by J. T. Woestman and E. M. Logothetis

Controlling Automotive Emissions

Continued reduction in emissions from vehicles powered by internal combustion depend on advanced emissions-sensing technology and feedback control

Air pollution, especially smog, has been a problem in the Los Angeles basin since the late 1940s. In 1952 A. J. Haagen-Smit of the California Institute of Technology demonstrated that the smog problem resulted from sunlight-driven reactions involving oxides of nitrogen and hydrocarbon compounds, which come from motor vehicle emissions, among other sources. Moreover, motor vehicles contribute to high levels of carbon monoxide in urban areas. As a result, emission standards for motor vehicles were introduced—first in California and then throughout the United States—starting in the mid-1960s.

Meeting the early emissions requirements—as well as the increasingly stringent ones introduced in subsequent years—accelerated or forced the installation in motor vehicles of such emissions control devices as electronic fuel injection systems, on-board computers, catalytic converters and feedback control systems for metering air and fuel mixtures. As a result of these significant advances in automotive technology, vehicle emissions were reduced greatly. By 1992, hydrocarbon and carbon monoxide emissions had been reduced on vehicles sold in the United States by 96 percent and nitrogen oxides by 76 percent, compared to uncontrolled levels.

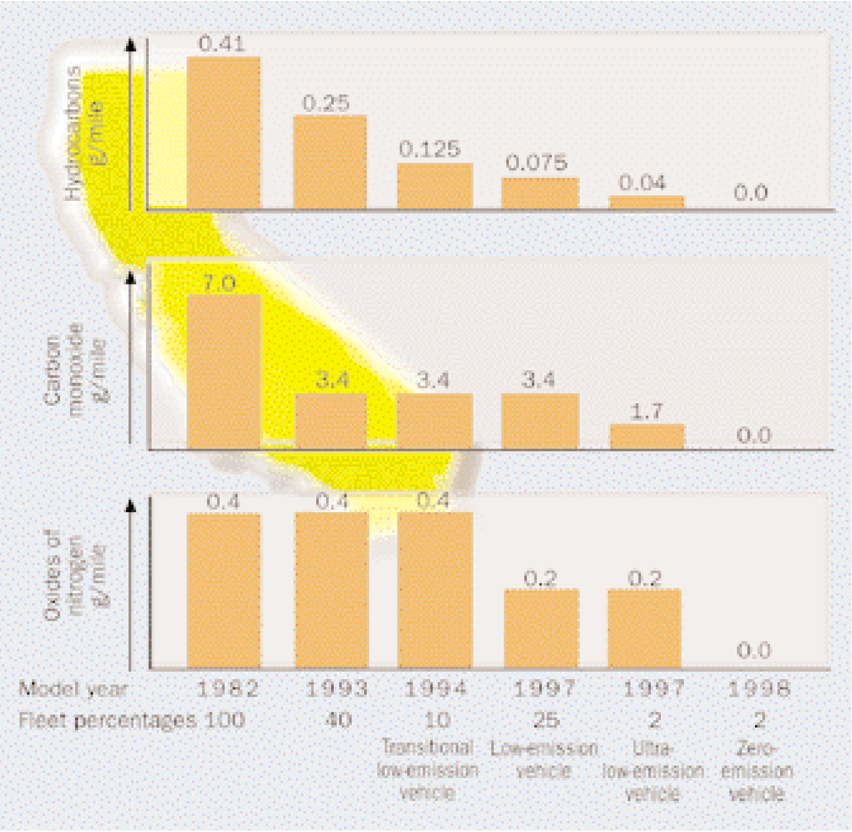

Figure 1. Regulatory timetable for vehicle emissions in California.

In 1990 Congress enacted the Clean Air Act Amendments, which imposed new federal regulations on automotive emissions, including a timetable for systematically lowering emissions over a ten-year period. Some states, especially California (figure 1), have established emissions standards that are more stringent than the federal ones. Ultimately, in California and possibly some other states, the level of hydrocarbons must be reduced by a factor of 10 relative to the current levels and, in all states, carbon monoxide and oxides of nitrogen levels need to be at least cut in half. In addition to enforcing stricter emissions standards, the 1990 regulations require on-board diagnostic systems to monitor the performance of several emissions control components. Also, compliance with these regulations must be met by new vehicles for 100,000 miles or 10 years, which ever comes first.

The 1990 regulations pose major technological challenges. In fact, members of the automotive engineering community cite emissions regulations as the top technological challenge they now face and will face in the future. In May 1995 the engineering journal *Design News* reported: “In a recent Survey conducted by DuPont Automotive, the engineers put the emissions regulations at the top of the list [of technological challenges] (36%), followed by cost reduction (28%) and alternate fuels (27%).”

Physicists can easily understand the magnitude of the basic requirement—devising a system that will make very accurate measurements of several quantities under dynamic conditions, and will do so for a period of ten years, without calibration. Meeting this engineering need will depend on a collaborative effort among scientists, with physicists at the forefront.

The control system

Motor vehicle emissions from spark-ignited engines using unleaded gasoline come from two main sources: (1) volatile organic compounds—largely hydrocarbons—that escape from the fuel system through evaporation, and (2) postcombustion compounds—hydrocarbons, carbon monoxide and oxides of nitrogen—that leave the engine through the exhaust system. Hydrocarbon emissions from the fuel system, which are released whether the car is being operated or not, are controlled with a carbon canister that adsorbs the vapors. Hydrocarbon gases that escape past the piston rings into the crankcase can be drawn back into the engine and burned by using a positive crankcase ventilation system. Emissions released through the exhaust pipe are controlled by use of a three-way catalyst (catalytic converter) in the exhaust system and electronic control of the engine's fuel metering system.

The three-way catalyst efficiently converts carbon monoxide, hydrocarbons and oxides of nitrogen to carbon dioxide, water and nitrogen when the engine is operated at or close to the stoichiometric air mass to fuel mass ratio.

Figure 2 shows that precise control of the ratio around stoichiometry is essential for efficient emissions abatement. Control is achieved by using an electronic feedback control system that includes a heated exhaust gas oxygen sensor. This device is used to sense the stoichiometric point so that the overall system can balance the average air mass to fuel mass ratio as close as possible to stoichiometry.

The system controls the air mass to fuel mass ratio by determining the intake air and actuating the electronically controlled fuel injectors to dispense the appropriate amount of fuel. The strategy used in this control system must optimize all of the engine-related parameters for minimal emissions, as well as the desired performance. These parameters include air mass to fuel mass ratio, cylinder compression, valve timing, air pump operation, exhaust gas recirculation and combustion timing.

Figure 3 shows the basic components of the control system related to exhaust system emissions abatement. During the exhaust stroke of the engine's pistons, the combustion products are pushed out of the cylinders and into the exhaust manifold. These gases travel through the exhaust pipe, are sensed by the heated exhaust gas oxygen sensor, pass through the catalyst (where they are converted) and exit the tailpipe. Ideally the heated exhaust gas oxygen sensor generates a voltage that indicates whether the air and fuel mixture is rich (excess fuel) or lean (excess air) relative to the stoichiometric point, and the control logic alters the fuel injector pulse width to simultaneously minimize emissions and maintain satisfactory performance.

A large amount of work is going into the development of heated exhaust gas oxygen sensors and the entire emissions control system.

The sensor

A typical zirconia oxygen sensor (figure 4) consists of a thimble of yttria-doped zirconia with porous platinum electrodes on its inner and outer surfaces. The outer electrode is coated with a porous protective layer

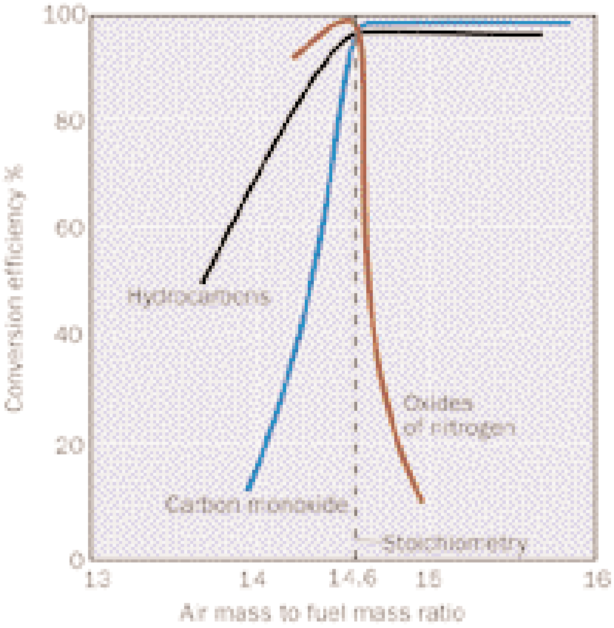

Figure 2. The three-way-catalyst conversion efficiency versus air mass to fuel mass ratio for hydrocarbons, carbon monoxide and oxides of nitrogen.

(usually spinel, a magnesium aluminate mineral), and a metal shroud covers the entire thimble. The shroud has openings so that exhaust gas can flow into the sensor and reach the outer electrode's surface. The inner electrode is exposed to ambient air, for reference. In a heated exhaust gas oxygen sensor, a resistive heating element is placed in the center of the thimble. The entire device is about the size and shape of a spark plug.

In exhaust gas the zirconia heated exhaust gas oxygen sensor produces a large change in voltage near the stoichiometric air mass to fuel mass ratio, because of a similar change in the oxygen pressure in the exhaust gas (figure 5). Oxygen sensing can be used in engine control because, in thermodynamic equilibrium, there is a one-to-one correspondence between the oxygen partial pressure in the exhaust and the air mass to fuel mass ratio. In the exhaust stream of an operating automobile, however, the heated exhaust gas oxygen sensor rarely if ever operates at thermodynamic equilibrium. At times, therefore , the response of the sensor can be different from the ideal plot shown in figure 5.

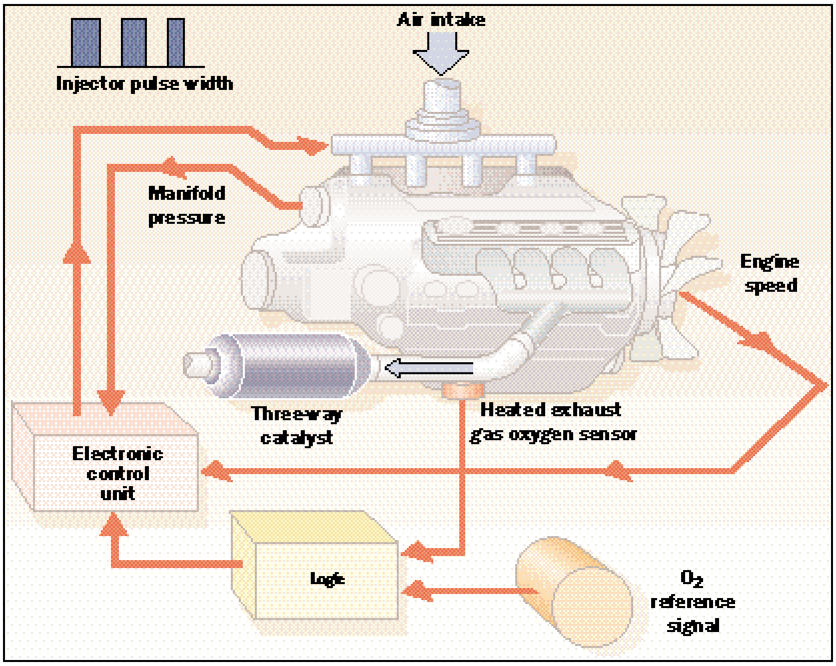

Figure 3. Basic components of the engine control system related to exhaust system emissions abatement.

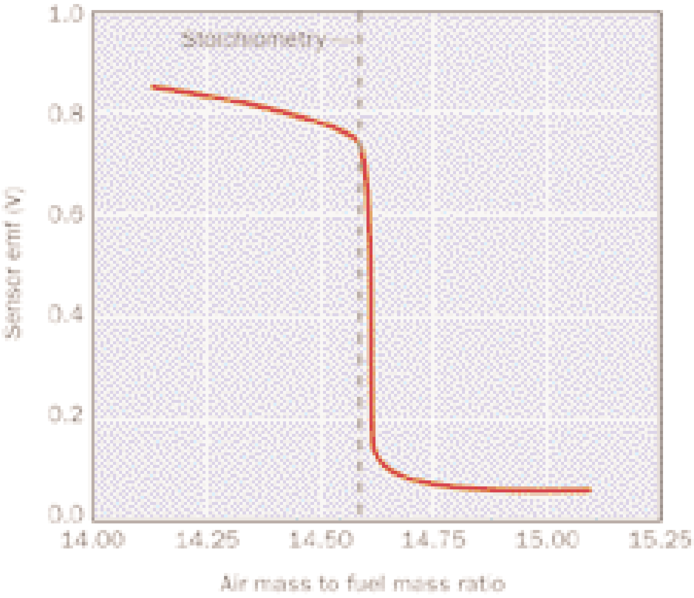

Figure 5. Typical response of a zirconia heated exhaust gas oxygen sensor to a slow ramp in the air-mass to fuel-mass ratio.

The detailed equations that model the sensor's behavior are beyond the scope of this article, but they depend on a few fundamental concepts. There is negligible chemical reaction in the gas phase between the oxidant (oxygen and oxides of nitrogen) and reductant (hydrocarbons, carbon monoxide and hydrogen) gases that comprise the engine exhaust gas. These gases flow into the sensor through the shroud openings and diffuse through the porous spinel, where they are adsorbed on the heated, porous and catalytic exhaust-side (outer) electrode. Adsorbed molecular oxygen on the electrode dissociates into single adsorbed oxygen atoms. Inside the yttria-doped zirconia thimble are mobile, charged oxygen vacancies. The single adsorbed oxygen atoms interact with the charged oxygen vacancies at the zirconia-platinum-gas intersections. This interaction affects the internal charge distribution within the zirconia, and the charge distribution determines the sensor's voltage output. Reductant gases adsorbed on the exhaust-side electrode further modify this charge distribution by reacting with the adsorbed oxygen.

In very lean mixtures, adsorbed oxidant species are in excess on the exhaust-side electrode. Their concentration is similar to that on the reference-side (inner) electrode in contact with the ambient air, thereby generating a low voltage, about 50 millivolts. In rich mixtures, the reactions of the reductant adsorbates on the exhaust-side electrode enhance the zirconia's oxygen-vacancy concentration in the vicinity of that electrode relative to the one on the reference side, which gives rise to a relatively large sensor voltage, around 800–1,000 mV. The transition from a small sensor voltage to a large one develops as the adsorbed-gas concentration passes through stoichiometry on the exhaust-side electrode.

Therefore, determining the air mass to fuel mass ratio at which the heated exhaust gas oxygen sensor's voltage switches from low to high is equivalent to determining the air mass to fuel mass ratio that causes stoichiometric conditions on the exhaust-side electrode (which does not necessarily correspond to stoichiometry in the bulk gas). These concepts have been used by the authors and their colleagues to develop some physically based mathematical models of sensor behavior, which can predict a sensor's output at a given temperature and exhaust gas composition.

Concluding remarks

Although significant progress has been made in reducing automotive emissions, the task continues. Two of the major issues of current focus are integrating the on-board diagnostics system in the emissions control system and minimizing emissions during the first few minutes of engine operation.

The three-way catalyst's conversion rate depends largely on its operating temperature, and no significant treatment of emissions takes place until the converter reaches an operating temperature of approximately 300° C. Operating temperatures of about 400° to 800° C provide ideal conditions for maximum efficiency and extended service. Temperatures above 800° C, though, can substantially reduce the catalyst's lifetime. Currently it takes about a minute for the engine exhaust gas to heat up the three-way catalyst enough for it to work at or above 50% efficiency. This means that a significant amount of the total emissions that a vehicle emits in a single trip are emitted in the first few minutes of operation. To meet the new hydrocarbon emissions regulations, a supplemental source of energy to enhance catalyst warm-up may be needed.

A very large amount of work is going into the development of heated exhaust gas oxygen sensors and the entire emissions control system. These devices provide an otherwise impossible level of accuracy in feedback control of automotive internal combustion engines. Together with the three-way catalyst, this technology is enabling automobiles to meet the ever-tougher emissions regulations throughout the world. In the future, more sophisticated emissions control systems can be expected, possibly including electrically heated catalysts and sensors that measure the number of individual exhaust gas constituents.

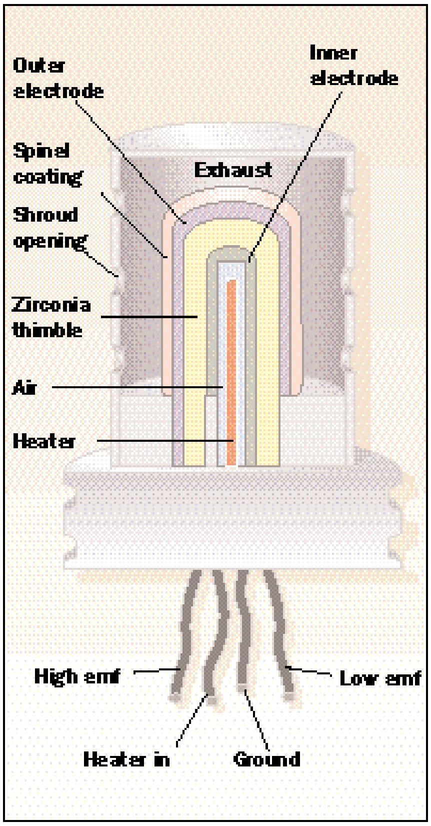

Figure 4. Diagram of a typical thimble-type zirconia heated exhaust gas oxygen sensor.

Recommended Reading

A. D. Brailsford, E. M. Logothetis, M. Yussouff and J. T. Woestman. Estimation of the switch point of an exhaust gas oxygen sensor in general exhaust environments. Paper presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, February, 27–March 2, 1995. Society of Automotive Engineers Technical Paper Series, number 950531.

A. D. Brailsford, M. Yussouff and E. M. Logothetis. Electrochemical zirconia sensor model for reducing gas mixtures. In K. T. V. Grattan and A. T. Augousti, editors., *Sensors VI: Technology, Systems and Applications*. Philadelphia: Institute of Physics Publishing, 1993, page 39.

Robert Bosch Gmbh. *Automotive Handbook.* Warrendale, Pa: Society of Automotive Engineers, 1993.

J. B. Heywood. I*nternal Combustion Engine Fundamentals*. New York: McGraw-Hill, 1988.

F. Jamerson, ed. *Physics in the Automotive Industry*. Philadelphia: Institute of Physics Publishing, 1981.

M. H. Westbrook and J. D. Turner. *Automotive Sensors*. Philadelphia: Institute of Physics Publishing, 1994 (see chapter 10).

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