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Development of the Volvo Lambda-Sond System

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DEVELOPMENT OF THE VOLVO LAMBDA-SOND EMISSION SYSTEM

During the last two decades there has been a continuous search for engine control systems to meet proposed exhaust emission standards in a cost effective way. Although several promising systems have been demonstrated with the ability to meet low exhaust emission requirements, most have been judged impractical due to fuel economy, cost and driveability considerations.

One system that simultaneously exhibits excellent exhaust emission control and fuel economy performance is the Volvo Lambda-sond system. The system utilizes a "three-way" catalytic converter, and an additional closed loop to the fuel injection system to provide feed-back control of the inlet air/fuel ratio.

DESCRIPTION OF PRODUCTION SYSTEM

Volvo has developed a three-way emission control system for its 2.1 litre 4 cylinder engine to meet the 1977 California exhaust emission requirements. In addition to excellent exhaust emission characteristics, the system has demonstrated good fuel economy and driveability compared with alternative control systems.

The Volvo application utilizes a feed-back control loop added to the normal CI (continuous injection) fuel injection system, and a "three-way" catalyst, as shown schematically in figure 1. Figure 2 shows the positions of major components in relation to the engine.

An oxygen sensor, situated at the exhaust manifold outlet, can detect the momentary oxygen level in the exhaust gas, which is an indication of whether the inlet A/F ratio is leaner or richer than stoichiometric ($\lambda = 1$). The sensor transmits a continuous non-linear electrical signal to the electronic control module which converts it into a control signal for the continuously oscillating on/off frequency valve. When the on/off bias time is altered the frequency valve raises or lowers the differential pressure over the metering slots in the fuel distributor, providing accurate and continuous control of the quantity of fuel injected.

The resulting accuracy and speed of response in mixture preparation, even under transient conditions (as in traffic driving), ensures that the exhaust gas fed to the catalyst is always within the very narrow composition band which enables the catalyst to operate in the "three-way" manner, thus achieving

ABSTRACT

Volvo has developed the first production emission control system to fully utilize a three-way catalyst. Called the "Volvo Lambda-sond system", it is applied to the 4-cylinder in-line B21 engine, and employs three essential new components - an exhaust gas composition sensor, an additional feed-back loop to the continuous fuel injection system, and the catalyst. Outstanding certification results were achieved, especially for NOx, combined with good driveability, power output, and fuel economy. The development and performance of the system, and the test procedures used, are described in detail, and its future potential and limitations are discussed.

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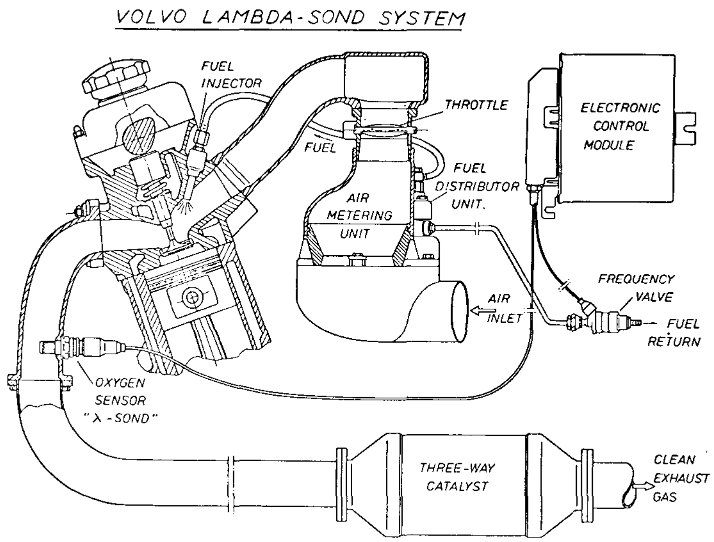

Fig. 1 - Volvo Lambda-sond system

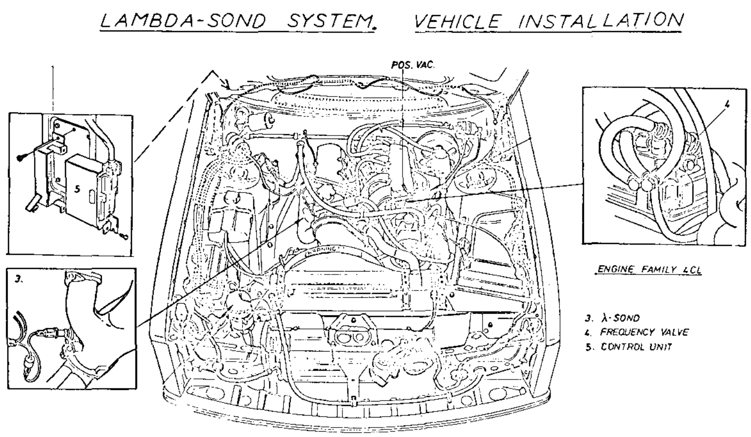

Fig. 2 - Lambda-sond system. Vehicle installation

simultaneous control of all three major pollutants HC, CO, and NOx.

The goal of this paper is to discuss the development process and the design restraints in the application of this three-way emission control system.

SYSTEM APPROACH

During the development of catalytic converters for exhaust gas aftertreatment it became evident that simultaneous conversion of all three presently regulated pollutants - hydrocarbons, carbon monoxide and oxides of nitrogen could be achieved in a single bed catalyst. Figure 3 shows the variation of HC, CO and NOx emissions from a spark ignited engine as a function of inlet A/F (air/fuel ratio) or λ (lambda) where

$$\lambda = \text{equivalence ratio} = \frac{\text{actual A/F}}{\text{stoichiometric A/F}}.$$

The solid lines show emissions before the con-

of all three pollutants is achieved within a very narrow A/F ratio band around the stoichiometric condition.

Present carburetors and fuel injection systems fall short of the required A/F ratio accuracy. To achieve the necessary accuracy and speed of response in mixture preparation under continuous transient engine operating conditions Volvo found it necessary to enhance the performance of the CI fuel injection system by adding a feed back control loop. (Figures 1, 6).

ALTERNATIVE SYSTEM STRATEGIES

Three alternative system strategies were initially evaluated. Two approaches used engine inlet A/F ratio modulation of the exhaust gases, while the third approach used a generally rich engine A/F setting with secondary air dilution of the exhaust gases.

The secondary air modulated system shown an airpump and an air valve. The feed rate of dilution air into the exhaust gas was controlled by an electromagnetic valve to give the proper mixture of exhaust components to provide for effective three-way conversion in the catalyst. Fuel setting always had to be on the rich side of stoichiometric.

The engine A/F modulated electronic fuel injection shown in figure 5 used an oxygen sensor mounted at the exhaust manifold outlet upstream of the three-way catalyst. A logic unit continuously corrected the injector opening duration to obtain stoichiometric A/F ratio. (1) (2)*

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*Numbers in parentheses designate References at end of paper.

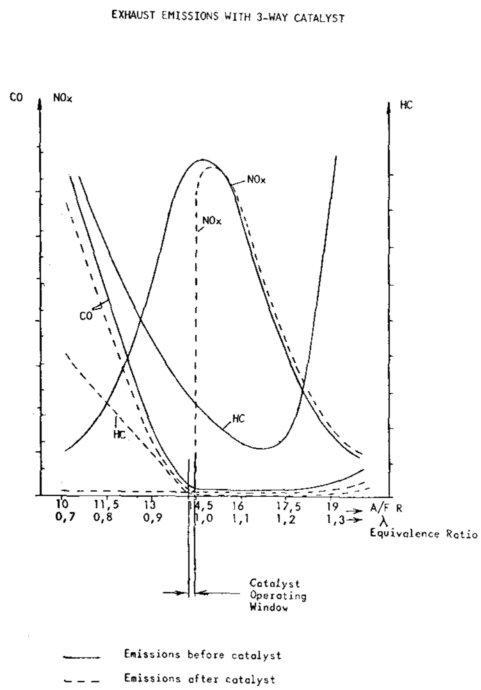
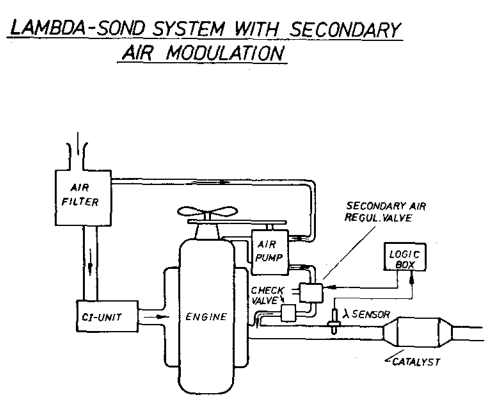


Fig. 3 - Exhaust emissions with 3-way catalyst

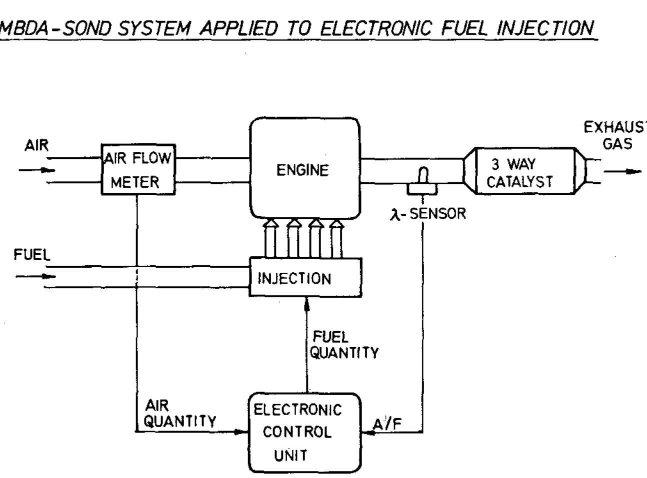


The mechanical fuel injection three-way control system shown in figure 6 also used an oxygen sensor mounted at the exhaust manifold outlet upstream of the three-way catalyst. A logic unit controlled an electromagnetic valve regulating the fuel governing pressure of the CI system to continuously achieve stoichiometric inlet A/F ratio, so that the exhaust gases were of the correct composition for the three-way catalyst to function.

The three concepts were evaluated for exhaust emissions, fuel economy, cost, weight, high altitude characteristics and driveability. Another important factor considered was compatibility with present production engine and fuel systems. These factors affecting the selection of a candidate system for further development are summarized in table 1. The secondary air modulated system was abandoned mainly because of its inability to achieve the required A/F accuracy in our testing. This was caused by long response time of the regulation system, but other negative factors were the need of a man-air-ox system, and inferior fuel economy due to rich engine A/F setting.

In combination with closed loop control both the electronic and the mechanical injection systems showed good potential for meeting future emission requirements. The traditional emission control systems such as EGR, air pump, and spark retard could be eliminated. The selection of the mechanical fuel injection approach was mainly due to its compatibility with existing engine systems, and to its good driveability. A further advantage was that the system continuously corrected the engine A/F ratio for production variations, atmospheric conditions, and fuel system drift between service intervals.

The implication of the above is to allow engine operation near ideal fuel economy and driveability, and the continuous correction of engine A/F ratio provides a low level of base engine exhaust gas pollutants for engines in



mass production, giving a good net conversion over the catalyst throughout the life of the car. It was therefore decided to initiate a project to develop a three-way emission control system based upon the CI (continous injection) fuel injection system. The objective was to develop a system that would meet future emission control standards in a cost effective way.

DESCRIPTION OF PROTOTYPE SYSTEM

THE OXYGEN SENSOR used in the initial evaluation was of the solid electrolyte type. As shown in figure 7 it was constructed from a cylindrical tube closed at one end. Generally, the ceramic tube is made of stabilized zirconium dioxide and acts as a solid electrolyte. Initially, the inside and outside were coated with platinum serving both as conductive electrodes to sense the electric potential over the sensor and as a catalyst. The outside of the sensor is exposed to exhaust gases and the inside to ambient air. A protective spinel layer is coated outside the outer platinum layer. (3) (4) (5)

The resulting electrical potential of the sensor varies from 700 millivolts under rich conditions to 100 millivolts under lean conditions. This produces an on-off type of signal around stoichiometric A/F conditions, as shown

LAMBDA-SOND SYSTEM APPLIED TO CI FUEL INJECTION

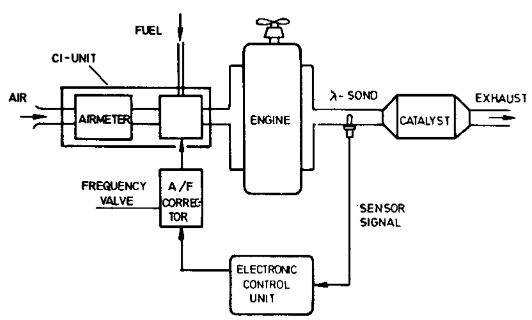


Fig. 6 - Lambda-sond system applied to CI fuel injection

in figure 8, which generally follows the Nernst equation:

$$E = RT/K \ln (P1/P2)$$

where E is the sensor signal in millivolts
R is a thermodynamic constant
T is absolute temperature
K is the efficiency factor
P1 is partial pressure of ambient oxygen
P2 is partial pressure of exhaust gas oxygen

After initial evaluation, the following design requirements for the oxygen sensor were found:

1. Ability to withstand exhaust temperatures up to 900^{o}C continuously.
2. Thermal shock resistance up to 50^{o}C/second.
3. Mechanical vibrations in all directions of 60 g.
4. Small characteristic changes for exhaust gas temperature between 350 and 800^{o}C.
5. Stable characteristic with ageing.

THE ELECTRONIC LOGIC SYSTEM is shown schematically in figure 9. Generally the sensor signal is compared with an electronic reference signal to produce the integrator output. The resulting integrator characteristic shown in figure 10 causes the A/F regulation system to oscillate continously around stoichiometric conditions.

THE AIR/FUEL REGULATION SYSTEM consists of an electromagnetic frequency valve which corrects the fuel flow by influencing the pressure drop over the fuel flow metering slots in the fuel distributor. The CI system itself (figure 11) is capable of controlling the A/F ratio within ± 3.5 % of stoichiometric, but much closer tolerances are necessary to enable a three-way catalyst to operate correctly. The initial approach of governing the fuel system regulating pressure was abandoned when it was found that direct regulation of the differential pressure over the fuel flow metering slots (which is normally kept constant in the CI system) offered a faster response time and extended control range, thus allowing full high altitude compensation on the lean side, without the addition of extra parts. Figure 12 illustrates the principle of this differential pressure control system.

Table 1 Prototype systems - selection for further development

System	Emissions HC	CO	NOx	Fuel economy	Altitude compensation	Driveability	Weight	Compatibility present product	Notes
	CVS g/mile								
Oxygen sensor Air pump module	0.2	6	2.0	poor	limited	good	fair	good	Can be used with carburetors
Oxygen sensor Electronic fuel* injection	0.2	2.5	0.4	good	yes	fair	good	poor	No mechanical regulation system required
Oxygen sensor Mechanical fuel injection	0.2	2.5	0.4	excellent	yes	good	good	good	

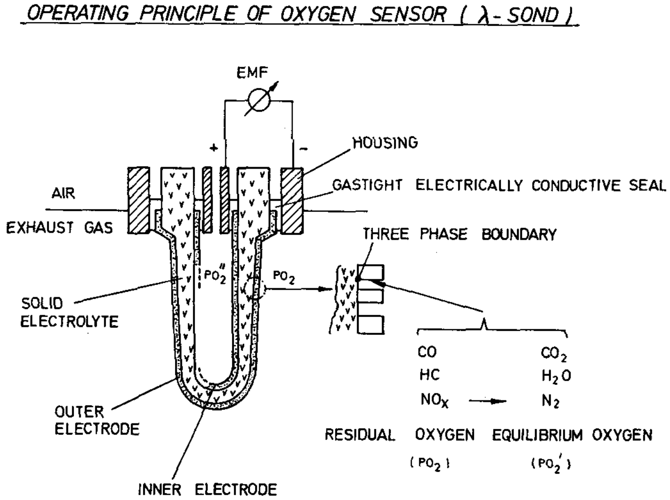


Fig. 7 - Operating principle of oxygen sensor (λ-sond)

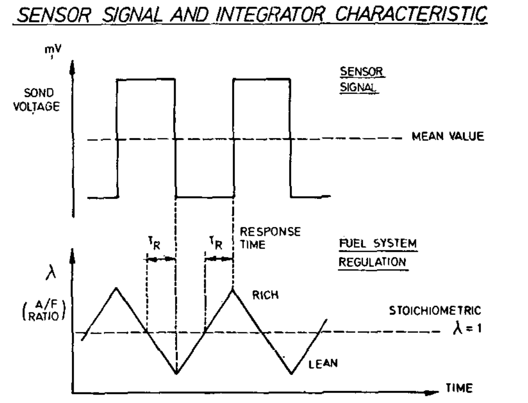


Fig. 10 - Sensor signal and integrator characteristic

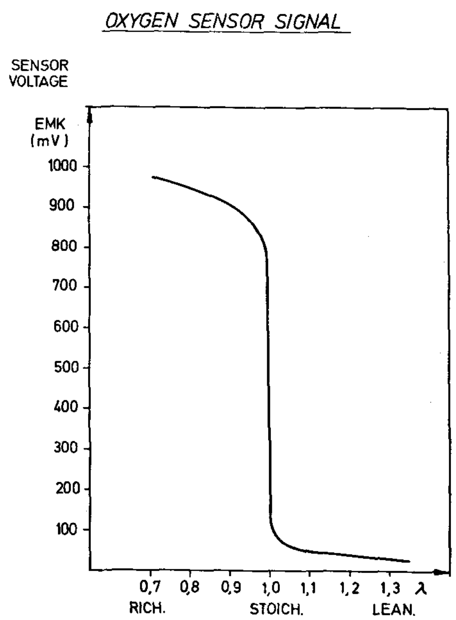


Fig. 8 - Oxygen sensor signal

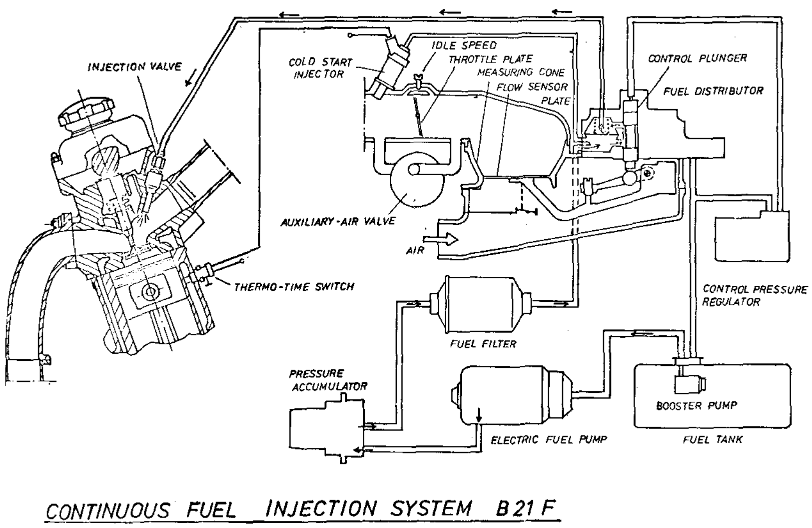
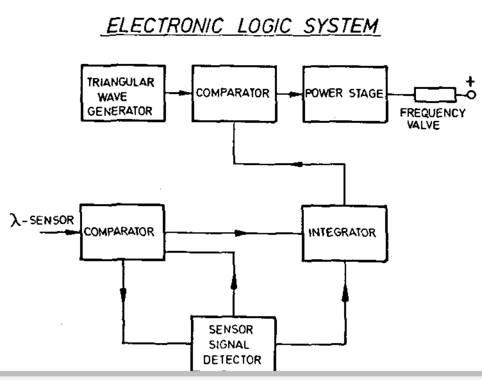
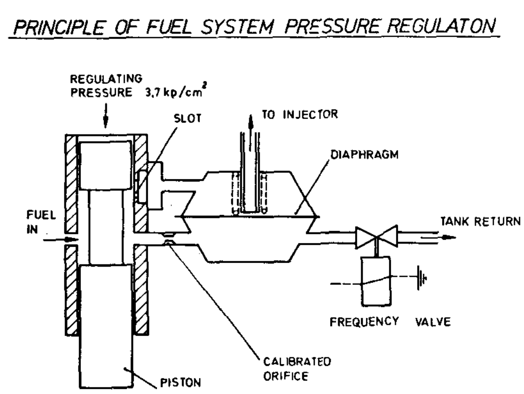


Fig. 11 - Continuous fuel injection system B21F





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