DRIVING OXYGEN SENSOR TECHNOLOGY

An Industry White Paper

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I. THE OXYGEN SENSOR: HOW AND WHY

When the U.S. Environmental Protection Agency (EPA) launched very stringent exhaust gas regulations in the early 1970s, the catalytic converter emerged to clean up the exhaust. With it came the pressing need to use closed loop air/fuel mixture controls to keep the converter operating properly – and this required a sensor to read the exhaust gases. Robert Bosch GmbH, one of the premier automotive engineering organizations in the world, enjoyed extensive experience working with promising sensor technology, and set out to create an automotive oxygen sensor.

But first, we go back to the 19th Century.

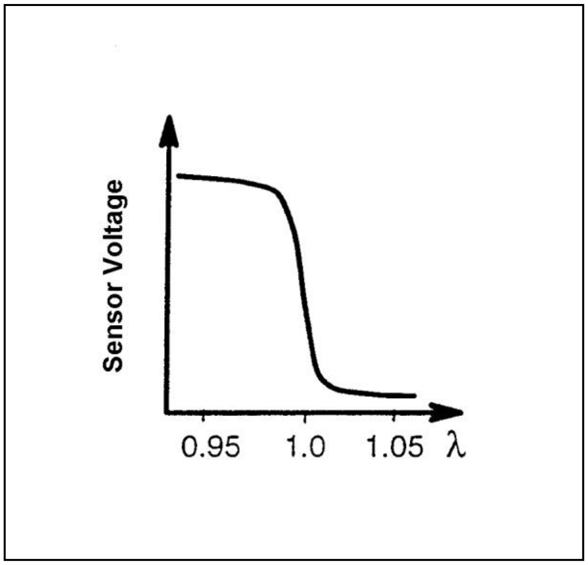
In 1899, Professor Walter Nernst, working in Leipzig, Germany, developed the theory of a "concentration cell" which, much like a battery, uses a gas-tight ceramic electrolyte which becomes electrically conductive above 625-650° F. This "Nernst cell" transfers oxygen ions from “reference air” inside the cell to the outside environment -- or from the outside environment to the reference air in the cell -- and this flow of ions generates measurable voltage reflecting the difference in the oxygen content between the gas outside the sensor and the reference air inside the sensor.

Three quarters of a century later, the internal combustion engine and the automobile had become the primary means of transportation for much of the industrialized world. Automotive design, engineering and manufacturing technology had progressed and matured tremendously, and tens of millions of automobiles and trucks traveled the highways of the world -- and sent millions of pounds of unchecked, harmful emissions into the atmosphere. The world was beginning to realize that something must be done to rein in pollution -- and the automobile internal combustion engine became a prime target for pollution-fighting regulation.

The Basic Oxygen Sensor

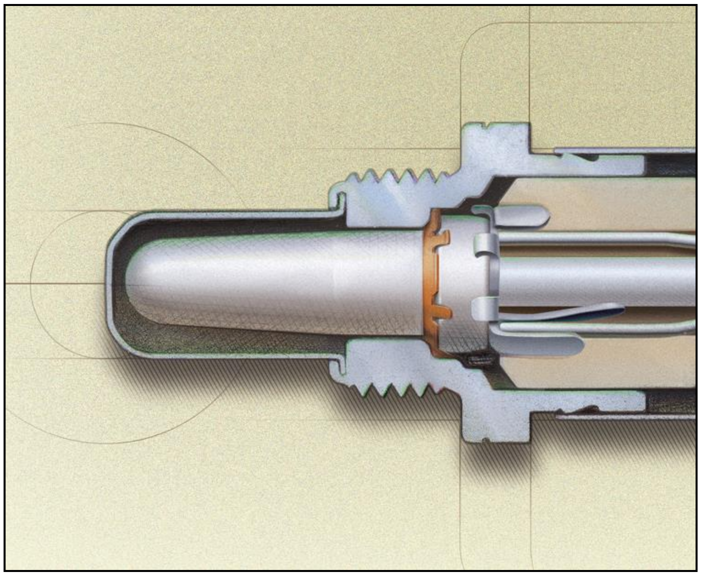
As the world's automotive industry was coming to grips with automotive emissions, Bosch engineers used the basic Nernst equation and experiments with zirconium-oxide ceramic to create the automotive oxygen sensor to help reduce these emissions.

Bosch called the new oxygen sensor a "Lambda sensor" because the oscilloscope curve showing the sensor's reaction to the level of oxygen it was monitoring resembled the shape of "Lambda," the 11th letter of the Greek alphabet.



The "Lambda" curve

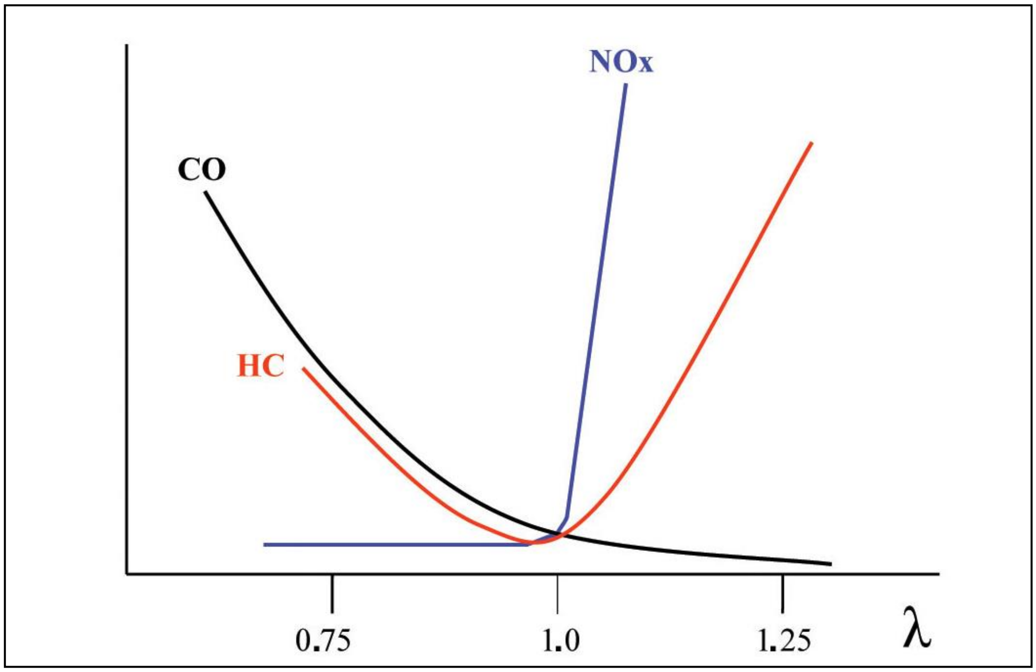
Following extensive experimentation, testing and engineering development, the first oxygen sensor was produced by Bosch and installed in a 1976 Volvo. The basic oxygen (O_2) sensor resembles a spark plug with a ceramic "thimble" protruding from the business end, which is inserted into the exhaust stream. The oxygen sensor reacts to the amount of oxygen in the exhaust. Using the Nernst cell ion exchange, the Lambda sensor sends electrical signals back to the vehicle's engine management system so the engine computer can adjust the air to fuel ratio for optimum efficiency.



"Thimble" oxygen sensor cutaway drawing

Mounted in threaded openings in the exhaust system, virtually all O_2 sensors before 1998 utilize this zirconia ceramic thimble, shielded from the exhaust gases by a tube with slots or holes in it and projecting directly into the exhaust gases. The sensor's ceramic element becomes electrically conductive at temperatures above 625-650° F. The sensor element produces a voltage signal that switches almost instantaneously from low voltage to high voltage as the air/fuel mixture changes from lean (too much oxygen) to rich (too little oxygen) and vice versa.

The catalytic converters used along with automotive internal combustion engines are most efficient when operating with an ideal, 14.7:1 (stoichiometric) air/fuel ratio, and the goal of the oxygen sensor is to help the engine's fuel management system approach or maintain this stoichiometric ideal. In nearly all oxygen sensors, a lean mixture (greater than 14.7:1) causes the oxygen sensor output voltage to drop, while a rich mixture (less than 14.7:1) causes the sensor output to go up. If the mixture is perfectly balanced at stoichiometric, the sensor sends a minimal signal (about 0.45 volts) which tells the vehicle computer the air/fuel mixture is correct.



The air/fuel ratio effect on harmful emissions

II. THE OXYGEN SENSOR TACKLES EMISSIONS

In the three decades since Bosch developed the pioneering automotive oxygen sensor, oxygen sensors have taken on the job of helping maintain the engine's ideal, 14.7:1 stoichiometric air/fuel ratio for tens of millions of vehicles. Today, 92 % of the 218 million automobiles and light trucks on the road in the United States are equipped with at least one oxygen sensor. These sensors contribute every day and every mile to reducing automotive exhaust emissions, and maintaining or restoring performance to millions of vehicles.

All oxygen sensors except titania sensors operate on the Nernst cell theories. There are four major types of oxygen (O_2) sensors operating in automobiles and light trucks in the United States today. These are:

- Unheated "thimble" sensors
- Heated "thimble" sensors
- Heated "planar" sensors
- Heated "wide-band" sensors

The “titania” sensor is in use in less than 1% of vehicles in the United States.

All fulfill their primary function, which is to "read" the level of oxygen in the exhaust gas and send a signal reflecting those readings to the vehicle’s engine management system.

The reaction speed of O_2 sensors to changes in the oxygen level in the exhaust is determined by the sensor itself and by the type of fuel delivery system the engine is using. Oxygen sensors used with older feedback carburetors switch once every second at 2500 rpm. Sensors installed with throttle body fuel injection systems switch two or three times per second at 2500 rpm, while O_2 sensors installed with multipoint fuel injection systems can switch five to seven times per second at 2500 rpm.

Each type of sensor, however, operates somewhat differently.

Unheated "Thimble" Oxygen Sensors

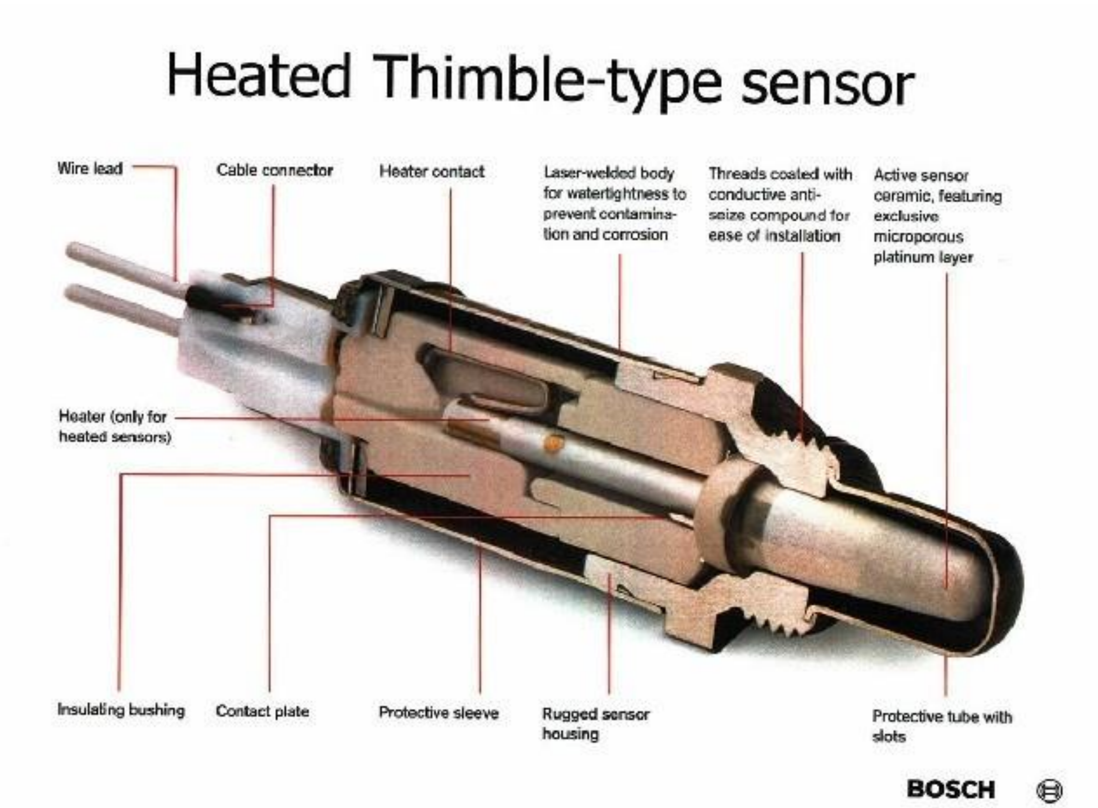
The original automotive oxygen sensor, the unheated type, is installed in the exhaust upstream from the catalytic converter. Until 1982, all O_2 sensors were unheated but these were still installed in some vehicles into the mid-1990's. Straightforward and durable, these are the simplest type of O_2 sensor -- they use a ceramic element in the shape of a thimble which projects into the exhaust gas stream, and the sensor generates a voltage when it reaches operating temperature. The engine computer reads the voltage and determines if the exhaust gas contains either too much unburned fuel ("rich") or too much oxygen ("lean"). A high reading (about 0.9 volts) indicates excess fuel in the exhaust (rich), while a low reading (about 0.2 volts) means too much oxygen (lean).

These sensors have worked well in millions of cars and light trucks for nearly 30 years. But they have one drawback -- they take no readings or send no signals while the sensor is cold (which occurs during start up) when harmful emissions are often highest.

Unheated sensors, because they rely on hot exhaust gases to reach operating temperature, also require a large volume of exhaust gas to contact the active ceramic element in order to function. This exposes these sensors to extremes of contamination, and they should be checked every 30,000 to 50,000 miles and if necessary, replaced.

Heated "Thimble" Oxygen Sensors

As emissions regulations became more stringent, the need for a faster reacting O_2 sensor that would provide readings while the engine was still cold. To monitor cold starting as well as normal engine operation, Bosch developed the first *heated* oxygen sensor in 1982, which utilizes an electrical heating element inside the "thimble" to bring the sensor up to operating temperature in about a minute -- irrespective of exhaust gas temperatures.



Heated zirconia thimble O_2 sensors operate much like unheated sensors, but begin sending voltage signals to the engine computer sooner. In the years since their introduction, heated thimble sensors have become the standard O_2 sensors for most automobiles and light trucks around the world. Heated sensors, as well as unheated sensors, have been improved and updated over the years to make them more effective, more durable, and easier to install.

Heated sensors, with their built-in heating element, require less exposure to exhaust gases to function properly, lessening their susceptibility to contaminants in the exhaust. Heated thimble oxygen sensors should be checked every 60,000 to 100,000 miles, and if necessary, replaced.

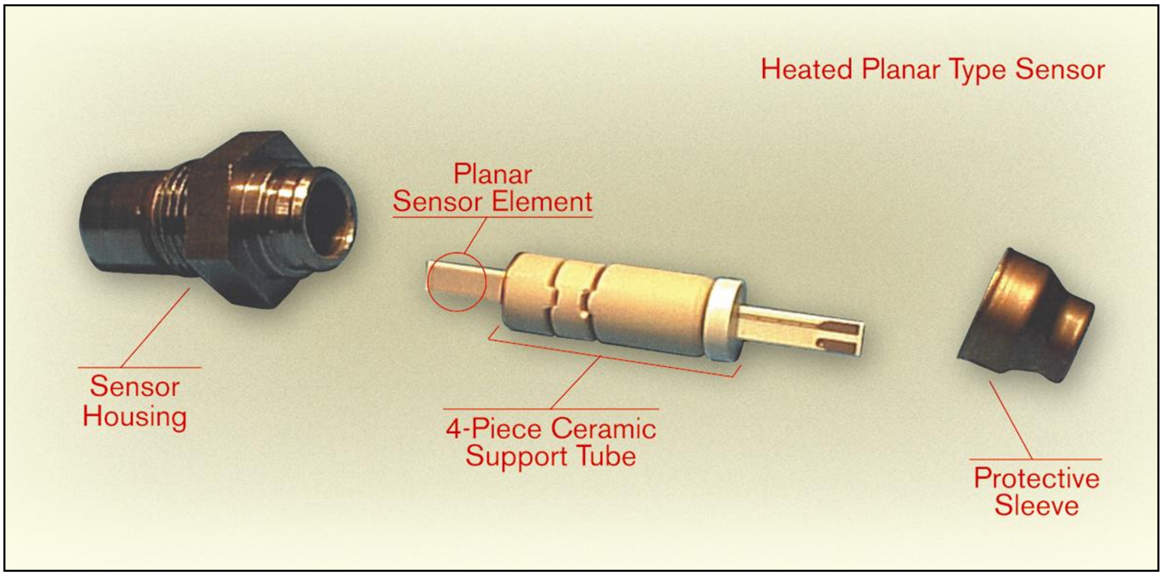
Heated thimble sensors are currently the predominant O_2 sensors, and continue to be installed in many vehicles, even to the present day.

III. OXYGEN SENSOR TECHNOLOGY AND TODAY'S AUTOMOBILE

Continually more stringent emissions requirements brought with them the need for even faster oxygen sensor "light off" (the time required for the O_2 sensor to begin sending readings), and new types of more sensitive and durable oxygen sensors have been developed to meet these requirements. The first of these is the *heated planar sensor,* which provides lean or rich exhaust gas readings in as little as 10-12 seconds after the engine is started, helping to reduce cold-start emissions.

Heated Planar Oxygen Sensor

Instead of the ceramic thimble, heated planar sensors utilize a flat ceramic zirconia element, less than 2 millimeters thick, projecting into the exhaust stream. The electrodes, conductive layer of ceramic, and heater are all laminated together on a single layered strip, which makes it smaller, lighter, and more resistant to contamination. The integrated heater element also uses less power as it brings the sensor up to operating temperature.



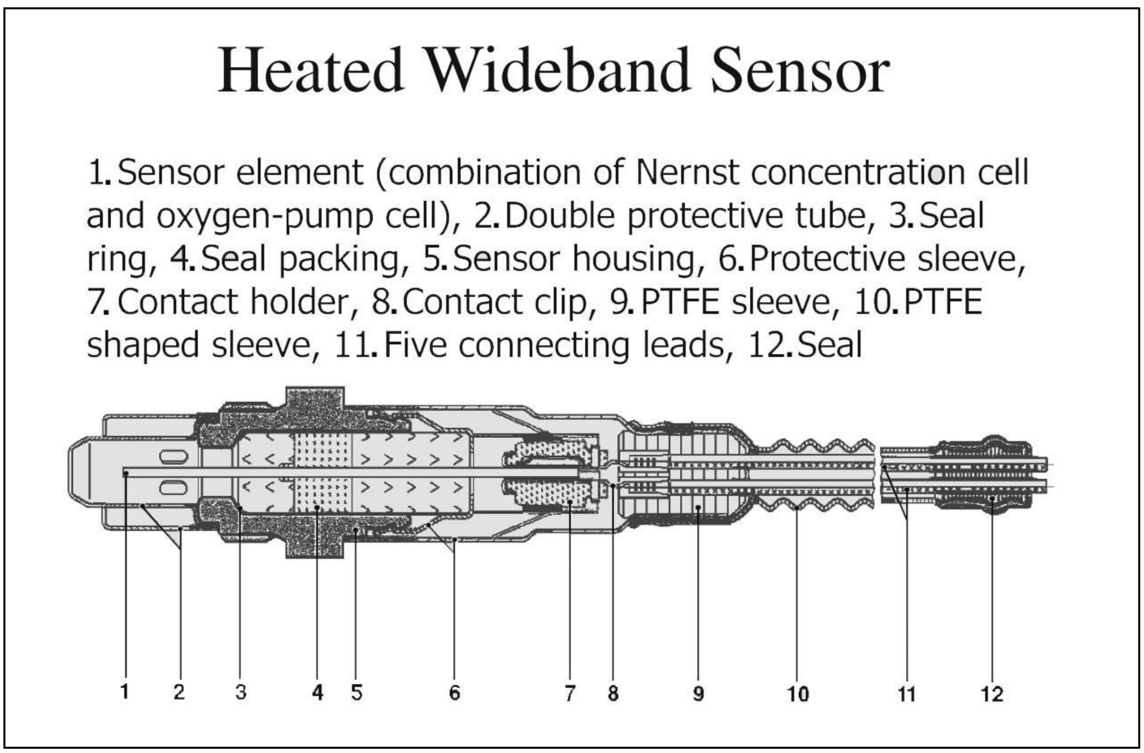
Components of a heated planar sensor

Planar sensors replenish reference air from a small port in the center of the ceramic strip and through the sensor's external electrical connector. And because they are installed exclusively with multipoint fuel injection systems, once they reach operating temperature they send readings to the engine computer several times per second, enhancing the ability to control the air/fuel ratio for greater efficiency and reduced emissions.

First introduced in the United States on the 1998 Volkswagen Beetle, the planar sensor has won widespread acceptance and already accounts for nearly 50 percent of O_2 sensors installed in new vehicles.

Wide-Band Sensors Provide Variable Readings

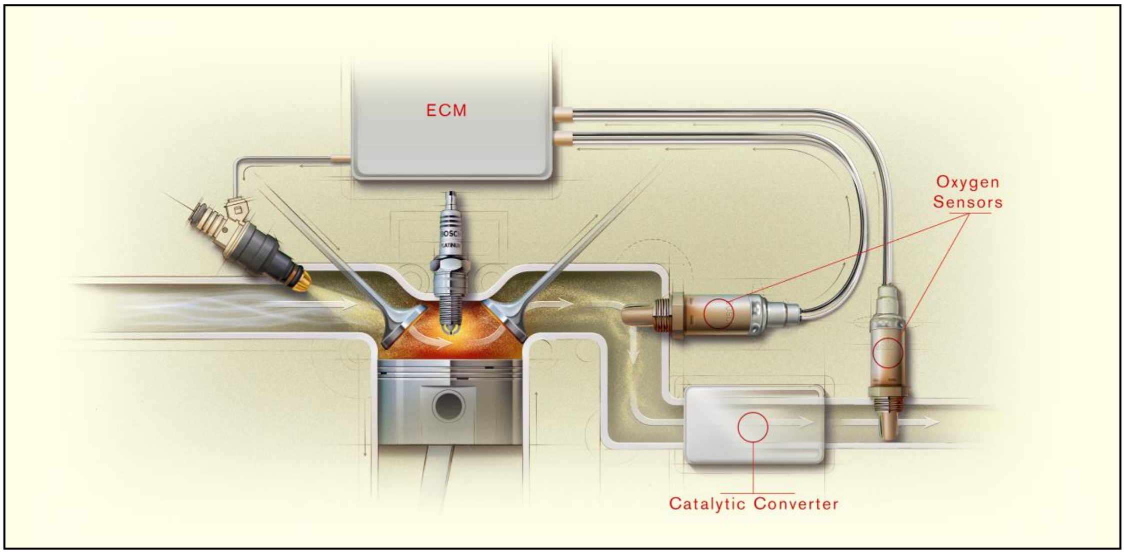
The next generation of oxygen sensors has already begun with the *heated wide-band sensor*. This highly sophisticated O_2 sensor utilizes the planar sensor's layered ceramic strip and adds a whole new concept -- a "pumping cell." This pumping cell allows the wide-band sensor to accurately measure the air/fuel ratio and produce a variable signal that continually reports readings all the way from very lean to very rich, and anywhere in between.



Producing a signal directly proportional to the air/fuel ratio, this sensor allows the vehicle's engine management system to more accurately and continually add or subtract fuel as needed to maintain the optimum performance level. Bosch's wide-band O_2 sensor responds to changes in the air/fuel mixture in less than 100 milliseconds, and reaches its operating temperature of 1400° F within 20 seconds or less, offering greatly enhanced fuel management.

Downstream Sensors for OBD II

Before 1996 and OBD II, automobiles used one or two O_2 sensors in the exhaust system *upstream* (before) the catalytic converter. Vehicles built from 1996 on under OBD II regulations also use O_2 sensors *downstream* (after) the catalytic converter. These downstream sensors ensure that the catalytic converter is operating properly.



Over half of the 218 million vehicles on America's highways are OBD II vehicles, and OBD II vehicles are growing in predominance with every year as new vehicles come into use.

IV. SUPERIOR ENGINEERING, PRECISION MANUFACTURING

Oxygen sensors are subjected to constant thermal stress-- intense heat, severe cold, immersion in cold water while very hot -- vibration, and the ravages of contaminants in the exhaust as well as external contaminants. Temperatures in the exhaust stream can exceed 1000° F, and vibration often exceeds 130g. But oxygen sensors still are expected to function properly for tens of thousands of miles.

Although Bosch's engineering is world-renowned, and they had extensive experience with Nernst cell projects, developing the first automotive oxygen sensor was no easy task. Bosch painstakingly developed its own ceramic formulas and compounds to handle the intense heat, thermal shock and vibration to which the oxygen sensor would be subjected. They conceived a solid, long zirconia element with rounded edges suitable for ceramic molding and a graphite gasket with electrical contacts. Then they perfected a silicone rubber protective boot. After nearly a year of testing and development, the first oxygen sensor was ready to be installed in a Volvo 240. It was projected to last for 20,000 miles.

This was followed by further exhaustive testing and development in conjunction with a major United States automaker, leading directly to numerous improvements and increased reliability. The refined O_2 sensors utilize a base zirconia ceramic construction, an improved application process for platinum electrodes, and a new manufacturing method for the porous protection layer. They were now ready for widespread use and major mass production, first in Germany and then in the United States. The continued success and longevity of oxygen sensors today is made possible by years of painstaking research and development, engineering excellence and manufacturing precision.

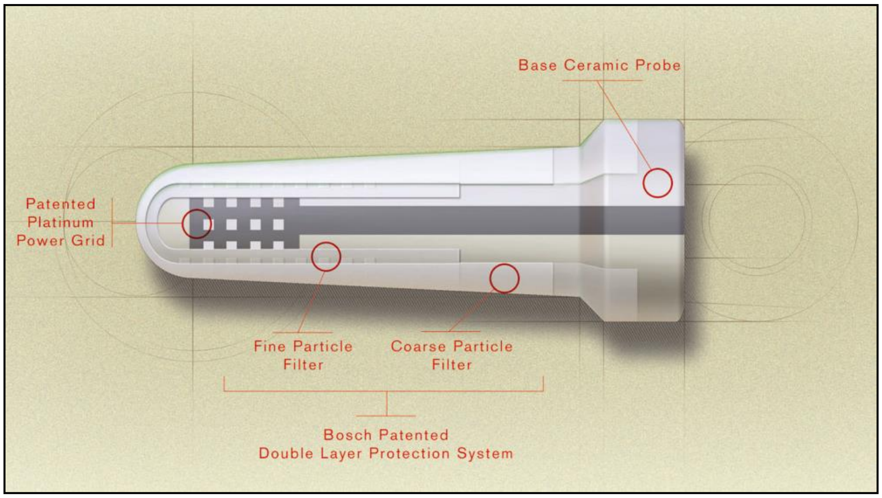
Quality definitely counts, and sensors that go the distance are produced in plants such as Bosch's facility in Anderson, SC. This state-of-the-art, high-tech facility operates under rigid quality control, utilizes a high level of automation, stringent testing at every step, and inspection throughout the manufacturing process. For the last four years, the Anderson plant has produced tens of millions of oxygen sensors while achieving a defect rate of well under 10 parts per million.

Ceramics Mixed, Cured, Tested

The heart of any oxygen sensor is the ceramic element, and the materials and processes that go into these ceramics are all-important to the performance and longevity of the sensor itself. Bosch sensors today utilize a carefully blended mix of oxides of zirconium, yttrium and other elements to form a tough base that will withstand the intense stress the oxygen sensor is subjected to.

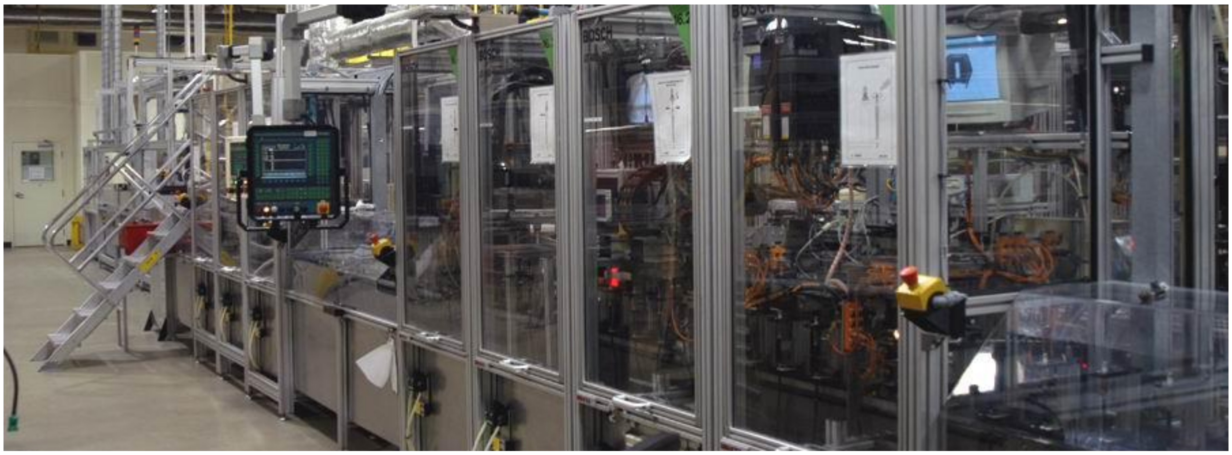
Ceramic Mixing Equipment

At Anderson, O_2 sensors are produced in a tightly controlled environment that utilizes precise mixing of zirconia ceramic base materials, grinding, inspection and testing, then pre-firing at 1000° F into the rough shape that will emerge as a sensor. Bosch's patented "platinum power grid" is then printed inside and outside of the ceramic. Exclusive to Bosch oxygen sensors, this "power grid" goes completely around the thimble and provides greater electrical conductivity and longer lasting construction.



Thimble ceramic element

The thimble is fired, tested again and then coated with a magnesium/aluminum oxide plasma coating for additional protection.



Automated planar sensor production line

Assembly of the ceramic element, the sensor housing, and heater group is completed with a laser welding cycle. It is highly automated – but carefully watched at every step by skilled, highly trained inspectors. Every sensor is functionally and electrically tested before being marked and packaged for distribution.

Planar "Layered Strip" Fired Under Intense Heat

Planar sensors utilize the same ceramic formulas and mixing, testing and firing procedures, and the planar sensor element and heating element are assembled and assiduously tested before the elements are laminated into the planar strip with many layers of different printed circuits. The assembled planar layered strip is then cut to shape and fired at 1400° F for approximately two days. After firing and grinding to assure smooth edges, the layered planar strip is mated to the housing and remainder of the planar sensor elements, and exhaustively tested, annealed for over twelve hours at high temperature, then tested again electrically and functionally.

Most of the test procedures have been developed by Bosch exclusively to ensure oxygen sensor performance and reliability, and some of the test equipment has been built right at the Anderson oxygen sensor plant to meet the plant's exacting standards. The result is a perfectly functioning oxygen sensor that performs flawlessly for thousands and thousands of miles.

Showplace of Oxygen Sensor Technology

Bosch's 457,000 square-foot Anderson, SC plant, which began production in 1985, occupies 132 well-landscaped acres near Greenville, SC. The plant is a model of attractive surroundings combined with spotless, well-organized component manufacturing and testing. Here Bosch employs a dedicated and skilled workforce of more than 1,200, and uses a high degree of automation, sophisticated testing, and rigid

Bosch Anderson plant

quality control. The plant manufactures 95% of all sensors sold by Bosch for the 218 million cars, light trucks, and vans in the United States. Wheel speed sensors, anti-lock brake electronic controls and integrated air/fuel modules are also manufactured at the facility.

The Anderson facility has received numerous quality and achievement awards, including awards from original equipment customers such as Chrysler, Ford, General Motors, and Nissan. Additionally, the plant has achieved certification to numerous international and industry quality standards such as QS 9000, ISO14001 and TS16949. In 2002 Bosch Anderson was named the South Carolina Manufacturer of the Year and in 2003 the plant was named recipient of the South Carolina Governor's Quality Award. Bosch was recently awarded the Silver Trophy for technical innovation at 2003 Equip Auto in Paris for the "Robert Bosch Universal Lambda Sensor" which features a patented design created by Bosch Anderson engineers.

Bosch manufactures three types of oxygen sensors at the Anderson facility: heated and unheated “thimble” sensors and heated “planar” sensors, including wide-band sensors. Since starting oxygen sensor production in 1988, Anderson has produced over 100 million oxygen sensors.

V. THE AFTERMARKET: KEEPING OUR AUTOMOBILES ENVIRONMENTALLY FRIENDLY

The modern automobile uses highly sophisticated engine and fuel management to extract greater performance from smaller and smaller engines – and to reduce automotive emissions. The oxygen sensor, with its measurement and readings of the exhaust gases, is a critical element in the highly sophisticated world of the modern automobile engine, and it must operate to specification for tens of thousands of miles in order to keep emissions in check and performance up to par.

Aftermarket Holds Key to Automotive Efficiency

A study by Sierra Research Laboratories in California, for instance, indicates that replacing a worn-out oxygen sensor in a pre-OBD II vehicle could reduce harmful emissions dramatically. In fact, this study concluded that replacing worn-out oxygen sensors would reduce automotive emissions more than all other repairs combined.

The aftermarket holds the key to efficient vehicle operation through inspection and maintenance, and proper O_2 sensor replacement when needed. How and when do sensors need replacement?

Depending on the vehicle in which the sensor is installed, recommended replacement levels are:

- Check/Replace unheated thimble-type O_2 sensors (on 1976 to mid-1990 vehicles) every 30,000 to 60,000 miles
- Check/Replace first generation heated thimble-type O_2 sensors (1982 to mid-1990 vehicles) every 60,000 miles

- Check/Replace second generation heated thimble-type or heated planar O_2 sensors (mid-1990 to current vehicles) every 100,000 miles

Rich condition

Oxygen sensors can also be damaged by contaminants in the exhaust, such as:

- The introduction of silicone at the sensor tip (the result of silicone spray lubricants under the hood, the use of a silicone-laden RTV sealer during a phase of engine assembly or repair, or engine antifreeze leaking into the exhaust)
- Phosphorous from burning engine oil (the result of worn valve guides/seals, etc.)
- A failed cylinder head gasket that allows engine coolant and/or oil into the exhaust stream
- Spilled oil on the sensor
- Rustproofing or other chemicals sprayed onto the sensor
- Very aggressive fuel additives such as injector or carburetor cleaners
- A too rich air/fuel mixture
- Anything that blocks the outside air vent supply source.

They can also suffer damage from external factors, such as:

- Thermal shock from temperatures often exceeding 1500^0 F
- Thermal shock from immersion in cold water while the sensor is exceedingly hot

- Pulsation stress (often up to $\leq$ +/-300 mbar)
- Vibration shock (as much as $\leq$ 1300 m/s^2, 5 kHz)

And they can simply wear out after tens of thousands of grueling miles at extremes of hot and cold.

Some symptoms that may indicate O_2 sensor trouble are:

- Increased fuel consumption
- Rough running and poor performance
- Pre-ignition or detonation (engine knock)
- Fouled spark plugs, from an overly rich air/fuel mixture if the vehicle is not burning oil
- The vehicle has failed an emissions test, with high CO and/or HC readings.
- A catalytic converter damaged by an overly rich or extremely lean fuel/air mixture
- OBD II vehicles (1996 and newer) will turn the MIL (malfunction indicator light) on when the system sees a failure or problem that will cause a 50% increase in tailpipe emissions

And they can be checked simply using a voltmeter or a scope. Contrary to what many believe, high NOx alone is not caused by a worn-out O_2 sensor. NOx is caused when combustion temperatures get above 2500° F. A slow operating or failed sensor *can* cause the converter to operate improperly, causing a higher level of HC, CO and NOx emissions – and a bad catalytic converter can cause excessive levels of all three pollutants.

If a worn out or failed O_2 sensor is suspected, the vehicle manufacturer's recommended procedure should be followed to determine whether it is actually working or not. On vehicles model year 1995 and older, most O_2 sensors can be verified as functional by checking for a proper response or switching time.

Bosch Generic Zirconia Oxygen Sensor Test Procedure

- Verify basic engine parameters (mechanical condition, ignition system components and timing, fuel delivery system and air induction)
- Run the engine to operating temperature and turn the engine off
- Disconnect the O_2 sensor lead and attach red voltmeter lead to sensor signal wire, black lead to ground
- Run engine at 2500 rpm
- Artificially enrich the fuel mixture by disconnecting and plugging the vacuum hose to the fuel pressure regulator
- The voltmeter should rapidly read 0.9 volts to indicate sensor's rich mixture performance
- Next, eliminate the enrichment and induce a small vacuum leak
- The voltmeter should rapidly show 0.2 volts or below to indicate sensor's lean mixture performance

To check the sensor's dynamic performance:

- Reconnect the sensor lead
- Run the engine at 1500 rpm
- Sensor output should fluctuate around 0.5 volts

Scope-Testing Switching Type Oxygen Sensors

- Do not disconnect the sensor connector
- Attach scope lead to the sensor signal wire
- Monitor sensor signal with the engine at operating temperature and 2500 rpm

- The signal should fluctuate between approximately 0.2 and 0.8 volts (lean-to-rich and rich-to-lean) in less than 300 milliseconds.

This procedure should work with nearly all oxygen sensors, heated or unheated, except the newest "wide-band" sensors. These “wide band” sensors are installed on some late model domestic and import models, and can be identified by the five or even six wires in the connector harness. They must be checked using the vehicle's own diagnostic system, and by reading the serial stream data.

Fuel control system faults can adversely affect O_2 sensor testing, including fuel injector problems, malfunctioning mass airflow sensor, excessive fuel pressure and volume, malfunctioning fuel pressure regulator, and anything that causes the engine to consistently operate rich or lean.

When worn out, oxygen sensors absolutely must be replaced to keep emissions within government requirements, and to restore fuel economy and performance. And it is essential to remember -- a replacement sensor should in almost all cases be the same type of sensor as the one it is replacing. A planar sensor should be replaced with a planar sensor, and not a thimble sensor, for instance.

Failure to pass an emissions test is one of the key signs an O_2 sensor is not operating. Many states, of course, have stringent automotive emissions requirements such as IM 240 regulations – and a vehicle with a worn-out O_2 sensor almost certainly will fail an IM 240 emissions test.

<u>State Programs Mandate Efficiency</u>

Oxygen sensors play a critical role in helping light vehicles pass a growing number of Inspection and Maintenance (I/M) emissions tests nationwide. According to the U.S.

Environmental Protection Agency (EPA), automotive emissions tests are now required in more than 38 different geographic areas in 33 states and the District of Columbia. The list of areas requiring auto emissions tests grows each year.

Properly functioning oxygen sensors are critical to passing almost every one of these emissions tests.

Nearly all emissions tests across the country, whether the older, idle-type test or the latest OBD II test, require sampling of tailpipe emissions. The oxygen sensor must be operating properly in order for a vehicle to pass these examinations. Top quality oxygen sensors, operating properly, are not only essential wherever emissions tests are required; long-term reliability and durability are also highly important. A worn out oxygen sensor can lead to damage to the catalytic converter, as well as causing emissions test failure.

A total of 33 states and the District of Columbia currently require some form of light vehicle emissions inspection at least biennially. Five states, Colorado, Illinois, Maryland, Missouri, Washington, and the District of Columbia utilize IM 240 emissions tests -- the IM 240 designation means, basically, that the emissions test is conducted for 240 seconds, and includes dynamometer testing.

Many states, including Arizona, California, Colorado, Kentucky, Pennsylvania, Utah and Washington, have levels of emissions standards which vary geographically within their individual states. Only three of the 33 states, Louisiana, Maine and New Hampshire, do not require tailpipe emissions tests. These states mandate visual inspection of certain emissions components to insure that they are operating properly.

The types of emissions tests required vary widely from region to region. Older Idle and 2-Speed Idle tests are the least stringent; ASM and IM tests frequently require use of a dynamometer; and OBD II (on-board diagnostics) tests tap into computers within the vehicles (required since 1996) to pinpoint possible emissions problems.

A number of states also have two or three different levels of required emissions for light vehicles. Typically, pre-1980 vehicles are required to meet an idle test; intermediate-age cars a more stringent requirement; and 1996 and later cars normally must pass an OBD II test.

VI. OXYGEN SENSOR MARKETS, AND NEW ROLES

Oxygen sensors have been installed in nearly every car and light truck sold in the United States since Bosch's pioneering oxygen sensor in 1976. Bosch estimates that more than 200 million of the 218 million automobiles and light trucks operating in this country are equipped with oxygen sensors. About 14 million carburetor gasoline vehicles and 4 million diesel vehicles are operating in the United States without O_2 sensors.

About 97 million vehicles were built with O_2 sensors before OBD II regulations came into effect, and are equipped with one or two unheated thimble-type O_2 sensors or heated thimble-type O_2 sensors, mounted upstream from the catalytic converter. The other half – about 111 million vehicles – are OBD II vehicles, and are equipped with two to four heated thimble-type or heated planar O_2 sensors. This includes sensors upstream (before) the catalytic converter and sensors downstream (after) the converter.

This means there are 420 million oxygen sensors of all types operating today in the United States, and 6.5 million oxygen sensors are currently being sold each year in the aftermarket domestically-- a large potential replacement market.

Replacing Oxygen Sensors Highly Beneficial

Oxygen sensors, of course, are built to last, and last, and last. Many are still functioning perfectly with 100,000 miles on them -- but unfortunately, the extreme thermal shock, vibration, and contamination they are subjected to day in and day out can take a toll. The ravages of contamination, thermal shock, and the other factors noted earlier can cause oxygen sensors to wear out before their normal life expectancy.

Oxygen sensors are absolutely vital to the efficient operation of modern automobiles and light trucks – making them prime candidates for replacement once they wear out -- or when they have so many miles on them they are likely to wear out in the near future. Oxygen sensors can become sluggish and less sensitive as they age, and a worn out sensor is often the main cause of failure to pass an emissions test. In many vehicles, this will cause a "Check Engine" light to come on. Replacing a sluggish or worn-out O_2 sensor can reduce emissions, improve fuel economy, and save the catalytic converter from damage.

Clearly, O_2 sensors must be replaced if they have been diagnosed as failed. And Bosch, which offers the industry's most comprehensive line of quality oxygen sensors for both original equipment and the aftermarket, recommends checking these sensors at regular intervals to maintain vehicle efficiency and performance.

Planar Sensor Gains Market Share

Heated thimble-type O_2 sensors have been the predominant O_2 sensors used in new vehicles for the past 10 years, despite the fact that some vehicles still used unheated sensors into the mid-1990's. Continually advancing emissions requirements have mandated more advanced, new oxygen sensors that are more sensitive while they are also more durable. As noted earlier, the heated planar sensor, introduced by Bosch in 1998, provides greater sophistication in exhaust gas measurement and fast “light-off” of about 10-12 seconds.

The planar sensor helps control cold-start emissions, and heated planar sensors are already making up nearly 50 percent of oxygen sensor installations in new vehicles in the United States.

For the moment, heated thimble O_2 sensors will remain as the predominant replacement O_2 sensor sold. As more and more vehicles equipped with the advanced, fast acting planar sensors enter operation, sales of replacement planar sensors will increase. It will take some years, but the heated planar sensor eventually will replace the heated thimble sensor as the predominant oxygen sensor operating in this country.

Replacement Sensors Can Be Better than Original

As sensor design and manufacturing technology continues to advance, sensors built to replace earlier sensors often reflect these advancements. Bosch replacement sensors, for instance, often outperform and last longer than the original sensor they are replacing -- so replacing a worn-out oxygen sensor can bring double benefits. Lost performance and efficiency are restored, and include other benefits include increased service life and reduced replacement frequency.

Unique Universal Heated Sensors from Bosch

In addition to the 99.8% market coverage of oxygen sensors with OEM-style connectors, Bosch offers a unique program of “universal” sensors. Fourteen different Bosch Universal Heated Sensors, for instance, provide the closest match to original equipment manufacturers' sensor performance. These fourteen part numbers meet specific exacting OE operating requirements, and cover over 280,000,000 sensor units in operation appropriate for replacement with universal heated sensors. Bosch Universal Heated Sensors are available for virtually every make of vehicle on the road in the United States today.

Bosch universal heated sensors are designed for ease of installation in any vehicle. Designed to perform flawlessly for as long as sensors are needed in a vehicle, they feature a revolutionary, patented submersible connection system that protects against water and contamination and withstands the effects of extreme temperatures and engine vibration. Unlike older butt connectors, these connectors make installation or service easy and foolproof, as the connectors can be unscrewed and reconnected.

Components of Bosch Heated Universal Oxygen Sensor (Thimble and Planar)

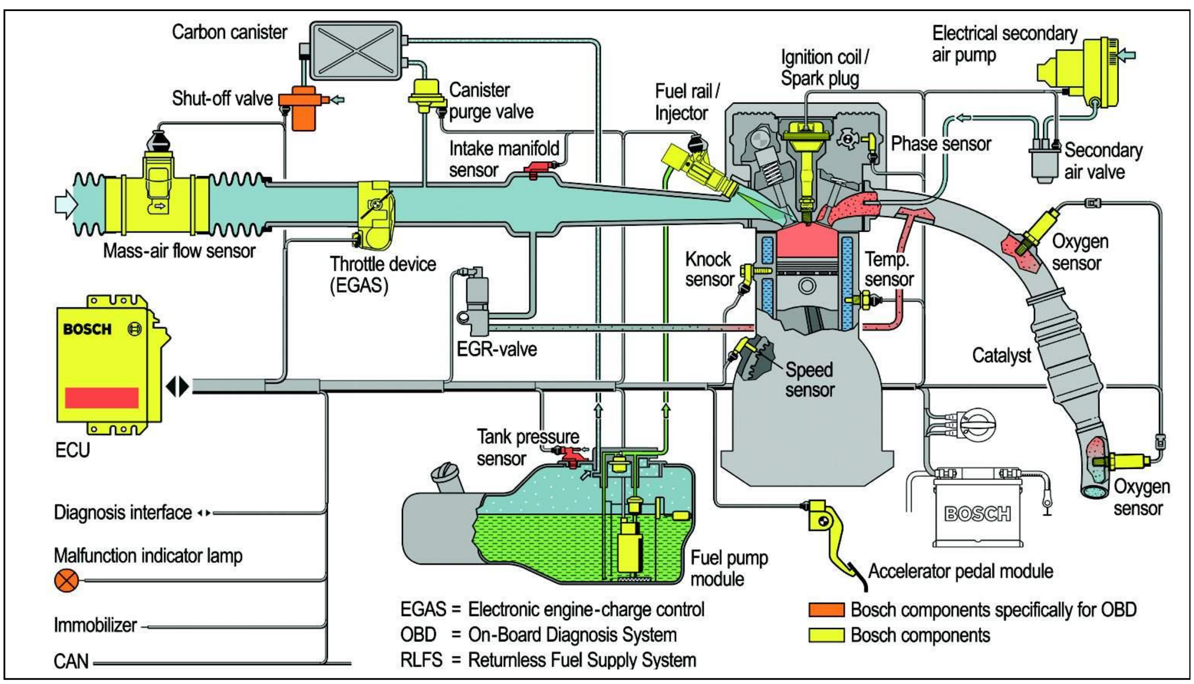
Motorsports Pushes the Envelope

Motorsports, as it has for more than a century, often spearheads new uses and advances in existing products – and motorsports has now embraced the oxygen sensor. Bosch, which invented the automotive oxygen (O_2) sensor three decades ago, has extensive involvement in the many aspects of the domestic motorsports scene, and

Bosch's expertise with O_2 sensors is translating into greater performance in all forms of motorsports.

Many of these activities ultimately play an important role in developing and improving everyday automotive products themselves.

Oxygen sensors are playing an increasing role in advancing the sophistication of engine management systems. For instance, the two-car C5R Corvette team has dominated the ALMS GTS class for the past several years, in its worldwide road-racing program ranging from Sebring to Le Mans. Running a race-tailored version of the highly sophisticated Bosch Motronic™ engine management system, they rely heavily on Bosch wide-band O_2 sensors to feed the Motronic system with a constant stream of vital air/fuel information – at any speed and any place on the race track. This team won its third consecutive championship in this highly competitive series in 2003, and they have enjoyed a commanding performance advantage in every race.



Bosch Motronic Engine Management System

The Motronic Engine Management System in these Corvettes is a combination of electronic ignition and fuel injection, and includes:

- An engine management computer
- Data storage and analysis using a Compact Flash card
- Telemetry, including input from multiple oxygen sensors

The Motronic system controls both ignition and fuel injection functions. These functions are measured at 12-degree crankshaft angle increments, which in a V8 engine at 10,000 RPM results in 40,000 calculations per minute. The highly sophisticated Bosch wide-band O_2 sensors they utilize, with their constant input of variable air/fuel data every 100 milliseconds, are keys to the success of the Motronic system and racing programs such as this.

This system processes and manages a lot of information. Motronic allows the race team to optimize every function of the engine package for peak performance on a variety of tracks and in ever-changing track and weather conditions – relying on wide-band O_2 sensors for constant, dependable data acquisition.

Carburetors on the Banked Ovals

Many NASCAR teams, which of course run carburetors and not fuel injection on the banked ovals, keep O_2 sensors hard at work, primarily in testing. Oxygen sensors are used on the dynamometer to calculate the best air to fuel ratio (usually from 0.80 to 0.85 lambda) to achieve maximum torque, and normally adjust the mixture to 0.82, or even higher.

And the O_2 sensors play an especially important role on the high banked tracks, where the G forces are so high at speed that the fuel is starving out of the left side of the carburetor and almost flooding the right side. The sensors help develop fuel curves for each track, and help the race teams adjust jets in one of the four carburetor barrels, and possibly adjust the manifold runners to compensate.

Chip Ganassi's NASCAR team, is a good example. This team uses eight Bosch wide-band sensors, mounted in the exhaust stream on each side close to the V8 engine, to achieve the best air/fuel mixtures for each track they run. Each combination of carburetor and manifold and camshaft offers a different dynamic the team must deal with, depending on the track and the anticipated weather and temperature.

This team takes the O_2 sensor readings with Bosch Motorsports' Electronic Sensor Interface Box. The ESIB is designed to measure and Data Log the signals from multiple sensors. This allows them to factor in measurements from eight sensors, and records the vehicle's speed, engine RPM, throttle position, and lateral acceleration. This device, in conjunction with the oxygen sensors, helps extract the maximum from the engines at every track.

In this scenario, as is often the case, the philosophy of racing influencing everyday driving is reversed -- a product developed for street use has found a very important use in racing.

Drag Racing Goes High-Tech

Bullish Motor Racing, which won the 2003 NHRA Summit Sport Compact Drag Racing Series Championship and the 2003 NDRA Pro Compact Xbox Cup championship, pulls more than 1600 horsepower from identically prepared turbocharged 3.0 Toyota six cylinder engines. One of this team’s “secrets” is their engine tuning techniques – using Bosch wide-band oxygen sensors to tell them exactly what they need to know to extract the ultimate from these engines.

For the 2003 season, the team won 13 of 19 NHRA/NDRA Sport Compact events as well the championships in both series and the runners-up in both series, a feat never accomplished before. Bullish also runs Bosch platinum spark plugs and fuel injectors. The spark plugs, like the wide-band oxygen sensors, are stock street plugs utilizing platinum center electrodes and welded-on ground electrodes with platinum tips. The fuel injectors are also stock, off-the-shelf Bosch units.

Bullish Motor Racing tunes their engines for maximum performance at the very edge of reliability, and the wide-band oxygen sensors are critical to the proper air/fuel mixture. The sensors are plugged in before every run to extract data log readings right to their laptop computers after each run. Then they analyze the printout to see if they can improve performance by changing any settings.

What Bosch learns as a result of testing and development of oxygen sensors, spark plugs, fuel injectors, engine control systems, and other components in racing competition, enables Bosch engineers to provide optimum performance and reliability to the motoring public. Sometimes, of course, the reverse is true. The extensive development going into vehicles for everyday driving often leads to new racing technology -- the benefits go both ways.

Conclusion: Oxygen Sensor Importance Continues

After three decades of continuous development, refinement and innovation, the oxygen sensor has made great advancements -- and has become absolutely vital to the efficient operation and performance of 92% of the 218 million vehicles in the United States alone. And as engine and fuel management systems continue to grow in sophistication and capacity, the oxygen sensor becomes even more important with every passing year. Where a handful of automobiles utilized one oxygen sensor back in 1976, millions of vehicles now utilize as many as eight advanced, highly sensitive

O_2 sensors that play a key role in vehicle efficiency, reduced emissions and improved fuel economy, and superior driveability.

Oxygen sensors are now also being used in a growing number of small engine applications, and their use in diesel-powered vehicles is only a few short years away. Professor Nernst -- and Bosch -- have created a highly useful piece of equipment for the modern automobile and society as a whole. And we all benefit, every day, from its accomplishments.

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