output voltage of the sensor.

**Sensor failures**

Normally, the lifetime of an unheated sensor is about 30,000 to 50,000 miles (50,000 to 80,000 km). Heated sensor lifetime is typically 100,000 miles (160,000 km). Failure of an unheated sensor is usually caused by the buildup of soot on the ceramic element, which lengthens its response time and may cause total loss of ability to sense oxygen. For heated sensors, normal deposits are burned off during operation and failure occurs due to catalyst depletion, similar to the reason a battery stops producing current. The probe then tends to report lean mixture, the ECU enriches the mixture, the exhaust gets rich with carbon monoxide and hydrocarbons, and the mileage worsens.

Leaded gasoline contaminates the oxygen sensors and catalytic converters. Most oxygen sensors are rated for some service life in the presence of leaded gasoline but sensor life will be shortened to as little as 15,000 miles depending on the lead concentration. Lead-damaged sensors typically have their tips discolored light rusty.

Another common cause of premature failure of lambda probes is contamination of fuel with silicones (used in some sealings and greases) or silicates (used as corrosion inhibitors in some antifreezes). In this case, the deposits on the sensor are colored between shiny white and grainy light gray.

Leaks of oil into the engine may cover the probe tip with an oily black deposit, with associated loss of response.

An overly rich mixture causes buildup of black powdery deposit on the probe. This may be caused by failure of the probe itself, or by a problem elsewhere in the fuel rationing system.

Applying an external voltage to the zirconia sensors, e.g. by checking them with some types of ohmmeter, may damage them.

Symptoms of a failing oxygen sensor includes:

- Sensor Light on dash indicates problem
- Increased tailpipe emissions
- Increased fuel consumption
- Hesitation on acceleration
- Stalling
- Rough idling
**Diving applications**

The diving type of oxygen sensor, which is sometimes called an oxygen analyser or ppmO$_2$ meter, is used in scuba diving. They are used to measure the oxygen concentration of breathing gas mixes such as nitrox and trimix.[3] They are also used within the oxygen control mechanisms of closed-circuit rebreathers to keep the partial pressure of oxygen within safe limits.[4] This type of sensor operates by measuring the electricity generated by a small electro-galvanic fuel cell.

**Scientific applications**

In marine biology or limnology oxygen measurements are usually done in order to measure respiration of a community or an organism, but have also been used to measure primary production of algae. The traditional way of measuring oxygen concentration in a water sample has been to use wet chemistry techniques e.g. the Winkler titration method. There are however commercially available oxygen sensors that measure the oxygen concentration in liquids with great accuracy. There are two types of oxygen sensors available: electrodes (electrochemical sensors) and optodes (optical sensors).

**Electrodes**

The Clark-type electrode is the most used oxygen sensor for measuring oxygen dissolved in a liquid. The basic principle is that there is a cathode and an anode submersed in an electrolyte. Oxygen enters the sensor through a permeable membrane by diffusion, and is reduced at the cathode, creating a measurable electrical current.

There is a linear relationship between the oxygen concentration and the electrical current. With a two-point calibration (0% and 100% air saturation), it is possible to measure oxygen in the sample.

One drawback to this approach is that oxygen is consumed during the measurement with a rate equal to the diffusion in the sensor. This means that the sensor must be stirred in order to get the correct measurement and avoid stagnant water. With an increasing sensor size, the oxygen consumption increases and so does the stirring sensitivity. In large sensors there tend to also be a drift in the signal over time due to consumption of the electrolyte. However, Clark-type sensors can be made very small with a tip size of 10 µm. The oxygen consumption of such a microsensor is so small that it is practically insensitive to stirring and can be used in stagnant media such as sediments or inside plant tissue.
**Optodes**

An oxygen optode is a sensor based on optical measurement of the oxygen concentration. A chemical film is glued to the tip of an optical cable and the fluorescence properties of this film depend on the oxygen concentration. Fluorescence is at a maximum when there is no oxygen present. When an O$_2$ molecule comes along it collides with the film and this quenches the photoluminescence. In a given oxygen concentration there will be a specific number of O$_2$ molecules colliding with the film at any given time, and the fluorescence properties will be stable.

The signal (fluorescence) to oxygen ratio is not linear, and an optode is most sensitive at low oxygen concentration. That is, the sensitivity decreases as oxygen concentration increases following the Stern-Volmer relationship. The optode sensors can, however, work in the whole region 0% to 100% oxygen saturation in water, and the calibration is done the same way as with the Clark type sensor. No oxygen is consumed and hence the sensor is insensitive to stirring, but the signal will stabilize more quickly if the sensor is stirred after being put in the sample. These type of electrode sensors can be used for in situ and real time monitoring of Oxygen production in water splitting reactions. The platinized electrodes can accomplish the real time monitoring of Hydrogen production in water splitting device. Calzaferri and his co workers employed this type of electrodes very extensively for photoelectrochemical water splitting research.

**See also**

- Pulse oximeter
- Oxygen saturation
- Pulse oximetry
- Carbon dioxide sensor
- List of sensors

**References**

[1] "30 years of the Bosch lambda sensor" (http://www.bosch-presse.de/TBWebDB/en-US/PressText.cfm?CFID=92815&CFTOKEN=62b94d8b3df48a54-0C1C366-EB6C-77EF-63359AA00DDD04A0&ID=2599).


Oxygen Sensor FAQ (http://www.walkerproducts.com/faqs_o2.html)
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