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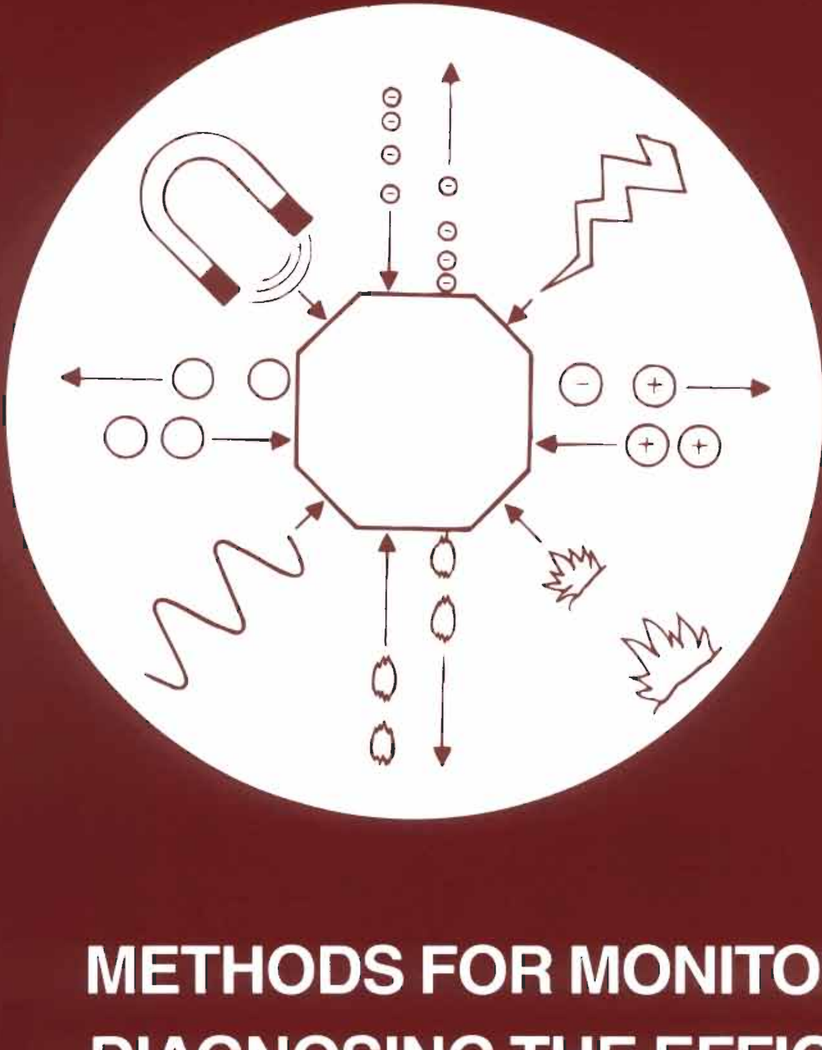

115

METHODS FOR MONITORING AND DIAGNOSING THE EFFICIENCY OF CATALYTIC CONVERTERS

A Patent - oriented Survey

Marios Sideris

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Advisory Editors: B. Delmon and J.T. Yates

Vol. 115

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Methods for Monitoring and Diagnosing the Efficiency of Catalytic Converters

Summary

The evolution of methods concerned with on-board (OBD) and non-OBD monitoring and diagnosing of efficiency of catalytic converters of internal combustion engines is described based on patents and published patent applications. Non-patent references are also used.

The basic principles of modern catalytic converters are described in an extensive Introduction, where the importance of monitoring and diagnosing the efficiency of catalytic converters is demonstrated.

The book is divided into four parts. The first part describes methods involving the use of oxygen or air/fuel ratio exhaust gas sensors to determine the oxygen storage capacity of a catalytic converter. The second part describes methods involving the use of temperature sensors to determine the exothermic reaction capacity of a catalytic converter. The third part describes all other methods existing in patent literature that monitor and diagnose the efficiency of catalytic converters. The great majority of the methods of the third part involves exhaust gas concentration measurements. The fourth part comprises a general discussion of all methods described.

In the beginning of each part, a short introduction is given to explain the problem that the methods attempt to solve. The methods in each part are presented in chronological order per patent applicant. This helps to evaluate how the patent applicant has improved his methods over time.

A patent number index with information about the patent applicants, inventors, priorities and patent-families, an inventor index, a company index and a subject index can be found at the end of the book.

Preface

The dramatic evolution of catalytic converters in the last thirty years was a result of a need worldwide to reduce pollution created by the exhaust gases of internal combustion engines. Environmental concerns have led American, Japanese and European Union (EU) legislation to pose continuously stricter emission limits for petrol engines in the last decades.

The catalytic converter has become the most important means of exhaust treatment to achieve the desired emission limits. The international legislation has also created a need for a regular assessment of the efficiency of the catalytic converter in order to detect a deterioration of its conversion efficiency as soon as this deterioration takes place. The assessment of conversion efficiency of a catalytic converter can take place during normal driving of a vehicle (on-board diagnosis or OBD) or in a workshop by specialized technicians. The most important methods nowadays are the OBD methods.

This book is an attempt to describe the evolution of methods concerned with on-board (OBD) and non-OBD monitoring and diagnosing of the efficiency of catalytic converters of internal combustion engines based mainly on patents and published patent applications. A limited amount of non-patent literature has been also used. All patent and non-patent documents cited in this book originate from the systematically classified documentation of the European Patent Office (EPO). For the Japanese patent literature the technical abstracts published in English by the Japanese Patent Office have been used.

The presentation has been focused on the sequence of steps used by each method to assess the conversion efficiency of a catalytic converter. Only a limited number of engine measuring set-ups and associated instruments used are described in detail to reduce the material to a manageable size. It should be noted that no verification of the feasibility of a method or a device or a measuring instrument or even the operation of a device or a measuring instrument is needed to render them patentable.

The methods in each part are presented in chronological order per patent applicant. This helps to evaluate how the patent applicant has improved his methods over time. The patent or patent application number, the name of the applicant and the date of publication are indicated for each document cited in the book. A patent number index, an inventors index, a company index and a subject index is found at the end of the book. A list of the non-patent literature used is also cited at the end of the book.

It is not unusual that the patent applications have been filed in several countries, each referring to a common first filing *i.e.* priority. These applications are said to belong to the same patent-family. In this book the earliest published document of a patent family has been selected to be cited. The reader may choose to consult a family document published in another language from the patent numbers index found at the end of the book.

The basic principles of modern catalytic converters are described in an extensive Introduction, where the importance of monitoring and diagnosing the efficiency of catalytic converters is proven.

The book is divided into four parts.
The first part describes methods involving the use of oxygen or air/fuel ratio exhaust gas sensors to determine the oxygen storage capacity of a catalytic converter.
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I would like to thank the editor, Simon Behmo, for his help and interest in this book, the directors Jean-Marie Schmitter and Hermann Nehrdich for their support, the director Roland Wohlrapp and my colleagues Simon Mansell, Alan Fordham, Peter Raven and Panos Triantaphillou for critically reading the manuscript and for their many helpful suggestions.

For permission to use certain figures and tables, thanks are extended to the Society of Automotive Engineers (SAE), to the Institution of Mechanical Engineers, to Springer-Verlag Wien-New York, to Elsevier Science B.V. and to the publishers of Automotive Engineer and Automobiltechnische Zeitschrift (ATZ).

I must not end without an expression of immense gratitude to my wife Virginia and to my sons Theodore and Dimitrios for their understanding and support which they have given me during the writing of this book.

Rijswijk, February 1998

Marios Th. Sideris

Contents

Symbols and Abbreviations

Latin

a	: amplitude
A	: Area
A/F	: air/fuel ratio
b	: amplitude
CA	: Crank Angle
CARB	: California Air Resources Board
C_P	: specific heat
CPU	: Central processing unit
DF	: Dilution factor
E	: Heat
ECU	: Electronic control unit
EHC	: Electrically Heated Catalyst
EGO	: Exhaust Gas Oxygen Sensor
EGR	: Exhaust Gas Recirculation
EPA	: Environmental Protection Agency of United States of America
EPO	: European Patent Office
f	: frequency
FTP	: Federal Test Procedure
HEGO	: Heated Exhaust Gas Oxygen Sensor
I	: Integral
I	: Electric current
I.C.E.	: Internal Combustion Engine
k	: constant
K_I	: integration correction amount
K_s	: skip correction amount
L	: length
LED	: Light emitting diode
LEV	: Low Emissions Vehicle
$\dot{m}$	: mass flow
MIL	: malfunction indication lamp
NEEGO	: Non-Equilibrium Exhaust Gas Oxygen Sensor
NEDC	: New European Driving Cycle
OBD	: On-Board Diagnostics
p	: phase shift
$\dot{Q}$	: mass flow, volume flow, heat transfer rate
S	: Area
SAE	: Society of Automotive Engineers
SOF	: Soluble Organic Fraction
SCR	: Selective Catalytic Reduction
t	: time

T : time, period, time delay, temperature
TDC : Top dead center
UEGO : universal exhaust gas oxygen sensor
ULEV : Ultra-Low Emissions Vehicle
V : Voltage, oxygen storage value, velocity
WIPO : World Intellectual Property Organization
$W_{sys}(s)$: Laplace transform transfer equation

Greek

$\Delta\lambda$: λ-1
λ : $\frac{\textit{existing oxygen content}}{\textit{stoichiometric oxygen content}}$ *or* $\frac{\textit{actual engine air / fuel ratio}}{14.7}$
ε : threshold
τ : time delay parameter
Φ_i : correlation function, deterioration index
Φ_j : complement function of Φ_i
Φ_{xx} : auto-correlation function
Φ_{xy} : cross-correlation function

Subscripts - Superscripts

1 : value referred to upstream sensor
2 : value referred to downstream sensor
air : air
cat : catalytic converter
f : filtered value
FB : Feedback value
FC : Fuel cut
HL : High load
in : value of a property entering catalytic converter
L : lean
lean : lean
lim : limit
mean : mean value
O2 : oxygen
R : rich
real : real
ref : reference value
rich : rich
tm : value calculated by means of a theoretical model
ε : threshold value
- : average

Note on Cited Patent Documents

An international two-letter country code is used for published patents and patent applications *i.e.*

AU	: Australia
BR	: Brazil
CA	: Canada
CH	: Switzerland
CN	: China
CZ	: Czechoslovakia
DD	: Deutsche Demokratische Republiek (DDR)
DE	: Germany (Federal Republic)
DK	: Denmark
ES	: Spain
EP	: European (EPO)
FR	: France
GB	: Great Britain
IT	: Italy
JP	: Japan
KR	: Korea
NL	: The Netherlands
NO	: Norway
RU	: Russia
SE	: Sweden
SU	: Soviet Union
US	: United States of America
WO	: World Intellectual Property Organization (WIPO)

The country code is followed by a one-letter publication code, *i.e.*

A	: First Publication Level
B	: Second Publication Level
C	: Granted Patent for DE documents
E	: Reissue Patent
T	: Translated
U	: Utility Model

Introduction

In order to meet increasingly stringent restrictions on the emissions of certain polluting gases by automotive internal combustion engines, it is common nowadays for the exhaust systems of such engines to include catalytic converters. The exhaust gas from the engine passes through such converters and pollutant gas constituents are converted into less undesirable gases by the catalytic action of the catalyst within the converter for venting to the atmosphere.

Catalytic action in general is the action of certain materials to provoke with their presence in a suitable environment chemical reactions, without themselves being modified by this reaction. In exhaust systems noble metals play the role of these catalytic materials (*catalysts*).

The dramatic evolution of catalytic converters in the last 30 years was a result of a need worldwide to reduce pollution created by the exhaust systems of internal combustion engines. Pollutants like nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons (HC) and particles (e.g. carbon) are produced from the incomplete combustion of the air/fuel mixture in the engine. These, in combination with the atmospheric conditions can lead to photochemical reactions which generate smog and contribute to the production of acid rain.

Studies in the United States have shown that about 10 per cent of vehicles are responsible for 50 per cent of the CO emissions at the sites studied. Besides, experience has shown that a desired durability (80000 Km) of anti-pollution systems of gasoline cars cannot be guaranteed with high confidence levels. Therefore, special emphasis is given to tailpipe inspections and maintenance programs ([1]). Environmental concerns have led American, Japanese and European Union (EU) legislation to pose continuously stricter emission limits for gasoline engines over the last decades.

Evolution of legislation

In general, petrol or spark-ignition engines emit oxides of nitrogen (NO and small amounts of NO_2 - collectively referred to as NO_x), carbon monoxide (CO) and organic compounds, which are unburnt or partially burnt hydrocarbons (HC). Compression-ignition or diesel engines emit smaller amounts of CO and HC, their main problem being particulate emissions

The Clean Air Act was the first law that sought to control auto emissions throughout the USA. This law set 1975 and 1976 exhaust requirements at

1.5 g/mile (0.93 g/km) for HC,
15 g/mile (9.37 g/km) for CO and
3.1 g/mile (1.93 g/km) for NO_x.

Emission levels were measured by the Federal Test Procedure (FTP) established by the U.S. Environmental Protection Agency (EPA).

The FTP '75 test cycle simulates an 11-mile driving cycle through Los Angeles at an average speed of 34.1 Km/h. The FTP test measures CO, HC and NO_x with a constant volume sampling system and involves a cold start after an engine sits idle for eight hours, a hot start and a combination of urban and highway conditions ([3]).

Fig. 1 shows the four phases of the American FTP '75 test cycle and the behavior of the HC in exhaust. The four phases of an engine according to this test cycle is: the cold start phase, the stabilized phase, the engine off phase and the warm phase. The upper part of the figure shows the variation of the velocity of the vehicle vs. time whereas the lower part of the figure shows the variation of HC emissions vs. time. It is obvious that from all phases, the cold start phase produces most of the HC emissions (80%) ([2]).

A change being assessed is to expand the FTP to include conditions that involve aggressive driving behavior at high speed and high acceleration, rapid fluctuation in speed, use of air conditioners and start-up after an engine is turned off for intermediate periods (e.g. 30 minutes). This will result in higher space velocities and greater concentrations of pollutants, which will place more demand on the converter.

Subsequent state and federal laws have set ever more stringent automobile emissions standards. Amendments to the Clean Air Act in 1990 phased in together standards over a period that extends well beyond 2000. After 1996, catalytic converters in new vehicles must last 100000 miles. The standards for 2004 are:

0.125 g/mile (0.078 g/km) non-methane HC

1.7 g/mile (1.062 g/km) CO
0.2 g/mile (0.125 g/km) NO_x.

California has even stricter laws. For example, non-methane HC emissions (NMHC) must be 0.075 g/mile (0.046 g/km) by 2000 in 96% of all cars. Through the remainder of the 1990s, California law stipulates standards for Transitional Low Emission Vehicles (TLEV), Low Emission Vehicles (LEV) and for Ultra Low Emission Vehicles (ULEV) (see [3], and [4]).

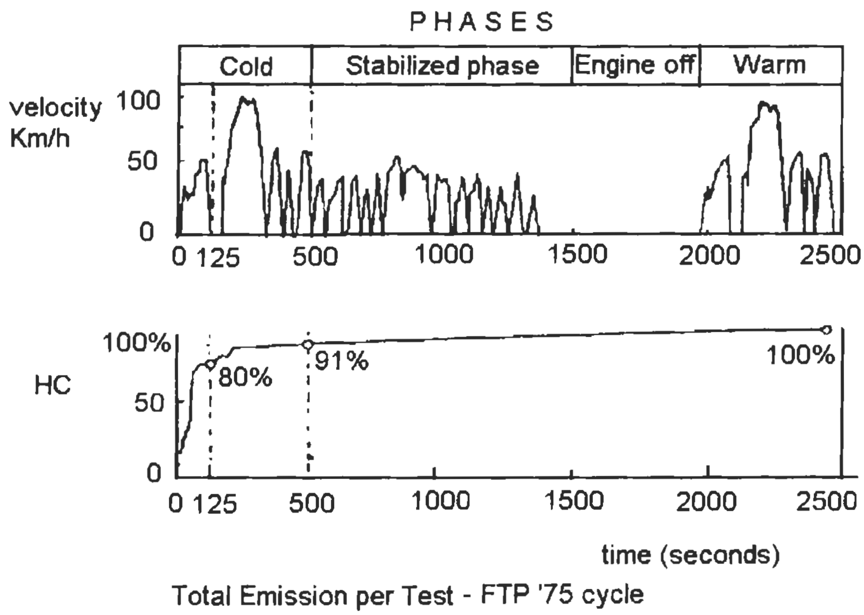


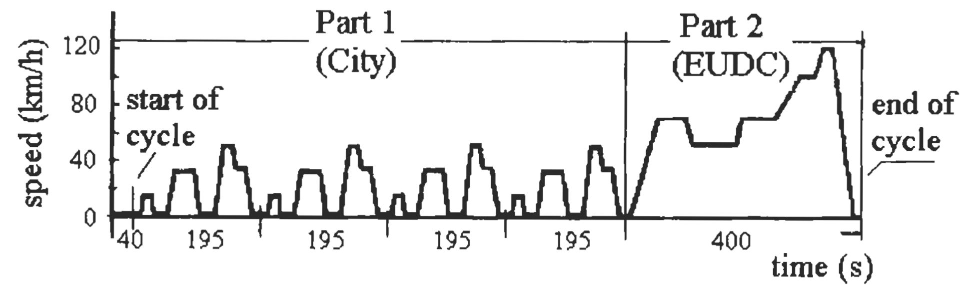
Fig. 1 (from [2], p. 19)

The first standards set in Europe to mandate the use of a catalytic converter were set by the EC93 standards. This brought European standards to levels comparable with those that were introduced in the USA in the 1980s.

In 1997, a second stage of European legislation was introduced for all new cars, covering both petrol and diesel engines. These standards brought EU rules into line with US standards introduced between 1994 and 1996.

A third state of legislation has been proposed by the European Commission to set emissions standards for 2000 and beyond. It comes as a draft directive, which also proposes that petrol vehicles with electronically controlled catalytic converters should be fitted with on-board diagnostic (OBD) systems that indicate when emissions are not conforming to standard and require further investigation ([5]).

Fig. 2 shows the so called New European Driving Cycle (NEDC) adopted in 1989, that is used in the European Union at the present and corresponds to the USA FTP '75 driving cycle of fig. 1 [34]. It has been applied since the beginning of 1993 to all passenger cars weighing less than 2500 kg. The driving cycle consists of two parts, a city driving part and an Extra Urban Driving Cycle (EUDC) part. The EUDC part uses car speeds up to 120 km/h. The city driving part consists of an extremely high idling time part (31%) and engine breaking and the mean driving speed is only 19 km/h. In this way the NEDC does not fulfil the aspect of a representative city driving and as it can be seen in fig. 3 it covers only a small part of a real engine operation field. This simply means that the emissions quantity allowed in this operation range of an internal combustion engine is limited by the law. The comparison of the FTP '75 and the NEDC cycles shows that the FTP '75 cycle comprises a higher collection of load and speed ranges when driving in the city than the corresponding European cycle (fig. 3).



test duration : 1220 s
test length : 11,007 km
average cycle speed : 32.5 km/h
max. speed : 120 km/h

Fig. 2 (from [34], p. 161)

Table 1 shows the European exhaust emission standards (restrictions) for passenger cars for the four main pollutants i.e. carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (HC) and particles. The EC96 (EURO II) is the current European standard (effective January 1997), whereas the EC2000 (EURO III) and EC2005 (EURO IV) correspond to the proposed

European standards to be met in years 2000 and 2005 respectively (see also European directive 94/12/EEC). The last four columns correspond to the current USA Federal emission standards (1996), to the Californian TLEV (1996-1998+), LEV (2000) and ULEV (2005) emission standards.

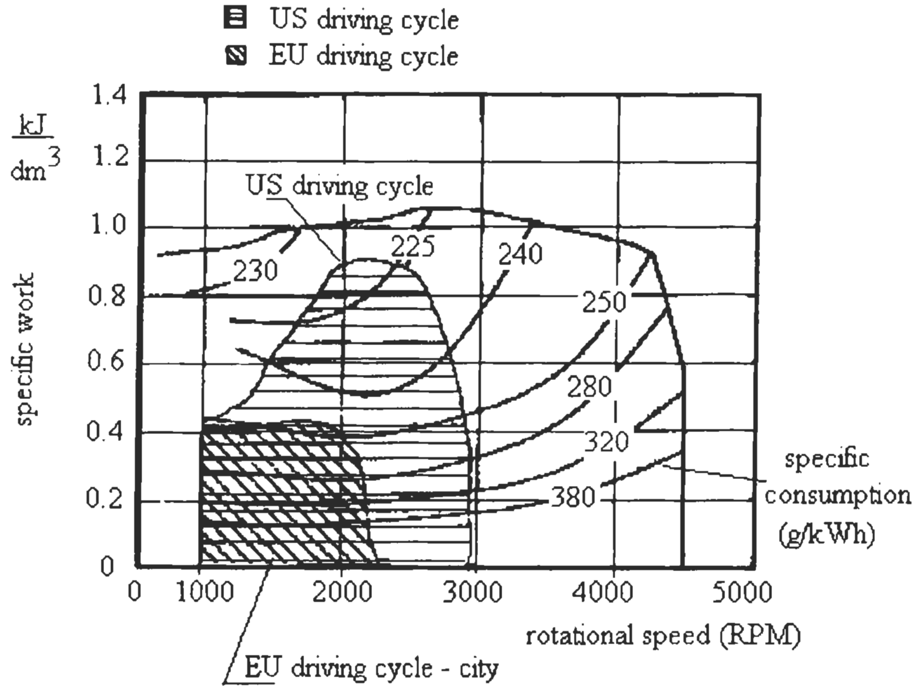


Fig. 3 (from [34], p. 162)

As Table 1 shows, in some respects the draft 2005 European regulations are more severe than the Californian ULEV standards, which until now have been seen as very close to the limit of what is technically feasible for the internal combustion engine. The proposed European 2005 limit of 0.25 g/km NO_x for light duty diesel engines is completely beyond the diesel's technology reach unless one key technology, the NO_x reduction catalytic converter, can be brought to full effectiveness and to production in the meantime. It must be borne in mind that the driving cycles of EC2005 and ULEV involved differ significantly (see [6] and [7]). For the TLEV, LEV and ULEV standards the HC is measured as non-methane organic gases (NMOG).

The current European exhaust emissions standards for heavy duty diesel vehicles over 3.5 tons (EURO stage II, effective October 1996) are:

CO 4.0 g/kWh,
HC 1.1 g/kWh
NO_x 7.0 g/kWh and
particles 0.15 g/kWh.

The German government has introduced incentives to encourage early adoption of the 2000 limits. It recently brought in tax incentives for the retro-fitting of existing vehicles with closed-loop three-way catalytic converters (petrol) or oxidation catalytic converters (diesel).

Similar standards like the ones of Europe and the USA have been adopted by Japan. However, the testing cycles in all three regions differ from each other, because the authorities try to reproduce conditions more typical of their own traffic patterns.

Emission standards like the ones of EC96 can be met only by making use of catalytic converters and especially three-way catalytic converters.

As shown in Table 1, compression-ignition or diesel engines produce smaller amounts of CO and HC than petrol engines, their main problem being particulate emissions. The NO_x emissions are comparable for the two engines, however the diesel engines emit significantly fewer hydrocarbons than the petrol engines. The different composition of pollutants of the exhaust gases for petrol and diesel engines has led to a different catalytic converter technology for each type of engine.

Before handling the problem of monitoring of catalytic converters, a few elements concerning the technology of catalytic converters will be presented below. Most of the technology described in this book refers to spark-ignition (petrol) engines. However a few elements concerning diesel engines are also described.

Type of engine	*Pollutant*	*EC96 Euro Stage II (g/km)*	*EC2000 Euro Stage III (g/km)*	*EC2005 Euro Stage IV (g/km)*	*US Federal emission standards (1996) (g/mile)*	*TLEV (1996-1998+) (g/mile)*	*LEV (2000) (g/mile)*	*ULEV (2005) (g/mile)*
	CO	2.2	2.3	1	3.4 / 4.2	3.4 / 4.2	3.4 / 4.2	1.7 / 2.1
	HC + NO_x	0.5	N/A	N/A				
	HC	N/A	0.2	0.1				0.04
Petrol	NO_x	N/A	0.15	0.08	0.4 / 0.6	0.4 / 0.6	0.2 / 0.3	0.2 / 0.3
	NMHC*				0.25 / 0.31			
	NMOG**					0.125 / 0.156	0.075 / 0.090	0.04 / 0.055
Diesel indirect injection	CO	1	0.64	0.5				
	HC + NO_x	0.7	0.56	0.3				
	NO_x	N/A	0.5	0.25				
	Particles	0.08	0.05	0.025				
Diesel direct injection	CO	1	0.64	0.5				
	HC + NO_x	0.9	0.56	0.3				
	NO_x	N/A	0.5	0.25				
	Particles	0.1	0.05	0.025				
Durability		80000 km	80000 km	80000 km	50000 miles (or 5 years) / 100000 miles (or 10 years)	50000 miles (or 5 years) / 100000 miles (or 10 years)	50000 miles (or 5 years) / 100000 miles (or 10 years)	50000 miles (or 5 years) / 100000 miles (or 10 years)

*NMHC: Non-methane hydrocarbons **NMOG: Non-methane organic gases

Table 1: European and American Exhaust Emission Standards for Passenger cars

Materials used in catalytic converters

A catalytic converter for an internal combustion engine comprises in general three main elements: the ceramic or metallic support, the alumina washcoat (usually stabilized gamma alumina γ-Al_2O3) and the noble metal (fig. 4). Single or double washcoats may be applied. Double coats are used to enhance specific reactions and improve durability by separating components of the catalyst [3]. The coated substrate is air dried and calcined to about 450-500 °C to ensure good adhesion. Washcoat thickness, which ranges from 20-60 μm, is engineered for minimal diffusional resistance, so gases readily reach the catalytically active sites. It is also configured for maximum resistance to contaminants, many of which deposit in the outer 10 to 15 μm of the washcoat. The washcoat is 5-15% of the converter weight and has a surface area of 100-200 m^2/g.

The noble metals are impregnated into the highly porous alumina washcoat. Active catalytic converters contain about 0.1 to 0.15% noble metals. The most commonly catalytic materials (noble metals) used in the automotive industry are Platinum (Pt), Rhodium (Rh), Palladium (Pd) and Ruthenium (Ru), which become efficient for temperatures over 140 °C. The quantity of noble metals contained in a catalytic converter is 2-3 grams.

Recent trends in improvement of the catalyst relevant properties of the fuels available in the U.S.A and Europe, along with the wide application of advanced engine management systems with a capability for much tighter air/fuel control close to stoichiometry (air/fuel ratio=14.7) , lead to the use of tri-metal catalysts (Pt, Rh, Pd).

Other materials used are common metals like Nickel (Ni), Chromium (Cr) and Copper (Cu). The disadvantage of these metals is that they become efficient at temperatures over 400 °C ([8]).

In oxidation catalytic converters for diesel engines, a silica washcoat is preferred over alumina in order to minimize sulfate production. Also, Palladium (Pd) is preferred over Platinum (Pt) for the same reasons.

A catalytic converter has an *oxidizing function* to transform chemically the carbon monoxide (CO) in carbon dioxide (CO_2) and the hydrocarbons (HC) to carbon dioxide (CO_2) and water (H_2O) according to the chemical reactions:

$$2\ CO + O_2 \rightarrow 2\ CO_2$$

$$C_X H_Y + \alpha\ O_2 \rightarrow \beta\ CO_2 + \gamma\ H_2O$$

A catalytic converter can also have a *reducing function* by accelerating the reaction of hydrogen (H_2) and carbon monoxide (CO) with nitrogen oxides (NO_x) to produce nitrogen (N_2) and carbon dioxide (CO_2) according to the chemical reaction:

$$2\ NO + 2\ CO \rightarrow N_2 + 2\ CO_2$$

Platinum and palladium promote the oxidation of CO and HC whereas rhodium promotes the reduction of NO_x.

Other chemical reactions that may take place on the surface of a catalytic converter are:

$$CO + H_2O \rightarrow CO_2 + H_2$$

$$2\ H_2 + O_2 \rightarrow 2\ H_2O$$

$$SO_2 + 3\ H_2 \rightarrow H_2S + 2\ H_2O$$

An alternative approach for catalytic conversion of NO_x in selective catalytic reduction (SCR) catalytic converters for diesel engines, is selective reduction using hydrocarbons. The reaction using propylene as model reactant is:

$$2\ NO_x + C_3H_6 + \frac{7}{2}\ O_2 \rightarrow N_2 + 3\ CO_2 + 3\ H_2O$$

The resistance of palladium against poisoning by lead and sulfur is considerably inferior to that of platinum and rhodium.

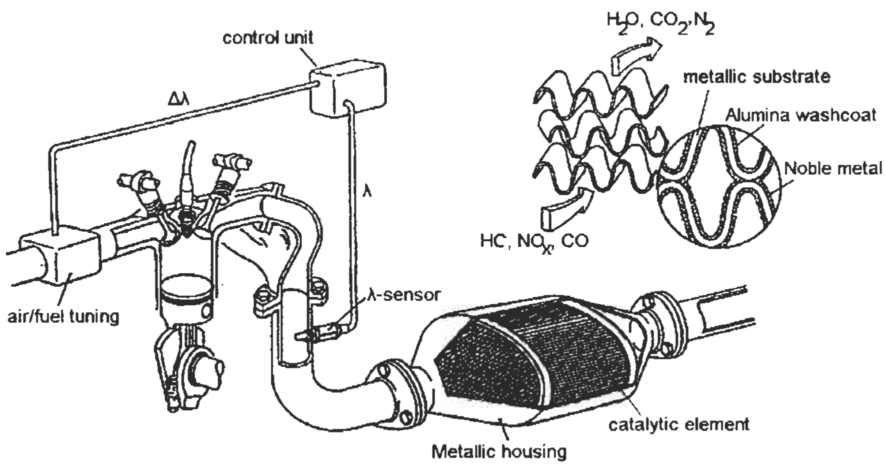


Fig. 4 (from [8], p. LXVII)

In addition to the noble metals, the alumina washcoat of a three-way catalytic converter also contains other components like La_2O_3 and/or BaO, which function as catalytic promoters or stabilizers against aging. La_2O_3 and BaO consist 1 to 2% of the washcoat. *Cerium* is normally present in high quantities in the washcoat in the form of CeO_2 (10 to 20%) and has multiple functions: stabilization of the washcoat layer and improvement of thermal resistance, enhancement of noble metal catalytic activity, promotion of the water gas shift reaction and an oxygen storage component. Iridium has remarkable activity for NO_x reduction under net oxidizing conditions but it tends to form volatile oxides. Ruthenium and Nickel have catalytic properties for NO_x reduction, as already mentioned, and nickel is also capable of suppressing H_2S formation ([9]).

An interesting historical overview of the development of materials for catalytic converters can be found in [3].

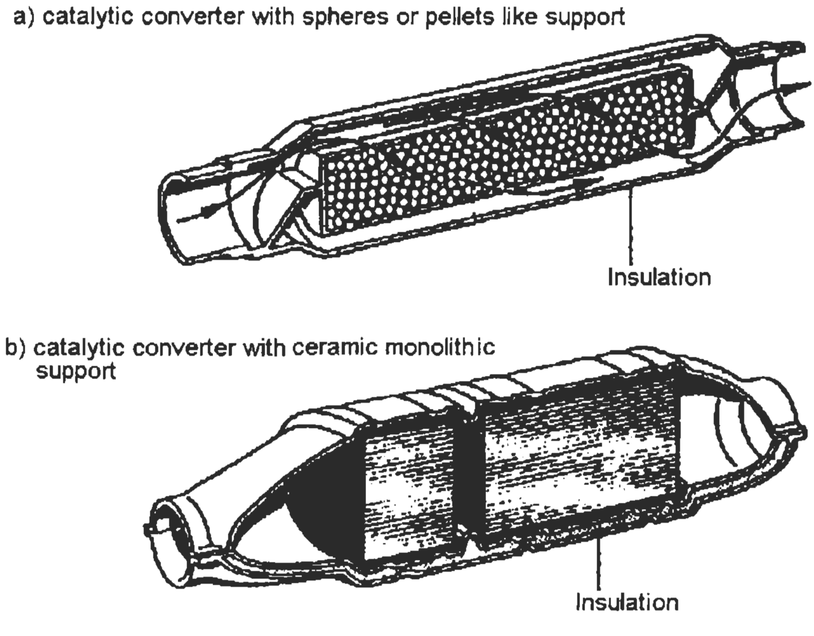


Fig. 5 (from [8], p. LXVII)

The substrate of a catalyst can be in the form of a metallic honeycomb (fig. 4). This usually consists of flat and corrugated metal sheets stacked one on top of the other which are fixed together (e.g. by welding). Other forms of the substrate are: pellets or spheres (fig. 5a) or ceramic monoliths (fig. 5b).

A typical monolith has square cross section channels with inside dimensions of the order of 1 mm separated by thin (0.1-0.15 mm) porous walls. The number of channels per cm^2 varies between 60 and 100, although even higher cell densities of the order of 200 channels per cm^2 have been demonstrated for metallic honeycombs.

At high operation temperatures of the catalytic converter, heat is transferred from the converter to the environment. This heat loss occurs via convection (free and forced) and radiation from the converter shell. For this reason insulation material is inserted between the substrate and the housing for thermal protection of the environment.

In the case of ceramic monoliths, a resilient mat is also provided between the housing and the substrate in order to protect the substrate from being damaged from vibrations or shocks (see e.g. patent disclosures **EP0492083 (1992)**, **EP0505720 (1992)**, **DE19509029 (1995)**).

Types of catalytic converters

There are three main types of catalytic converters used in spark-ignition engines, which are described in detail in [8].

A "*one-way or oxidation catalytic converter*" (fig. 6a) oxidizes the unburned CO and HC in the exhaust gases and converts them in CO_2 and H_2O. In fuel injection engines the necessary oxygen for the oxidation is simply received by increasing the quantity of air in the engine air/fuel mixture. In engines which use carburetors, a supply of secondary air in the exhaust pipe upstream of the converter is necessary.

A "*two-way catalytic converter*" (fig. 6b) comprises two consecutive catalytic bodies. The first body is used to convert NO_x to ammonia (NH_3). The second body converts non-burnt and partially burnt hydrocarbons (HC) to water and carbon dioxide (CO_2) and carbon monoxide (CO) to CO_2 by oxidation. The regulation of the engine air/fuel mixture becomes necessarily rich (excess of fuel) in order to convert the NO_x. The supply of secondary air between the two bodies may transform a part of NH_3 back to NO_x. The system is not optimal, but it can be used in the case of engines with carburetors without electronic control.

A "*three-way catalytic converter*" (fig. 6c) has the capability to eliminate efficiently the three basic pollutants CO-NO_x-HC. The main condition is that the engine air/fuel mixture should be kept stoichiometric (14.7 gram air for 1 gram of petrol), which is the theoretical proportion for a complete combustion of the mixture. The coefficient λ (definition of λ - see next chapter) characterizes the importance of the difference between the real air/fuel ratio and the ratio theoretically needed. This condition is satisfied by making use of a λ (lambda) sensor or an oxygen sensor upstream of the catalytic converter (fig. 4 and fig. 5c). These sensors detect the composition of the exhaust gases. An electronic unit receives the output signal of the λ or the oxygen sensor and corrects the quantity of fuel injected to the engine. Three-way catalytic converters are the most commonly used converters nowadays.

As shown in fig. 7, the three-way catalytic converter removes three pollutant in the exhaust gases, i.e., NO_x, HC, and CO at the same time by reducing NO_x and oxidizing HC and CO, when the air-fuel ratio of the exhaust gas is the stoichiometric air-fuel ratio. However, when the air/fuel ratio of the exhaust gas becomes rich compared to the stoichiometric air-fuel ratio, the ability of the three-way catalytic converter to oxidize HC and CO becomes low, and when the air-fuel ratio of the exhaust gas becomes lean compared to the stoichiometric air-fuel ratio, the ability of the three-way catalytic converter to reduce NO_x becomes low.

The rate of decrease in the ability to reduce NO_x when the air-fuel ratio is lean is more rapid than the rate of decrease in the ability to oxidize HC and CO when the air-fuel ratio is rich. Therefore, when the air-fuel ratio of the exhaust gas periodically swings between rich and lean under the air-fuel ratio control, as explained in next chapter, the purification of the NO_x by the three-way catalytic converter becomes insufficient when the air-fuel ratio is lean (see e.g. **EP0627548 (1994)**).

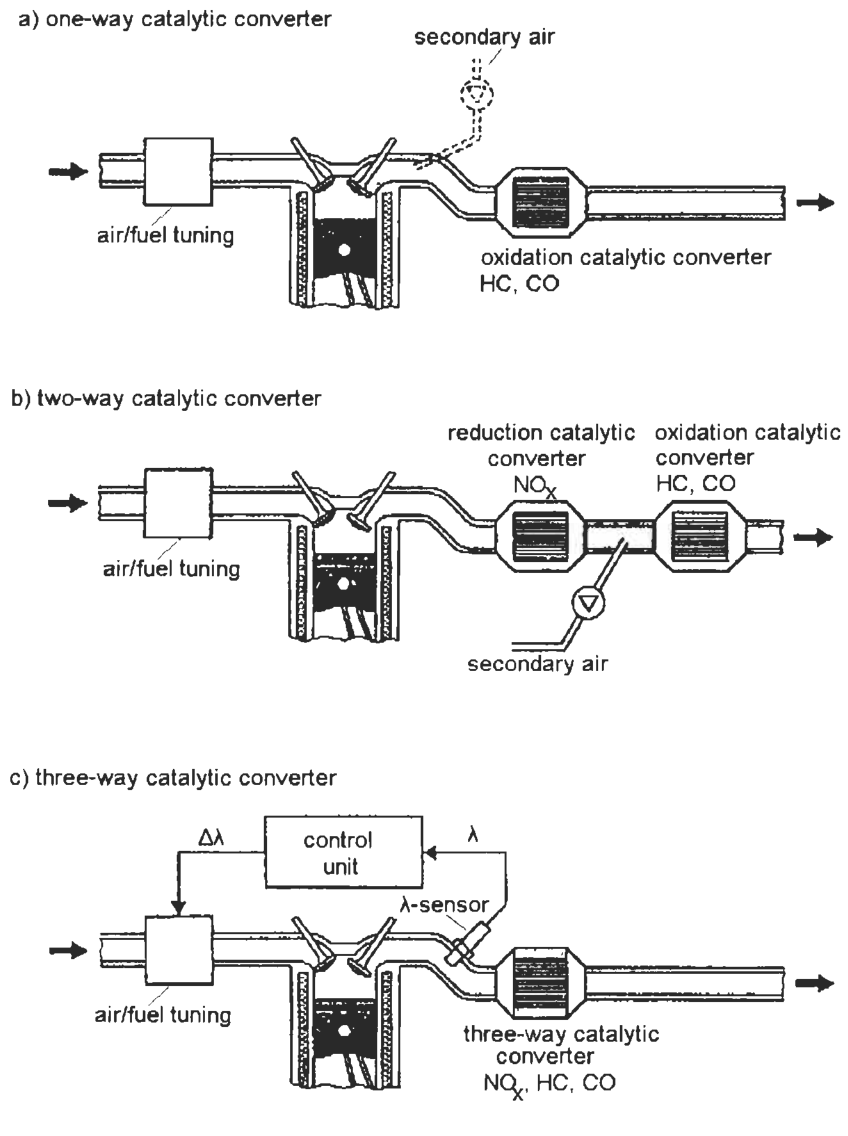


Fig. 6 (from [8], p. LXVII)

Further, when the concentration of NO_x in the exhaust gas becomes low, the ability of the three-way catalytic converter to purify NO_x in the exhaust gas becomes low since the possibility of the NO_x molecules in the exhaust gas being reduced on the catalytic converter becomes lower as the concentration of the NO_x in the exhaust gas becomes lower. Therefore, even if two catalytic converters are disposed in the exhaust passage in series, the ability of the catalytic converter disposed downstream becomes very low since a large part of NO_x in the exhaust gas is already removed before flowing into the downstream catalytic converter by the upstream catalytic converter, and the concentration of NO_x in the exhaust gas flowing into the downstream catalytic converter becomes low. Thus, it is difficult to increase the ability of the catalytic converter to remove NO_x in the exhaust gas by using two three-way catalytic converters in series when the air-fuel ratio of the exhaust gas is lean.

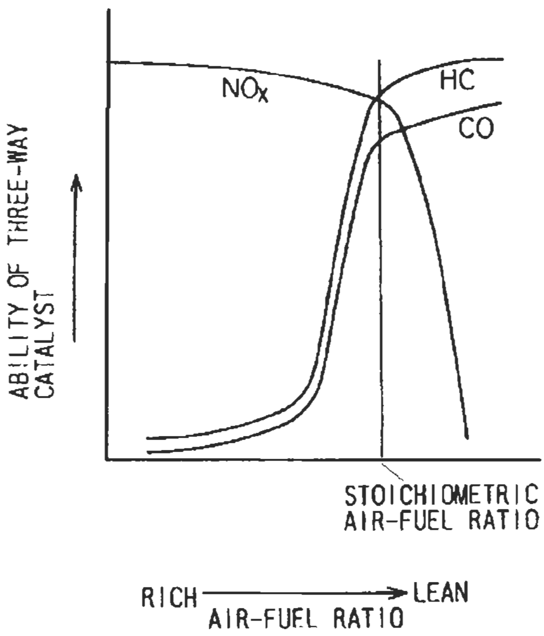


Fig. 7 (from EP0627548)

Examination of modern trends shows that designs are concentrated on operation at air/fuel ratios leaner than stoichiometric for fuel economy benefits and reduction of CO_2 emissions. Nowadays, *lean-burn* four-stroke, two-stroke and diesel engines operate at air/fuel ratios greater than 20:1. Conventional three-way converters control the CO and HC at these air/fuel ratios but they cannot control the emissions of NO_x since they must operate at stoichiometric air/fuel ratios to obtain simultaneous control of all emissions. A great effort is put on the development of converters that can control NO_x emissions with lean calibrations. The development of a catalyst system that could control NO_x under a lean operation of a diesel engine (14.5<air/fuel ratio<22) would be a significant breakthrough (lean NO_x catalytic converter).

The new catalysts are based on zeolites containing active metals exchanged within the zeolite structure e.g. zeolite converters containing platinum, rhodium and iridium (see e.g. [10]).

A recent trend to control exhaust emissions is to install a *NO_x absorbent* downstream of the three-way catalytic converter. This absorbs NO_x when the engine operates with a lean air/fuel ratio and releases NO_x when the engine operates with a rich air/fuel ratio. The CO and HC passing through the three-way catalytic converter during the rich operation reduce then the NO_x released from the absorbent (see e.g. **EP0627548 (1994)**, **US5388403 (1995)**).

Fig. 8a and fig. 8b explain the mechanism of the absorption and the releasing operation of NO_x in the case where platinum Pt and barium Ba are carried on the carrier of the absorbent, as an example, but it is considered that a similar mechanism is also applied even if other precious metal, alkali metals, alkali earth metals, or rare earth metals are used.

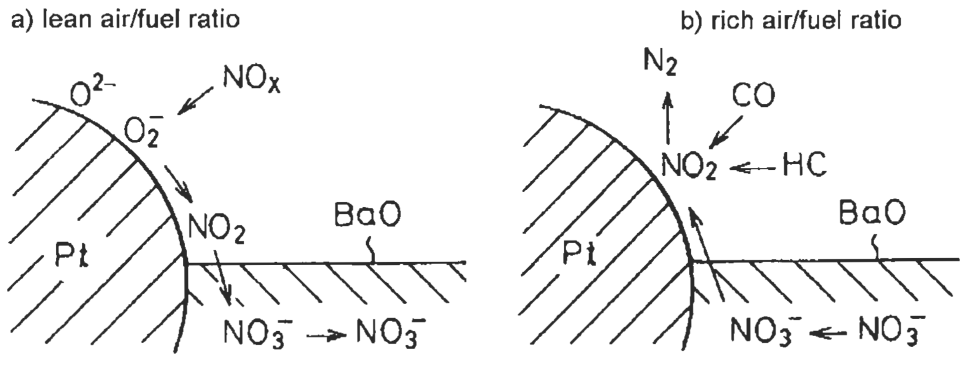


Fig. 8 (from EP0627548)

When the air-fuel ratio of the in-flowing exhaust gas is lean (fig. 8a), the oxygen is deposited on the surface of platinum Pt in the form of O_2^- or O^{2-} which react with NO to produce NO_2 ($2NO + O_2 \rightarrow 2NO_2$). Then, a part of the produced NO_2 is oxidized on the platinum Pt and absorbed into the NO_x absorbent. While bonding with the barium oxide BaO, it is diffused in the absorbent in the form of nitric acid ions NO_3^- (fig. 8a). In this way, NO_x is absorbed in the NO_x absorbent.

When the oxygen concentration in the in-flowing exhaust gas is lowered, the production of NO_2 is lowered and the reaction proceeds in an inverse direction ($NO_3^- \rightarrow NO_2$), and thus nitric acid ions NO_3^- in the absorbent are released in the form of NO_2 from the NO_x absorbent. In this case, components such as HC and CO, which exist in the exhaust gas, react with the oxygen O_2^- or O^{2-} on the platinum Pt and are oxidized. After oxygen O_2^- or O^{2-} on the platinum Pt are consumed by HC and CO in the exhaust gas, NO_x released from the NO_x absorbent as well as NO_x emitted from the engine are reduced by the HC and CO remaining on the platinum Pt. This oxidation of the HC and CO consumes the oxygen component existing near the NO_x absorbent, and the concentration of oxygen in the atmosphere around the NO_x absorbent is lowered. Also, the NO_2 released from the NO_x absorbent reacts with the HC and CO in the exhaust gas as shown in Fig. 8b and is reduced to N_2. In this way, when the NO_2 on the surface of the platinum Pt reacts with HC and CO in the reducing agent, and when the NO_2 no longer exists on the surface of the platinum Pt, the NO_2 is successively released from the absorbent. Accordingly, when HC and CO components exist in the in-flowing exhaust gas, the NO_x is released from NO_x absorbent and quickly reduced to N_2. The HC and CO component in the exhaust gas immediately react with the O_2 or O^{2-} on the platinum Pt and are oxidized, and subsequently if the HC and CO still remain after the O_2^- or O^{2-} on the platinum Pt are consumed, the NO_x released from the absorbent and the NO_x emitted from the engine are reduced.

In diesel engines, oxidation catalytic converters are used to convert a large part of the hydrocarbon constituents of the soluble organic fraction (SOF), as well as gaseous HC, CO, odor creating compounds and mutagenic emissions.

The NO_x reduction in diesel engines and lean-burn petrol engines is achieved by the so called selective catalytic reduction (SCR) catalytic converters. A reducing agent is introduced in the exhaust gases upstream of the catalytic converter to promote reduction of the NO_x. Such reducing agents are: hydrocarbons, ammonia, urea, hydrogen etc. More information on supplying reducing agents to the exhaust gases can be found in **EP0709129 (1996)**, **EP0737802 (1996)**, **EP0723805 (1996)**, **EP0537968 (1993)**, **EP0498598 (1992)**.

In some other cases like the one described in **EP0510498 (1992)**, an ammonia synthesizing catalytic converter is introduced in the exhaust system that transforms part of the NO_x of the exhaust gases to ammonia. The ammonia produced plays the role of a reducing agent and reacts with the remaining of nitrogen oxides of the exhaust gases to produce nitrogen so no external addition of ammonia is necessary.

Other ways to reduce NO_x in the exhaust gases is to recirculate part of the exhaust gases (e.g. 10%) back to the engine or to inject water in the combustion chamber. The recirculation systems are called EGR (Exhaust Gas Recirculation) systems. The recirculated exhaust gas decreases the flame temperature in the engine cylinder and provides a shortage of oxygen in the combustion chamber that does not allow the formation of NO_x. Water also reduces the flame temperature inside the diesel engine cylinder and contributes to reduction of NO_x. However, both methods complicate considerably the control of the engine and a lot of additional components and instrumentation must be added to the engine system [33].

As already shown in Table 1, the main pollutant of diesel engines is the particulate matter (soot). Particles are captured in filters or traps. The accumulated particulate raises filter backpressure, i.e. the pressure difference across the filter or trap which is necessary to force the exhaust through it. The filters are cleaned periodically by oxidizing the collected particulate (regeneration of filter) to decrease the high backpressure. In modern diesel engines catalytic coated filters and oxidation catalysts are used to eliminate particulate matter from the exhaust gas.

Table 2 summarizes the application of catalytic converters in different technology engines ([9]).

Pollutant	***Spark-ignition engine***	***Lean-burn spark-ignition engine***	***Diesel engine***
CO	Precious metal loaded three-way catalytic converter	Precious metal loaded oxidation catalytic converter	oxidation catalytic converter
HC	three-way catalytic converter	oxidation catalytic converter	oxidation catalytic converter
NO_x	three-way catalytic converter	lean zeolite based or precious metal loaded NO_x reduction catalytic converter	lean NO_x reduction catalytic converter
Particulate			Filter regeneration aid (catalytically coated filters, fuel additives to lower filter regeneration temperature)

TABLE 2: Application of catalytic converters in different technology engines

Control of catalytic converters during a cold engine start-up

The temperature of the exhaust gas in a warmed-up spark-ignition engine can vary from 300 to 400 °C during idle, to about 1000 °C in full load operation. The temperature of the exhaust gas of a warmed-up compression-ignition (diesel engine) contains a substantial quantity of oxygen and is at lower temperatures (100-700 °C). However, during a cold engine start up, the temperature of the catalytic converter is very low and the converter is not activated. Till the moment that the activation (light-off) temperature of the converter is attained (~200-300 °C), the HC and CO produced by the engine are not converted and contribute to a high pollution of the atmospheric air. About 60-80% of existing HC emissions are produced from the time that the converter takes to start operating after vehicle ignition (fig. 1) for both the FTP '75 cycle and the New European Driving Cycle (NEDC). This problem is discussed in detail in [2, 7, 9-12].

Two main approaches exist to face this problem:

a) *active approach*, which relies on the controlled supply of additional energy to raise exhaust gas temperature during cold start-up and consequently to the accelerated activation of the catalytic bodies. Systems like electric heaters, afterburners and fuel burners belong to this category.

b) *passive approach*, which relies on the employment of exhaust system design changes in order to reduce cold start-up emissions (e.g. positioning of the catalytic converter closer to the engine, use of secondary converters, HC adsorbents, heat storage systems and heat exchangers and insulated exhaust pipes to reduce the heat transfer of the exhaust gas between engine and catalytic converter)

Electric heaters

An electric heater is installed upstream or inside the converter, or the converter itself consists of electrically conductive material that can be heated if supplied with electric current (fig. 9d). The addition of secondary air assists the oxidation of HC and CO and consequently to the warming of the converter. In many cases, an electrically heated secondary converter (EHC) is installed upstream of the main converter (fig. 9e). This EHC converter is of a small volume and can be heated up very fast. It oxidizes the HC and the CO of the exhaust gases and the heat produced warms up the main catalytic converter.

The heater is provided with electric current from the battery or the alternator of the vehicle. The typical car battery is not a practical power source to supply the electrical power needed because the electrical load on the vehicle battery during the period required may exceed the rated battery output. Also, there is a measurable delay between the time the operator places the ignition switch in thc "on" position and the time the heater brings the converter to the light-off temperature. An alternator powered electrically heated catalytic converter (APEHC) still requires a 5 to 10% increase in battery capacity to cope with the EHC start-up scenario.

The development target is to obtain an electrical power consumption of 1 kW. Up to now this target has not been reached and electrical power of 3-4 kW is still required for larger engines. This leads to an unacceptable increase in size of the engine generator system or else in the battery (see [2]).

An alternative solution is to expose the upstream part of the catalytic converter to an alternating magnetic field or to electromagnetic radiation having such a frequency that the washcoat of the converter and the particles dispersed in the washcoat are heated to light-off temperature without a corresponding increase in the temperature of the entire converter. A magnetron producing microwave radiation can be used for this purpose (see **WO9014507 (1990)**).

Afterburners

An afterburner can be also installed upstream of the catalytic converter. In this case during cold engine start up, the engine operates with a rich air/fuel mixture and air is introduced in the exhaust pipe (fig. 9f). An ignition plug ignites the produced air/fuel mixture upstream of the catalytic converter and the heat produced warms up the converter. Such a method is described in [13]. The solution of an afterburner can produce smoke and the combustion is not very reliable.

Fuel burners

In the case of fig. 9g, a fuel burner is positioned parallel to the exhaust pipe and near the converter. The burner consists of a burning chamber with a fuel/air mixing system and ignition device. Contrary to the afterburner chamber of fig. 9f, this heating system operates in principle independently of the engine's current running mode. During cold engine start up, the fuel burner burns the air/fuel mixture provided in its combustion chamber and the hot exhaust gas produced heats fast the catalytic converter. Heating rates exceeding 40 °C/s are common for systems that are heated electrically or by means of fuel burners.

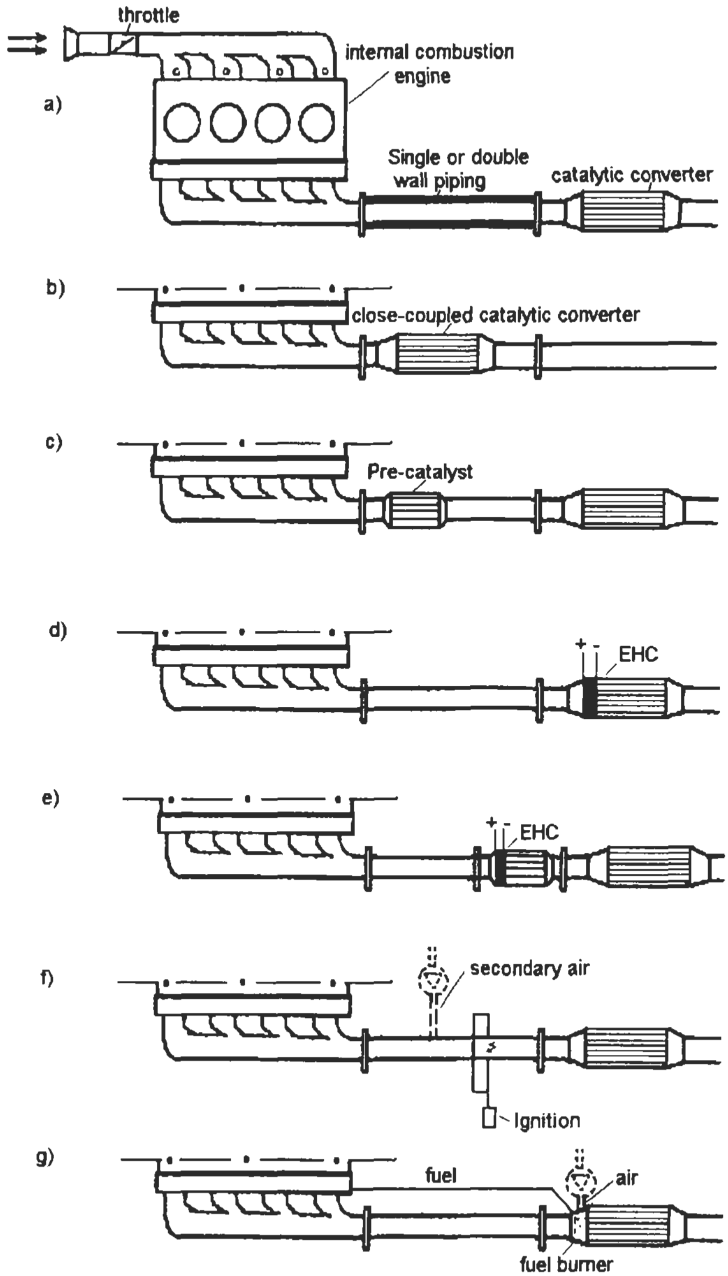


Fig. 9 (from [9], p. 18)

Disadvantages of the method are: increased fuel consumption, a significant number of components, the necessity to monitor safe ignition procedures and to protect the converter from overheating. Advantages and disadvantages of the above described methods are extensively discussed in [12].

Close-coupled converters

Positioning the converter close to the exhaust port of the internal combustion engine is an efficient way of increasing the inlet temperature of the converter during cold start-up of the engine (fig. 9b). In high load condition of the engine the aging of the catalyst material can be accelerated due to high temperatures of the exhaust gases (up to 1000 °C).

Palladium is a more suitable catalyst material for close-coupled converters than rhodium and platinum because:

a) it has a lower operating temperature
b) it is extremely effective in removing hydrocarbons, particularly with rich air/fuel mixtures
c) it is much more tolerant of high temperatures

Secondary converters

A secondary or starter or light-off or auxiliary or pre-catalytic converter or pre-catalyst upstream can be also installed upstream of the main catalytic converter (see fig. 9c). This converter is installed close to the exhaust manifold and has a small volume in order to be activated very fast (small thermal inertia). The oxidation of the HC and CO on this converter releases heat that activates fast the main converter. After the main converter is activated, the secondary converter is usually bypassed to protect it from high temperatures developed close to the exhaust manifold (see **US5089236 (1992)**, **EP0727567 (1996)**). As already mentioned above, an electric heater may also be installed in the secondary converter to activate even faster the main converter (fig. 9e).

Secondary converters use palladium-rhodium or palladium only as catalysts with high precious metal loading thus favoring exothermic oxidation reactions and consequently producing heat utilized to heat-up the main converter.

Secondary converters create a high back pressure which reduces the overall engine efficiency and robs the engine of power output.

Hydrocarbon adsorbents

Another approach to control the hydrocarbon emission during the cold-start of the engine is by installing a HC adsorbent upstream of the catalytic converter. This adsorbs HC during cold operation of the engine and releases HC during a hot operation of the engine, when the catalytic converter is activated. The catalytic converter then converts the released HC. Crystalline molecular sieves such as zeolites have HC adsorbing properties. Zeolites are aluminum silicates with controlled porosity used as cracking catalysts in petrochemical refineries and retain hydrocarbons on their surface via the attraction of electric charge. As the exhaust temperature increases, the heat desorbs the trapped hydrocarbons by breaking the electric bonds, permitting them to flow into the main catalytic converter for oxidation.

The HC adsorbent can be also bypassed during a hot operation of the engine to spare the HC adsorbent from harmful thermal excursions (see **EP0727567 (1996), EP0602963 (1994)**).

Secondary air

During the cold start phase, most engines must operate with richer than stoichiometric fuel mixtures in order to ensure smooth operation without stalling. The lack of oxygen in the exhaust allows non-oxidized CO and HC to be emitted to the environment. This problem is solved by injecting secondary air in the exhaust gas downstream of the engine exhaust ports. The injected air oxidizes the CO and HC of the exhaust gas and the heat produced lights-off the catalytic converter.

The light-off time achieved in this way in FTP '75 test cycle is less than 40 sec (compared to 100 sec of the conventional catalytic system). The respective reduction of cumulative HC emissions in the FTP '75 test cycle can reach even 50% (depending on the engine and exhaust piping characteristics).

Secondary air injection requires a separate piping system, as well as an electrically driven pump ([9, 17]).

Other systems to facilitate light-off temperature of catalytic converters

Another way to make a catalytic converter effective for cold engine start-up is to keep it hot with some kind of heat storage system while the car is parked. This device might be similar to a thermos bottle or air-gap pipe that fits over the converter. The problem with this technique is releasing the heat once hot exhaust starts pouring in so the contents do not overheat ([14]).

An alternative approach is to heat the main catalytic converter by means of a cross-flow catalytic converter-heat exchanger combination like the one of fig. 10d. The exhaust gas leaving the engine and passing through the converter heats the part of the converter that is on the far downstream side, thus reaching the light-off temperature to oxidize the HC released for example by a HC adsorbent.

Combinations of the above mentioned approaches as well as other methods not described in this book may be also found in the literature. An example of such combinations is given in fig. 10, where a HC adsorbent, an electrically heated catalytic converter (EHC), a close-coupled converter, a main catalytic converter and a heat exchanger are combined in the exhaust pipe of an internal combustion engine (see **WO9508702 (1995)**).

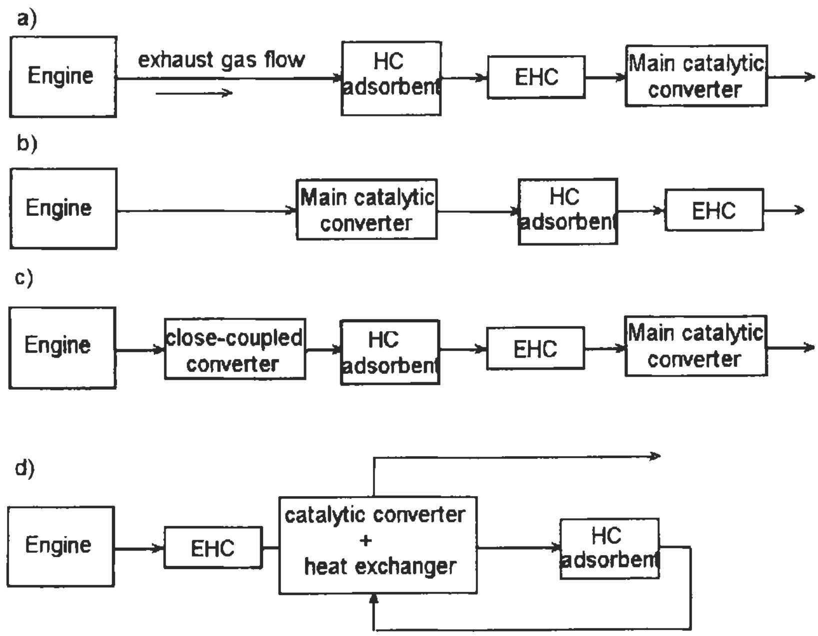


Fig. 10 (from WO9508702)

Oxygen storage

As shown in fig. 4, a λ-sensor is used in the exhaust pipe with a three-way catalytic converter as a feedback-control of the engine air/fuel ratio. In modern engines, an oscillation cycle of the engine air/fuel ratio around the stoichiometric value (from rich to lean and vice-versa) is deliberately imposed by the management system of the engine. In such dynamic conditions, the catalytic converter converts bigger quantities of NO_x, CO and HC than when operating under a steady state condition. At least part of the improved performance is thought to be due to the ability of the catalyst to undergo reduction-oxidation reactions. Such a catalyst component is usually referred to as an oxygen storage component.

In its oxidized state, the catalyst can provide oxygen for CO and HC oxidation in a rich exhaust gas environment, and in the process be reduced. When the exhaust cycles to lean conditions, this reduced component can adsorb oxygen or NO_x (which removes NO_x directly or indirectly by reducing the oxygen concentration). The oxidized component can, in turn, provide oxygen for CO and HC oxidation in the next rich cycle. Components such as CeO_2 or ReO_2, which exhibit this reduction-oxidation behavior are included in the washcoat of commercial three-way catalytic converters.

Studies have shown that oxygen adsorption and desorption phenomena, under periodically varying inlet conditions, are attributed to the presence of cerium and, to a much lesser extent, other washcoat materials ([9]). The function of cerium as oxygen storage component is based on its ability to form both 3- and 4-valent oxides. Under net oxidizing conditions the following Ce oxide reactions may take place.

$$Ce_2O_3 + \tfrac{1}{2}O_2 \rightarrow 2CeO_2$$

$$Ce_2O_3 + NO \rightarrow 2CeO_2 + \tfrac{1}{2}N_2$$

$$Ce_2O_3 + H_2O \rightarrow 2CeO_2 + H_2$$

Under net reducing conditions, CeO_2 functions as an oxidizing agent according to the following reactions:

$$2CeO_2 + H_2 \rightarrow Ce_2O_3 + H_2O$$

$$2CeO_2 + CO \rightarrow Ce_2O_3 + CO_2$$

The interaction of Ce oxides with HC is of minor importance. The oxygen storage availability is apparently a function of the washcoat Ce content and dispersion. Moreover, the stored oxygen available to react under operating conditions is a function of the local temperature and reduction-oxidation environment ([9]).

Monitoring and diagnosing the efficiency of catalytic converters

The catalyst within the catalytic converters has a limited lifetime so that the efficiency of the converter deteriorates with age and use. Table 3 summarizes all possible deactivation mechanisms for automotive catalysts ([1]). For current catalytic converter systems, deactivation resulting from the fouling (carbonaceous deposits) category is minimal.

One of the most important reasons for deactivation of automotive catalysts is the exposure of the catalyst to high temperatures. This enhances reduction of the alumina surface area and sintering of the noble metals resulting in losses of effective catalytic area.

The catalyst can be degraded or "poisoned" by the presence of some pollutants, such as lead compounds and oil additives (sulfur or phosphorous) in the exhaust gases. These chemically contaminate the washcoat and noble metals, and reduce the active catalytic area by covering the active centers of the coating.

Chemical	*Thermal*	*Fouling*	*Mechanical*
Poisoning: irreversible adsorption or reaction on/with the surface	Sintering (re-dispersion)	Carbonaceous deposits (coking)	Thermal sock
Inhibition: competitive reversible adsorption of poison precursor(s)	Alloying		Attrition
Poison-induced reconstructing of catalytic surfaces	Support changes		Physical breakage
Physical/chemical blockage of support pore structure	Noble metal-base metal interactions		
	Metal/metal oxide- support interactions		
	Oxidation (alloy segregation)		
	Noble metal surface orientation		
	Metal volatilization		

TABLE 3: Summary of deactivation mechanisms for automotive catalysts

Tests in [32] have clearly shown that converter performance in the form of HC conversion efficiency was found to generally decrease when the sulfur content in the fuel used was increased.

The catalyst activity after a certain vehicle mileage strongly differs along the substrate length. Typically, the front part of the substrate is deactivated much faster. On the one hand, poison deposits occur in higher concentrations in this area, on the other hand, the reaction zone located in the first few centimeters of the substrate results in higher structure temperatures.

It is also possible for the catalytic converters to be damaged during use, for instance by fracturing causing leaks to the atmosphere of exhaust gas.

For all the above mentioned reasons, it is desirable to monitor the performance of catalytic converters.

The present book refers to *on-board (OBD)* or *non-OBD* monitoring methods of the condition of a catalytic converter installed in the exhaust pipe of an internal combustion engine vehicle. The term "non-OBD" means methods of monitoring taking place in workshops by specialized technicians and special equipment. The term "on-board" means methods of monitoring taking place during driving of the vehicle and being executed by the control unit of the vehicle. On-board methods are the most recent ones and in some legislatures their application has become a statutory requirement.

The first generation of on-board diagnostics (OBD I) was introduced by the state of California in all vehicles sold by 1990. This first generation OBD did not monitor many important emission control subsystems, such as the evaporative emissions system, the secondary air injection and the catalytic converter.

Engine Management	***Combustion***	***Exhaust after-treatment***
Start control	Combustion chamber	Pre- or close-coupled catalytic converter
Warm-up control	Spark plug	Insulated exhaust pipes
Mixture preparation	Spark energy	Improved catalyst (Tri-metal)
Transient control		Secondary air injection
Electronic throttle control ETC)		Electrically or fuel burner heated catalytic converter
λ-control		HC adsorbent
Variable valve control alternatively EGR		

Table 4: Emission reduction measures to be monitored by on-board diagnostics

The starting point for legislation for monitoring catalytic converters was in 1988 in the United States, with the OBD II (On-Board Diagnostics) standard. The definite form of this standard was issued in 1991 by the California Air Resources Board (CARB) and was introduced in California in 1994. Further extensions of this legislation have been proposed in the United States by the Environmental Protection Agency (EPA), and also in Europe, under the common name of EOBD (European On-Board Diagnostics) (see **EP0588123 (1994)**).

The OBD II specifications include installation in motor vehicles of electronic systems which can monitor periodically the efficiency of anti-pollution devices, or in general, can detect and indicate the occurrence of phenomena liable to produce an excessive increase in emissions by the vehicle.
Table 4 summarizes all emission reduction measures that are monitored by a modern OBD system ([2]).

Legislation	***HC (g/km)***	***CO (g/km)***	***NO_x (g/km)***
EPA	0.12*	1.06*	0.31*
CARB (TLEV)	1.5 x the respective emission limits	1.5 x the respective emission limits	1.5 x the respective emission limits
CARB (LEV)	1.5 x the respective emission limits	1.5 x the respective emission limits	1.5 x the respective emission limits
CARB (ULEV)	1.5 x the respective emission limits	1.5 x the respective emission limits	1.5 x the respective emission limits
European	0.4	3.2	0.6

* Increase above emission limits

Table 5: Malfunctioning criteria for catalytic converters

The main anti-pollution device, which requires monitoring in order to indicate malfunctioning in terms of exceeding some predefined threshold values for emissions measured in the type-approval test cycle (for example the so-called FTP '75 cycle), is the catalytic converter installed in the exhaust pipe (see **EP0588123 (1994)**).

Tables 5 and 6 show the malfunctioning criteria for catalytic converters for different emission technology vehicles for EPA, CARB and European legislation. The case of Transitional Low Emission Vehicles (TLEV) is also included. ([9], [15] and [16]).

The objective of this book is to serve as a compendium of the literature and the methods existing in the field of monitoring of catalytic converters only, with a particular emphasis on patent disclosures. Of course, some selected non-patent literature is also included.

The book is divided in four chapters. Each of the chapters 1 to 3 reflects a group of methods for the monitoring of catalytic converters.

Chapter 1 comprises methods that use oxygen or air/fuel ratio (λ or lambda) sensors upstream and downstream of the converter in order to detect degradation of the converter.

Chapter 2 comprises methods that use temperature measurements of the exhaust gases inside or outside the catalytic converter in order to detect degradation of the converter.

Chapter 3 comprises all other methods not covered by the methods of chapters 1 and 2. Mostly this chapter comprises direct methods of diagnosis of catalytic converters by means of HC, CO or NO_x sensors.

CARB	***TLEV (models 1994, 1995)***	• Catalytic converter conversion rate HC<60-80% at steady state condition
CARB	***Non-LEVs (HC < 0.25 g/mile)***	• Catalytic converter caused deterioration of the HC-results by 0.4 g/mile (=1.5 x 0.25 g/mile)
CARB	***LEVs (NMOG < 0.125 g/mile)***	• *Main catalytic converter*: decline of the HC-conversion rate in the FTP-Test to 50-60% (i.e. final raw emission > 40-50% of raw emission • *Small vol. Catalytic converter*: decline of the HC-conversion rate in the FTP-Test by 40-50% in comparison to the value at 4000 miles (6400 km) (also valid for large primary catalytic converters if monitored together with downstream substrate) • defective front converters must be separately detected • monitoring of RHC with regard to HC-conversion rate and heating function
Federal OBD Regulation		• Catalytic converter caused deterioration of the HC FTP-results by 0.4 g/mile (=1.5 x 0.25 g/mile or HC FTP-result > 0.6 g/mile)

Table 6: Requirements OBD II catalytic converter monitoring (Malfunction Criteria)

Chapter 4 presents a comparison of the methods discussed in Chapters 1, 2 and 3.

The measuring arrangements of all three methods are summarized in fig. 11 and Table 7 [1]. In fig. 11, the different sensors used as well as their installation positions are clearly indicated.

The methods are presented in chronological order per patent applicant, starting from the older methods till the most recent ones. This helps to evaluate how a patent applicant has improved his methods in time. The main criteria for the order of presentation of the patent applicants are:

a) patent applicants with the earliest presentation dates of such methods and
b) patent applicants with the largest production of such methods.

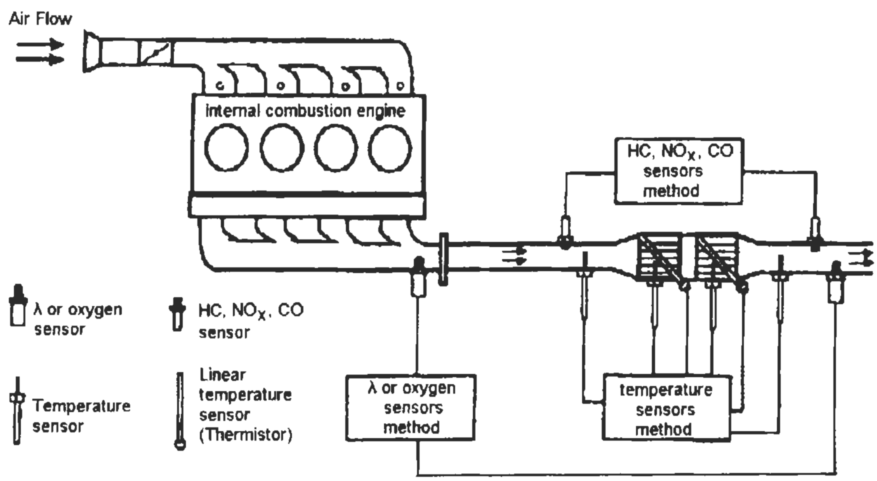


Fig. 11 (from [1], p. 174)

Each patent disclosure is given by its publication number followed by the year of publication e.g. **US5177463 (1993)**. Only one published member per family of documents (i.e. documents published in different countries by the same patent applicant and having the same priority number and date) is given. In most of the cases the earliest published family document number is given.

A patent number index, an inventors index, a company index and a subject index is found at the end of the book.

A few elements of theory are presented in the beginning of each chapter to contribute to better understanding of the described methods.

The original patent and non-patent literature available at the European Patent Office (EPO) i Rijswijk, Netherlands was the main source of information used in this book. For the Japanes patent literature the technical abstracts published in English by the Japanese Patent Office wer used.

	Chapter 1	*Chapter 2*	*Chapter 3*
Method	Dual O_2 Sensor	Temperature sensors	HC, CO, NO_x measurement
Sensors used	EGO, HEGO UEGO, λ-sensor	Thick film, Surface ionization, Variable resistance	HC, CO or NO_x sensors. Calorimetric sensors
Diagnosis principle	Measurement of O_2 storage capacity	Detection of exothermic heat	HC or CO oxidation, NO_x reduction
Suitable operation mode	Hot engine. Most of the times at steady state operation	Variable, also transient operation	All modes

Table 7: Overview of on-board efficiency diagnosis methods of catalytic converters

PART ONE

CATALYTIC CONVERTER FUNCTIONALITY DIAGNOSIS BY MEANS OF OXYGEN OR AIR/FUEL RATIO SENSORS

Chapter I

Catalytic Converter Functionality Diagnosis by Means of Oxygen or Air/Fuel Ratio Sensors

This chapter comprises methods of diagnosing degradation of the functionality of catalytic converters by making use of two oxygen or lambda (λ) sensors placed upstream and downstream of a catalytic converter (fig. 12). For reasons of simplicity the two sensors will be called from here onwards just *upstream* and *downstream sensor*.

Before explaining the principles used by these methods, a few definitions used further in the chapter are given followed by a short explanation of how the injection system of modern vehicle engines is controlled.

The composition of the combustible air/fuel mixture fed to the engine must be right to within close limits. The criterion is the ratio lambda (λ):

$$\lambda = \frac{\textit{existing oxygen content}}{\textit{stoichiometric oxygen content}} = \frac{\textit{actual engine air / fuel ratio}}{14.7}$$

where the existing oxygen content can be measured, for example, in grams of oxygen per gram of intake mixture. The *stoichiometric oxygen content* is what is theoretically necessary for complete combustion of the fuel. In a precisely correct intake mixture, λ is equal to one. The stoichiometric engine air/fuel ratio for petrol engines is equal to 14.7. When λ is less than one in the intake mixture (rich air/fuel mixture), carbon monoxide (CO) and hydrocarbons (HC) appear in the exhaust gases downstream of the converter. When λ is more than one (lean air/fuel mixture) nitrogen oxide (NO_x) appears.

In the patent literature different types of oxygen sensors are used for monitoring purposes like EGO (Exhaust Gas Oxygen) sensors or UEGO (Universal Exhaust Gas Oxygen) sensors or HEGO (Heated Exhaust Gas Oxygen) sensors.

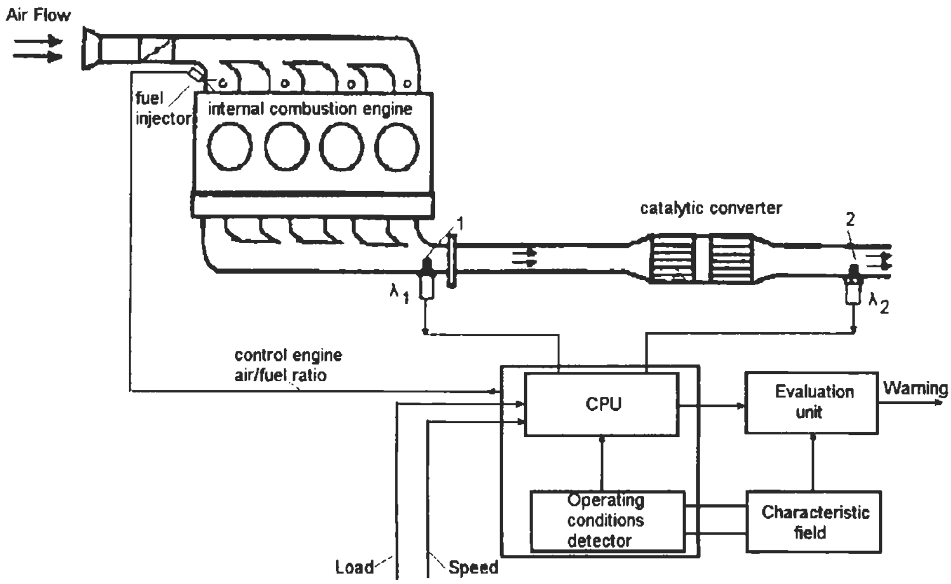


Fig. 12 (from [9], p. 22)

Before examining in detail the diagnosing methods that use λ or oxygen sensors, it is worthwhile to explain the operation principles of these sensors as described in [1].

λ-probe and UEGO sensor operation principles

The principle of operation of the λ probe is shown in fig. 13. The elongated thin-wall ceramic thimble isolates the exhaust gas from the atmospheric air which is in contact with the interior of the thimble. The interior and exterior surfaces of the thimble are coated with porous platinum bands or strips that serve as catalytic surfaces as well as electrodes which are connected by means of external circuitry.

The thimble is fabricated from zirconium oxide which contains a small amount of a lower valent oxide, such as yttrium oxide. The dispersion of the trivalent yttria within the tetravalent zirconia crystalline lattice results in valence 'holes' which allow oxygen ions to migrate through the zirconia wall of the thimble but prevent such migration by oxygen atoms and molecules or by any other kind of ion, atom or molecule.

The migration of oxygen ions through the zirconia thimble involves several processes. As the porous platinum electrode is on the air side of the thimble, atmospheric oxygen molecules are catalytically dissociated into oxygen atoms.

Each liberated oxygen atom gains two electrons and is thereby converted into an oxygen ion which migrates through the thimble under certain conditions. Catalyzed reactions also occur at the porous platinum electrode on the exhaust gas side of the thimble. Each oxygen ion that emerges from the thimble loses the two extra electrons to be converted into an oxygen atom. These 'migrated' oxygen atoms associate with each other to form diatomic molecules to become part of CO_2 or water vapor molecules. The net effect of the migration of oxygen ions through the thimble wall is the transport of electrons via the oxygen ions through the wall, from the inner surface, and the return flow of electrons from the outer surface to the inner surface via the external circuit. The net result in the circuit is the development of an electromotive potential of about 900 mV.

In the temperature range met in automobile exhaust systems, the operation of the zirconia cell involves oxidation/reduction reactions on the porous platinum electrode on the exhaust gas side of the thimble, mainly reactions of CO and H_2 with exhaust gas O_2. Therefore, voltage generation in the outer circuit can only take place if reducing agents are present and available for reaction with the oxygen ions that migrate through the cell thimble. Consequently, the concentrations of the reducing agents must be greater than those needed for stoichiometric reaction with exhaust gas oxygen.

The sensor output takes its high value (600-900 mV) when the exhaust gas mixture is rich and its low value (under 150 mV) for lean exhaust gas. It exhibits, therefore, a 'step function' characteristic, which can be used to detect deviations from stoichiometry. However, sensor output voltages for temperatures under 250 °C are low even in the presence of excess of reducing agents in which case it is not possible to detect deviations from stoichiometry.

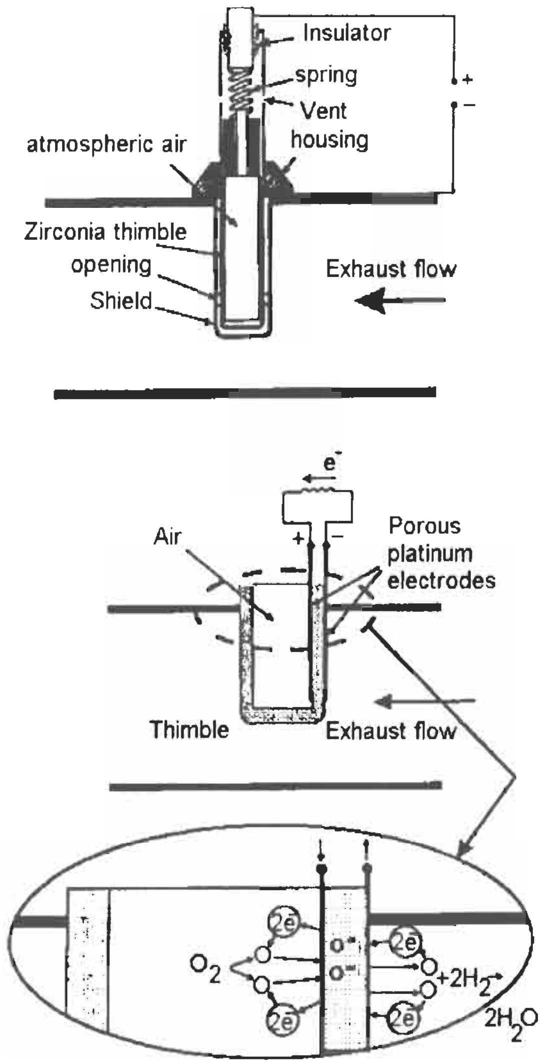


Fig. 13 (from [1], p. 175)

Usually an internal heating element is added to the sensor in order to minimize the time needed to reach the operating temperature after a cold start. For a typical four cylinder car driven on the FTP '75 test cycle, use of a heated sensor reduces the time required to achieve the operating temperature from 50 to 30 sec after a cold start up. The steady state output voltage of the sensor (Table 8 [1]), as well as its response, depends also on the concentration of the exhaust gas in a rather complex manner. For relatively small concentrations of reducing agents (CO, H_2), the response of the sensor becomes significantly slower.

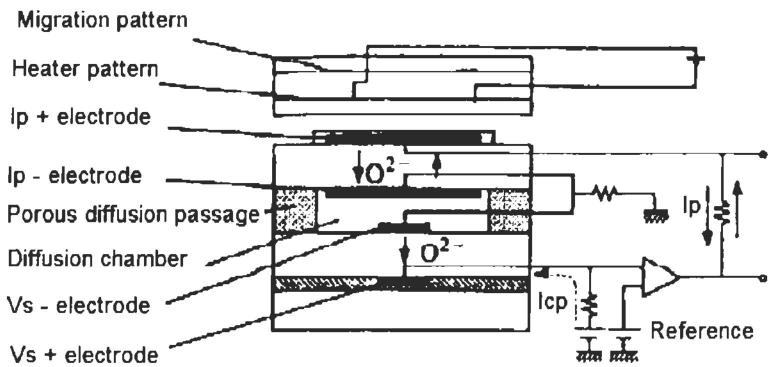


Fig. 14 (from [1], p. 175)

Fig. 14 shows a universal air/fuel ratio *heated exhaust gas oxygen sensor (UEGO)* presented by the NGK Spark Plug company. The main characteristic of the sensor is the output proportionality for large ranges of air/fuel ratio. It also exhibits faster response, improved accuracy and superior aging characteristics.

Sensor developments crucial to measurement and exhaust emission control are presented in [18]. A sensor with improved characteristics over the HEGO and UEGO sensors is the so called NEEGO sensor (*Non Equilibrium Exhaust Gas Oxygen Sensor*) presented in [19]. However this sensor is still under investigation and has not been applied yet in real OBD measurements.

Reducing agent	*Concentration (ppm in argon)*	*Voltage at 590 °C*
Hydrogen	349	800
Hydrogen	4700	900
Carbon monoxide	290	440
Carbon monoxide	8866	800
Indolene*	714	10
Indolene	2502	88
Indolene	9540	200
Methane	321	90
Propane	390	90
3-methyl pentane	456	-20
2,3-dimethyl hexane	531	-20

*Indolene clear fuel is a 470 ppm sulfur content fuel

Table 8: Typical voltage sensitivity of zirconia cells (λ-sensors)

Control of engine air/fuel ratio

The richness of the air/fuel mixture (i.e. ratio λ) of an internal combustion engine is mostly controlled by adjusting the duration of opening of each of the fuel injector valves. The adjustment of the ratio λ precisely enough to enable the catalytic converter to operate effectively, converting all three CO, HC and NO_x into harmless substances, is mostly achieved by controlling the engine air/fuel ratio by means of a *λ-sensor* (similar to this described in fig. 13) installed in the exhaust pipe of the engine upstream of the catalytic converter (*closed-loop control*) (fig. 12).

The λ-sensor responds to changes in exhaust-gas composition resulting from deviations from $\lambda=1$ in the intake mixture by producing an abrupt voltage jump in its output signal, a high voltage corresponding to a rich intake mixture (λ less than 1).
The voltage signal from the λ-sensor is transmitted to a proportional integral computer (fig. 12), which responds by changing the duration of opening of the fuel injection valves, so as to make the intake mixture richer or leaner, whichever may be required, i.e. the controlling computer, responding to the output signal of the λ-sensor, corrects the richness of the intake mixture to bring it back to $\lambda=1$. In practice, λ oscillates at high frequency but with a low amplitude, the effective λ being the mean of the oscillations (conversion window).

A catalytic converter, for example a three-way catalytic converter, has an oxygen storage function i.e. it absorbs and stores excess oxygen existing in the exhaust gases when the air/fuel ratio of the air/fuel mixture fed into the engine cylinder becomes lean, and releases oxygen when the air/fuel ratio of the air/fuel mixture fed into the engine cylinder becomes rich. Accordingly, where the air/fuel ratio is alternately changed on the rich side and the lean side of the stoichiometric air/fuel ratio, since excess oxygen is absorbed and stored in the three-way catalytic converter due to its oxygen storage function when the air/fuel mixture becomes lean, NO_x is reduced. Conversely, when the air/fuel mixture becomes rich, since the oxygen which has been absorbed and stored in the catalytic converter is released, HC and CO are oxidized. As a consequence, NO_x, HC and CO can be purified at the same time.

In theory a properly operating catalytic converter promotes the complete reaction between free oxygen in the exhaust stream resulting in the ideal products of combustion, i.e. CO_2 and water vapor. As a result the exhaust stream downstream of the catalytic converter is composed primarily of these products, and has a low concentration of reducing agents. The lack of oxygen and low concentration of reducing agents in the exhaust stream leads to a decrease in oxidation/reduction activity at the noble metal electrode (e.g. Pt) of a downstream oxygen sensor. In such conditions the output signal of the downstream sensor of a properly operating catalytic converter under steady state operating conditions will tend to stabilize with low fluctuations in the output response pattern (see **US5228335 (1993)**).

With continued use the catalytic converter becomes degraded by thermal aging, sintering and crystallization of the active surface layer, and it is poisoned by such substances as S, Pb, P, Zn and Mg, with the consequence that the oxygen storing ability of the converter falls away (see Table 3). Decreases in the ability of the catalytic converter to convert the reducing agents in the exhaust stream results in free oxygen passing through the catalytic converter without reacting during lean operation of the engine. Thus, the downstream sensor reflects the decrease of conversion activity with more rich-to-lean fluctuation of oxygen, as a result of the increase in untreated exhaust gases passing through the catalytic converter.

Summarizing, when the catalytic converter operates properly, it dampens the fluctuations in oxygen content, thus the downstream sensor produces a distinguishably different sensor response pattern from that obtained from the upstream sensor. The more advanced the deterioration of the catalytic converter the more the voltage response pattern of the downstream sensor tends to approach the voltage response pattern of the upstream sensor. When the catalytic converter has completely deteriorated, the oxygen conversion efficiency is completely lost. Therefore, the oxygen content of the exhaust stream downstream of the catalytic converter resembles much more the oxygen content upstream of the catalytic converter and therefore the response patterns of the two sensors resemble much more to each other.

However, the system is very dynamic and non-linear as the catalytic converter deteriorates with use over time. The ever changing oxygen storage capability of the catalytic converter makes a simple moment by moment comparison of voltage of frequency sensor output non-determinative of catalytic converter adequacy or failure. Additionally, other factors influencing the determination of the efficiency of a catalytic converter like aging of the two sensors, operating conditions of the engine, temperature of exhaust gases etc. complicate even further this determination. For that reason sophisticated substantially real time phase difference, crossing ratio, integration methods etc. applied by computer algorithms are necessary to result in a successful means of substantially real time determination of catalytic converter adequacy or failure.

As mentioned in the previous paragraph, an important factor that influences the precision of assessment of the efficiency of the catalytic converter is the deterioration or aging of the oxygen sensors installed upstream or downstream of the catalytic converter. Particularly the upstream oxygen sensor, which is directly exposed to hot exhaust gases, undergoes faster deterioration than the downstream oxygen sensor. The rate at which the deterioration proceeds is thus different between the upstream and downstream oxygen sensors, which results in an error in the result of deterioration determination (see **US5325664 (1994)**). For this reason, modern methods to assess the functionality of catalytic converters comprise simultaneous assessment of degradation of oxygen sensors and compensation of the errors due to this degradation.

Additionally, the sensors installed upstream and downstream of the catalytic converter may have different characteristics, due to manufacturing tolerances. These tolerances must be taken into account during the assessment of the condition of the catalytic converter.

The temperature of the catalytic converter is also an important factor that can influence the correct determination of the deterioration of a catalytic converter by means of oxygen or air/fuel sensors. The oxygen storage capacity of the catalytic converters in general varies with a change in the temperature, which causes a variation in the indication of the sensor placed downstream of the catalytic converter.

During the deterioration diagnosis procedure, the engine air/fuel ratio is controlled in such a way as to achieve certain operating conditions. Great attention should be paid in order not to increase the emissions of the internal combustion engine during this deterioration diagnosis procedure.

A typical engine layout for monitoring the efficiency of a catalytic converter is shown in fig. 12 (see e.g. **DE4139560 (1993)**). Fig. 12 shows a catalytic converter having an oxygen probe 1 arranged upstream of the converter and an oxygen probe 2 arranged downstream of the converter, a value-determining unit, an evaluation unit and a characteristic field.
The value-determining unit includes a computation device (CPU) and an operating-state detector and can work as a control unit to regulate the air/fuel mixture supplied to the engine.

The computation unit receives an upstream-probe signal λ_1 from the upstream probe 1 and a downstream-probe signal λ_2 from the downstream probe 2. From these signals, the computation unit evaluates the performance loss of the catalytic converter. The computation unit performs this evaluation during e.g. a steady-state operation of the engine to which the catalytic converter is connected. The operating state is announced by a detector when the engine is operated in the steady state. The value determined by the computation unit is compared to a characteristic-field value in the evaluation unit with the characteristic-field value being supplied from the characteristic field. If the comparison shows that the catalytic converter has a performance loss which is impermissibly high, then the evaluation unit emits a fault signal to the driver warning means e.g. a Malfunction Indication Lamp (MIL).

Values of variables are supplied to the operating-state detector and the characteristic field and indicate the operating state of the internal combustion engine. Such variables are: engine speed, vehicle speed, water coolant temperature, load, temperature of exhaust gases etc.(fig. 12). The control unit processes all the input and regulates the air/fuel mixture supplied to the engine.

The control unit may comprise calculation means, integrators, comparators, storage means etc. Signal filtering means, A/D converters and other necessary data equipment devices may be included in the system.

Most of the methods presented in this book concern on-board diagnostic methods although a few methods applied by skilled technicians in workshops are also presented.

Chapter 1.1

Robert Bosch GmbH

In **DE2328459 (1975)** the company Robert Bosch GmBH proposed one of the earliest methods for monitoring a catalytic converter by installing two oxygen sensors, one upstream and one downstream of the converter. A warning signal is produced when a voltage difference indication between the downstream and the upstream sensors of the oxygen concentration in the exhaust gases as a function of air/fuel ratio λ passes over a predetermined threshold (fig. 15, lines 28,29), showing that the catalyst cannot oxidize anymore the impurities and must be replaced.

The indication of the sensor can also be corrected for differences in temperature between the upstream and the downstream side of the catalytic converter (**US4007589 (1977)**). The disadvantage of the method is that it is accurate only in certain operational domains, which are quite difficult to define.

In **DE2444334 (1976)** an oxygen concentration sensor upstream of the catalytic converter sends a voltage change signal to a monitoring electronic system at certain operating conditions. If within a predetermined time interval a similar downstream sensor also changes its output voltage, then that is an indication of a too short time difference in this change, meaning that the catalytic converter is defective.

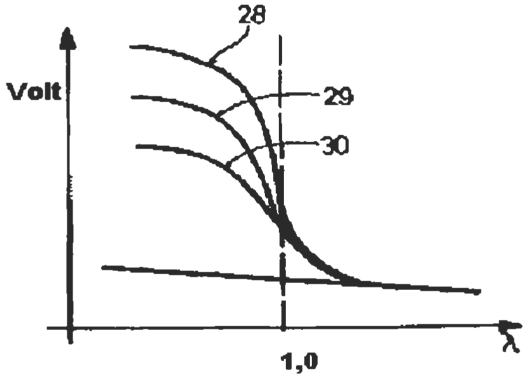


Fig. 15 (from US4007589)

In **DE4009901 (1991)** the air/fuel ratio of the engine starts oscillating at certain operating values of load and rotational speed. The signal from each probe then starts fluctuating around a mean value $\bar{V}_{1,2}$ within allowable limits $\varepsilon_{1,2}$. If both signals exceed their limits for longer than a preset period of time (fig. 16) then an alarm signal is produced indicating a failure of the catalytic converter.

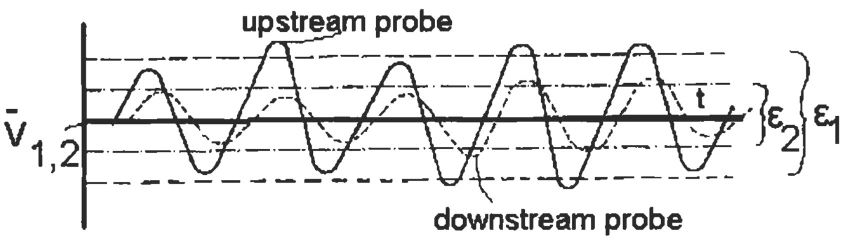


Fig. 16 (from DE4009901)

In **DE4024210 (1992)** the air/fuel ratio starts oscillating at predetermined operating conditions around a mean value from rich to lean and vice versa. The predetermined conditions are defined as a stationary load-rotational speed point, where load and speed changes remain between certain limits for a predetermined time interval. The measured ratio of the two probe signals is then formed:

$$R = \frac{\overline{|V_2 - \overline{V_2}|}}{\overline{|V_1 - \overline{V_1}|}}$$

The ratio R is used as an indication of the conversion rate of the catalytic converter (fig. 17). The catalytic converter is considered operational for a value of $R<0.6$. After this point the catalytic converter is considered as aged. The measured value of the ratio R is also used for controlled modification (reduction) of the amplitude of controlled oscillation with decreased conversion rate of the catalytic converter (compensation of aging of catalytic converter).

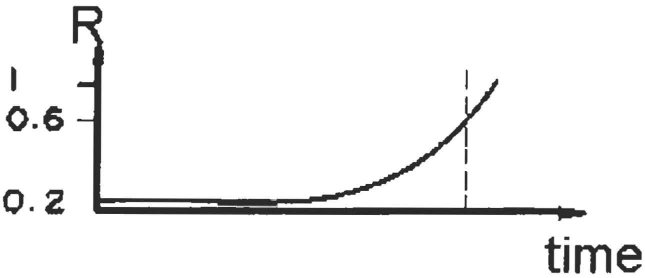


Fig. 17 (from DE4024210)

In **DE4039762 (1992)** the evaluation of the catalytic converter is based on the signal overshoot of the downstream sensor when the air/fuel ratio supplied to the engine changes from lean to rich within a predetermined time period. Fig. 18a (left part) shows the course of the upstream sensor output signal during this change, while fig. 18b shows the corresponding output signal of the downstream sensor. When the overshoot OS exceeds a predetermined amplitude the catalytic converter is considered as aged. Alternatively when the air/fuel ratio is regulated from rich to lean within a predetermined time period (fig. 18a, right part), the amplitude of the back-shoot BS of the output signal of the downstream sensor is used as the evaluation parameter of catalytic converter aging (fig. 18c).

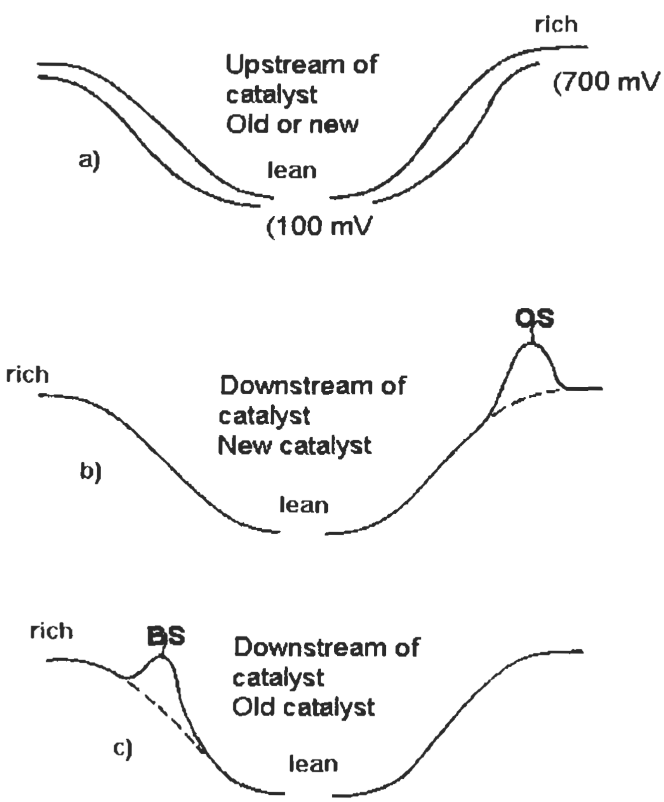


Fig. 18 (from DE4039762)

In **GB2254939 (1992)**, the evaluation parameter of aging of a catalytic converter is the difference of an actual and a simulated λ value of a downstream sensor. The estimation of the simulated value involves the measurement of the air mass flow inducted by the engine and computation of the oxygen flow to the engine (by multiplying the air mass flow by a factor k indicating the mass of oxygen in air).

$$\dot{Q}_{O2} = k \cdot \dot{Q}_{air}$$

where:

k = constant

The deviation $\Delta\lambda$ upstream of the catalytic converter compared to value "1" is determined. This deviation is positive for lean fuel mixture and negative for rich fuel mixture. The oxygen flow into the catalytic converter is determined then as the product of the computed oxygen flow to the engine and the above mentioned λ deviation.

$$\dot{Q}_{O2in} = \Delta\lambda \cdot \dot{Q}_{O2}$$

The oxygen storage of the catalytic converter is defined as that oxygen quantity from a continuous additive oxygen flow being able to be stored by the catalytic converter from an oxygen free empty state up to an overflow limit, at which the concentration of oxygen in the exhaust gas leaving the catalytic converter is above a predetermined value.

A simulated downstream value of λ is then set to "1" for as long as the catalytic converter is disposed in a filling (emptying) state below (above) an overflow (a depletion) threshold or it is set to the upstream λ value when either of the thresholds is crossed. The method thus utilizes a model of the temporal behavior of oxygen flows.
The method can be extended in measuring the actual λ_2 value, modifying the defined oxygen storage volume of the converter until the simulated temporal mean value of λ_2 corresponds with the actual λ_2 value and utilizing the modified oxygen storage volume as a measure of the state of aging of the converter.

In DE4112478 (1992) a controlled oscillation of the λ_1 value from rich to lean and vice-versa takes place (fig. 19a). When the downstream probe shows a significant variation of λ_2 (fig. 19b,c), then the time integrals of the products of the exhaust gas flow through the catalytic converter times λ_1 and times λ_2 are formed:

$$I_1 = \int_{t1}^{T2} \lambda_1 \cdot \dot{Q}_{O2in} \cdot dt$$

$$I_2 = \int_{0}^{T2} \lambda_2 \cdot \dot{Q}_{O2in} \cdot dt$$

As a measure of the performance loss of the catalytic converter, either the difference between said integrals or the quotient of said difference and one of said integrals is used:

$$AZ = |I_1 - I_2| \qquad \text{or}$$

$$AZ = \frac{|I_1 - I_2|}{I_1}$$

When one of these values is out of a predetermined range then the catalytic converter is considered to be of low performance.

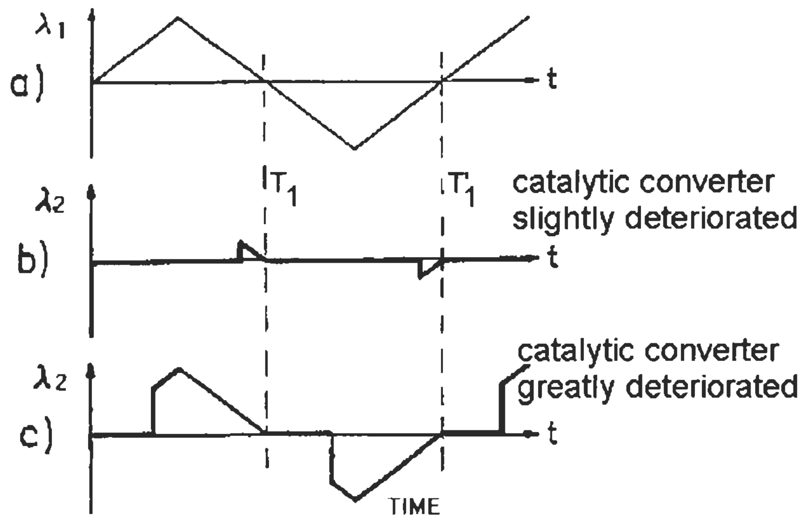


Fig. 19 (from DE4112478)

In **DE4112479 (1992)** the engine air/fuel ratio is forced to oscillate between a rich and a lean value. The quotient of the measured downstream maximum λ_2 value over the upstream maximum λ_1 value is used then as a deterioration variable AZ for determining the deterioration of a catalytic converter.

$$AZ = \frac{\lambda_{2max}}{\lambda_{1max}}$$

The method then comprises correction of AZ based on values of the operating variables, in order to reduce the influence of the operating conditions on AZ.

In this way AZ can be reliably determined for a variety of operating conditions rather than only a few selected operating conditions.

$$AZ' = AZ \cdot \frac{\text{standard air mass flow}}{\text{actual air mass flow}} \cdot \frac{\text{standard oscillation frequency}}{\text{actual oscillation frequency}}$$

$$AZ'' = AZ' \cdot k_1 \cdot (1 - k_2 \cdot \frac{|\Delta\lambda|}{AZ'})$$

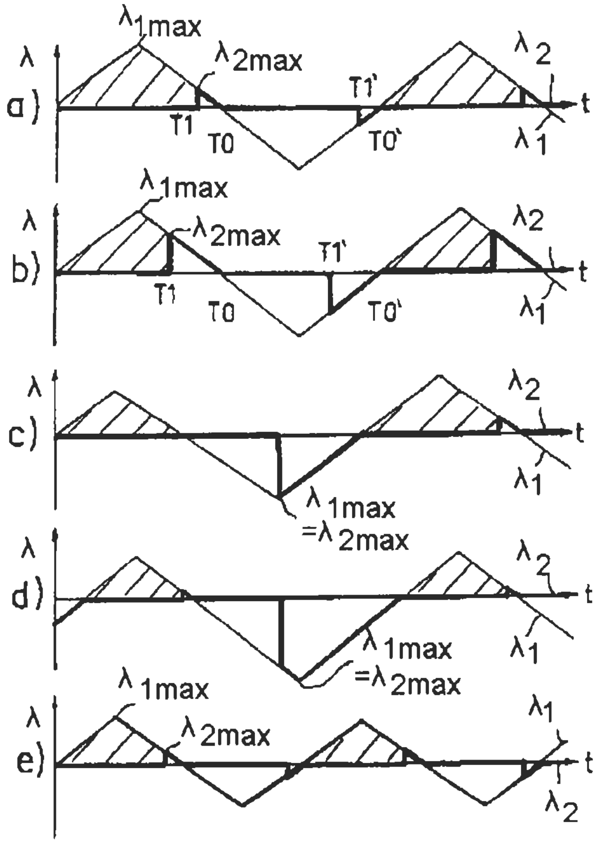


Fig. 20 (from DE4112479)

where:

$\Delta\lambda = \lambda - 1$
k_1, k_2 : constants

Fig. 20 shows the case of a deteriorated catalytic converter at different operating conditions. An idealized time-dependent variation of λ_1 from lean to rich state and vice-versa is shown, which is symmetrical around "1". This means that for a new catalytic converter so much oxygen is stored in the catalytic converter in the lean phase as taken therefrom in the following rich phase for oxidizing non-combusted exhaust gas components. The thick line corresponds to the corresponding measured λ_2 value, which, as it can be noticed at time point T_1, changes indicating that at this point the catalytic converter is exhausted (deteriorated catalytic converter). At T_0 the catalytic converter is emptied of stored oxygen. The ratio of the maximum amplitudes of these two λ values defines the variable AZ.

As shown in fig. 20b, the reduction of storage capacity of the catalytic converter leads to a shift of T_1 to the left and consequently to an increase of λ_{2max} and of AZ.

Figs. 20c-e show different AZ values which depend on the operating conditions of the catalytic converter and not necessarily to a change of the state of the catalytic converter. Fig. 20c shows the case of a low λ_{1max} due to a long time period of work of the catalytic converter in the lean region. In fig. 20d the control position is shifted towards rich, while in fig. 20e a higher control frequency of air/fuel ratio oscillation is used than that of fig. 20a.

In **DE4112480 (1992)** the engine is first brought into a forced inertia and idling condition. It is then operated with a lean air/fuel ratio mixture (λ=1.05) for a certain time (e.g. 5 sec) until the catalytic converter is completely filled with oxygen and the rotation speed is stabilized (fig. 21a). Then from time point T_1 onwards, the engine is operated with a λ varied in the opposite sense (rich) so that the upstream λ_1 value changes in the corresponding direction. The time taken between the starting time instant T_1 till a time instant T_3 is measured. T_3 is the time instant at which the signal λ_2 of the downstream probe changes in the same sense as the upstream one and exceeds a certain threshold ε (figs. 21abc). The aging state is defined by the parameter AZ which is calculated as follows:

$$AZ = k \cdot \frac{\Delta t}{\int_{T1}^{T3} \dot{Q}_{air}\, dt}$$

where

$\Delta t = T_3 - T_1$
k: constant

$\dot{Q}_{air}$: the volume of air introduced to the engine during the time interval Δt.

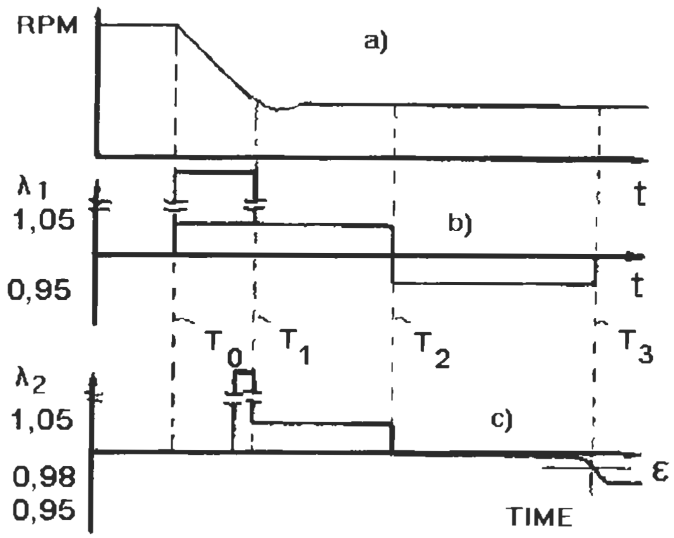


Fig. 21 (from DE4112480)

The method of **DE4128823 (1993)** can be better explained with reference to fig. 22. T_0 is the moment where the signal of the upstream probe changes from lean to rich. The broken line indicates the corresponding behavior of the downstream sensor output signal. The symbol t_s is the time span defined as

$$t_s = t_{PS} - (t_{G1} + t_{GK2})$$

where

t_{PS}: measured phase shift time of the signals from the two probes

$t_{G1} = \frac{k_1}{\dot{Q}_{air}}$: gas travel time from the upstream probe to the catalytic converter upstream face

$t_{GK2} = \frac{k_2}{\dot{Q}_{air}}$: gas travel time from the catalytic converter upstream face to the downstream probe

k_1, k_2: constants dependent on probe arrangement and the catalytic converter volume
$\dot{Q}_{air}$: the volume of air measured at the intake of the engine.

The actual storage capacity of the catalytic converter is then calculated from the formula:

$$AZ = \int_{T0}^{T0+ts} k_3 \cdot \Delta\lambda_1(t) \cdot \dot{Q}_{air}(t) \cdot dt$$

where

$$\Delta\lambda_1(t) = \lambda_1(t) - 1$$

and k_3 gives the content of oxygen in the air.

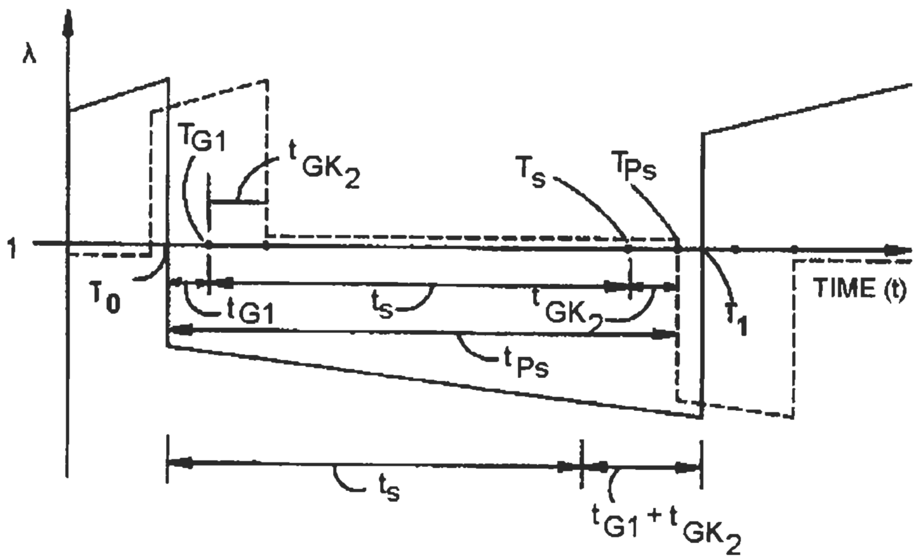


Fig. 22 (from DE4128823)

It is also logical to assume that the value of the air mass flow is constant and equal to the one at time T_0. By also setting k_3 1 the above mentioned formula is drastically simplified.

If t_{AT} is a predefined time interval and

$$n = {}^{t_s}\!/_{t_{AT}}$$

then the formula becomes

$$AZ = \sum_{m=1}^{n} k_3 \cdot \Delta\lambda_1(t_m) \cdot \dot{Q}_{air}(t_m)$$

If the value of AZ is lower than a predetermined threshold ε then the catalytic converter is considered to have been deteriorated.
The method requires no special test running of the engine and can be carried out at any stationary running state of the engine.

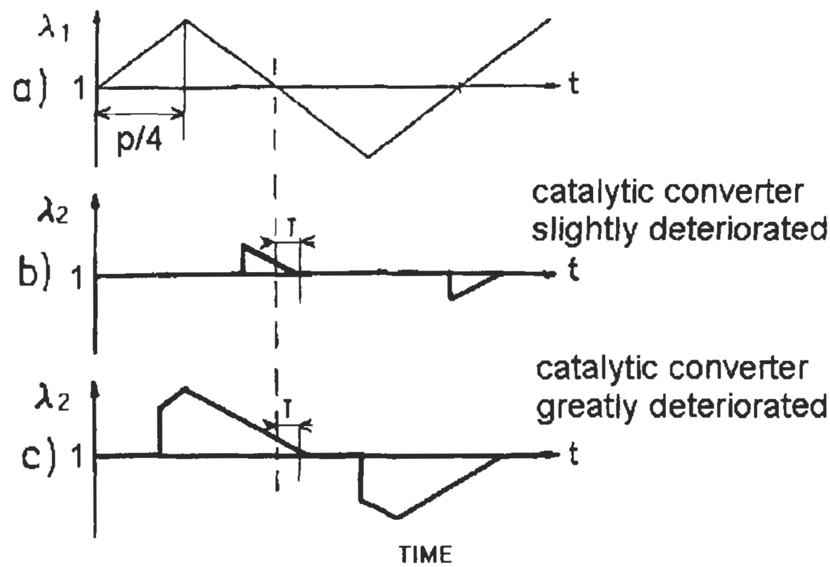


Fig. 23 (from DE4139560)

In **DE4139560 (1993)** a method is presented, which is applicable at stationary conditions of the engine (e.g. idling). A number of n oscillations of the upstream λ_1 signal takes place between a rich and a lean value. The product of the two λ signals is formed

$$P = \lambda_1 \cdot \lambda_2$$

Then the sum of all these products is formed and the average value is calculated

$$AZ = \frac{\sum_{i=1}^{n} P_i}{n}$$

If $AZ<\varepsilon$, where ε is a predefined threshold, then the catalytic converter is considered to be of low efficiency.

For a higher precision, the upstream signal can be correlated with a phase shift with the downstream signal. This correlation value is used for evaluating the performance loss of the catalytic converter. This can be better explained by means of fig. 23, where the air/fuel ratio variation measured by the upstream sensor (fig. 23a) and the corresponding air/fuel ratio variation measured by the downstream sensor are shown for the case of a slightly deteriorated catalytic converter (fig. 23b) and for the case of a greatly deteriorated catalytic converter (fig. 23c). A phase shift τ is present between λ_1 and λ_2, which is essentially dependent upon the running time of the exhaust gas from the upstream sensor to the downstream sensor. This phase shift τ is hardly dependent upon converter performance loss. The simplest correlation used is the cross correlation by multiplying the upstream phase shifted signals $\lambda_1(t + \tau)$ with the downstream measured signals $\lambda_2(t)$ and by summing the individual products.

Another correlation used is the orthogonal correlation. The signals $\lambda_1(t)$ and $\lambda_2(t)$ are multiplied with each other in order to obtain a real component RE after averaging. The upstream signal is then shifted by a quarter period (p/4) with respect to the output signal and the two signals are multiplied and an imaginary component is obtained. The amplitude and the phase p of the output signal can then be computed from the real and imaginary components. All four signals, that is the real and imaginary components, the amplitude and the phase p can each be used individually for evaluating the state of the performance loss of the catalytic converter.

In patent application **EP0546318 (1993)** the following method is considered. At time instant t_0 it is assumed that the oxygen deficient input quantity in the catalytic converter is higher than the oxygen stored. The quantity of fuel injected in the engine then starts oscillating. The engine air/fuel modulation factor FR has a square wave form and the mean value slowly runs down in time towards a lean shift of mean air/flow ratio (fig. 24a). The hatched areas over 1 indicate a deficiency of oxygen, while the areas under FR=1 represent an excess oxygen input quantity.

The corresponding indication of upstream probe is given in fig. 24b, where it simply shows the rich-lean or reverse change in each case with a low signal level being characteristic for oxygen excess.

Fig. 24c shows that the downstream probe registers the rich phase when the oxygen deficient input quantity is greater than the oxygen storage capability of the catalytic converter. With advancing test duration the oxygen deficient input quantity decreases and finally falls below the oxygen quantity that can be stored in the catalytic converter. The oxygen quantity stored in the oxygen excess phases is then no longer compensated by the oxygen deficient input quantity and the voltage signal V_2 no longer reaches a threshold value ε at time point t_d (fig. 24c). After t_d it only shows a lean mixture.

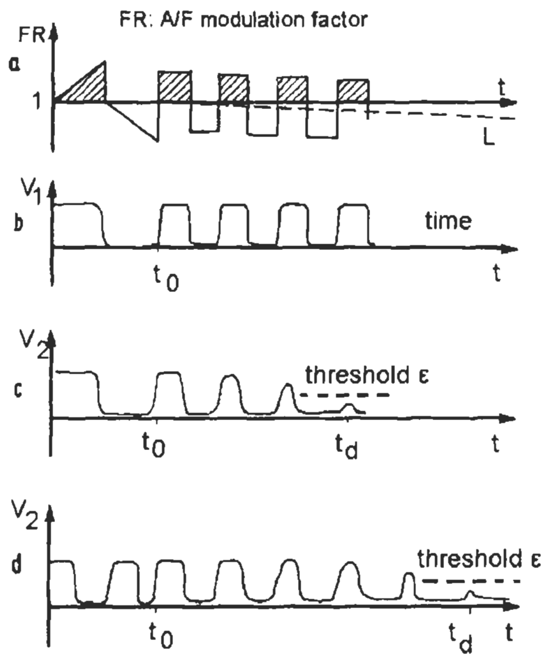


Fig. 24 (from EP0546318)

Finally, the lower the oxygen storage capacity of the catalytic converter, the later point t_d will occur. In this way the oxygen deficient input quantity is used to some extent as a criterion for the condition of a catalytic converter. Fig. 24d shows a case with a time (t_d-t_0) higher than the one of fig. 24c, showing a less efficient catalytic converter.

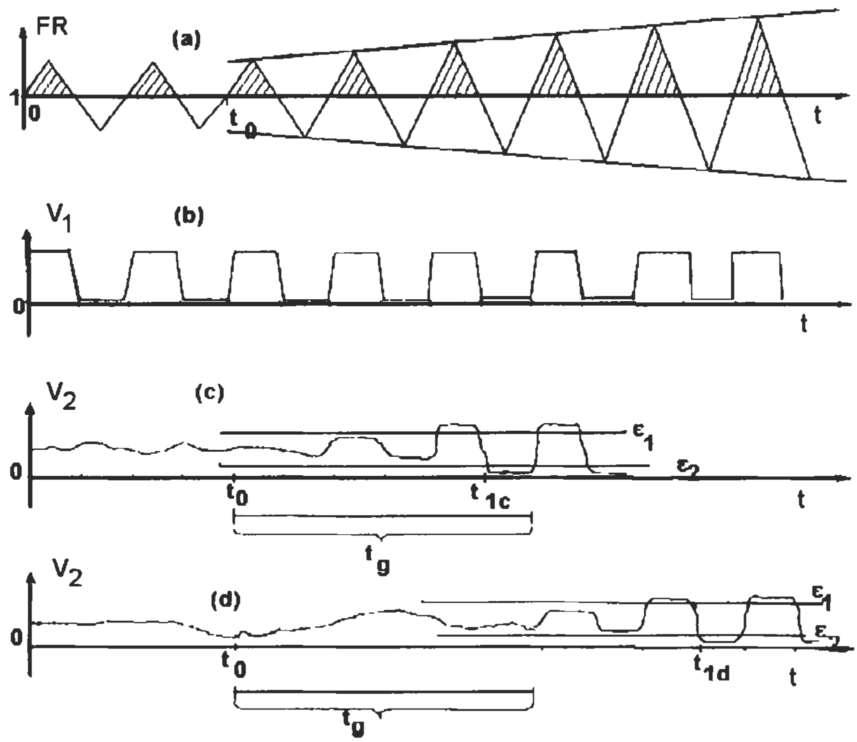


Fig. 25 (from DE4211116)

In **DE4211116 (1993)**, at a certain time t_0 a number of oscillations of the engine air/fuel ratio takes place from rich to lean and the opposite. The mean value of the variation is maintained constant, while the amplitude of the variation increases (fig. 25a). The corresponding voltage indication V_1 of the upstream sensor is shown in fig. 25b, while the corresponding voltage indications V_2 of the downstream sensor for a non-efficient and for an efficient converter are shown in figs. 25c and d respectively. The time t_1 at which simultaneously the upper peak of the V_2 variation passes over an upper predefined threshold value ε_1 and the lower peak of the V_2 variation passes under a lower predefined threshold ε_2 is considered to be the degradation criterion of a catalytic converter. The smaller the oxygen storage capability of the catalytic converter the earlier point t_1 appears.

Patent application **DE4323243 (1995)** refers to a need-based method of heating a catalytic converter. The converting power of the catalytic converter is determined by means of the two oxygen sensors which are arranged upstream and downstream of the converter respectively. Such methods are known in the prior art. If the converting power determined in this manner is not sufficient, measures are taken for heating the converter until a sufficient converting power is reached. If the heating measures do not lead to a sufficiently high converting power of the catalyst within a predetermined time interval, a diagnostic function is started in order to determine whether the converter is damaged. In this way, a damaged converter is not heated unnecessarily strongly and measures can be taken to limit the damage and to warn the driver. On the other hand, if the catalyst has sufficient converting power, the heating is stopped or not even started.

In **DE4337793 (1995)** a two-point regulation method is used. The signal λ_1 of the upstream probe is used as the first air/fuel regulation signal from rich to lean and vice versa with a certain frequency. When the frequency of the downstream signal is fixed and certain operating conditions of the engine are set (e.g. idling), then a two-point engine air/fuel ratio control is taken as the actual control signal with the downstream signal considered as a first control signal. The frequency f of this regulation is averaged and compared to a threshold frequency value f_c. If averaged $f > f_c$ then the catalytic converter is considered as aged and should be replaced.

The method of **DE4408504 (1995)** uses a specially built gas component concentration sensor for monitoring the efficiency of catalytic converters. The sensor comprises a solid oxygen-ion conducting electrolyte having two measuring electrodes. The electrolyte consists of ZrO_2 which is stabilized with Y_2O_3. The first measuring electrode catalyzes the equilibrium setting of the exhaust gas, whereas the second electrode does not. A heating device controls the temperature of the electrodes. The catalytic activity of the electrodes can be adjusted via temperature by arranging them in different temperature regions of the electrolyte. The first measuring electrode consists of platinum (Pt) or a platinum alloy with rhodium or palladium. The second measuring electrode consists of gold and/or silver, a platinum alloy with gold and/or silver or platinum-bismuth.

The method of **DE19623335 (1997)** comprises the following steps:

1) determining an actual output signal value of the downstream oxygen sensor
2) estimating an expected output signal value of the downstream oxygen sensor by means of the measured output signal of the upstream oxygen sensor and the measured quantity of air/fuel mixture introduced in the combustion chamber of the engine. The expected values correspond to a model catalytic converter that still has a sufficient conversion ability
3) calculating the sum (or integral) of differences of the determined actual and expected output signals of the downstream oxygen sensor during a time period
4) inhibiting the summation of step 3 when
   a) the oxygen filling degree of the converter is higher than a predetermined maximum value or the oxygen filling degree of the converter is lower than a predetermined minimum value, or

b) the per time unit oxygen surplus or shortage of exhaust gas oxygen flowing into the converter is higher than a predetermined maximum value

5) determining that the catalytic converter is deteriorated when the calculated sum (or integral) of differences of step 3 during said time period is higher than a predetermined threshold

Fig. 26 shows the criteria to determine the deterioration of a catalytic converter with the present method. The distribution in time of the integrated differences of the actual and expected values of the output signal of the downstream sensor is shown for four catalytic converters with different efficiencies.

Line 1 corresponds to a catalytic converter almost suffering the same deterioration as a model catalytic converter that is used to define the expected values of the output signal of the downstream sensor. The fact that the integral of differences between actual and expected values is almost zero means that the catalytic converter is similar to the one used as a model and the conversion ability is still high.

Line 2 corresponds to a new catalytic converter with superior conversion ability than the model catalytic converter, because it damps the oxygen oscillations better than the model converter. The differences between actual and expected values of the output signal of the downstream sensor are negative. In other words, the converters that show a line like 2 under the zero line are in good condition.

Lines 3 and 4 correspond respectively to a deteriorated converter and to a catalytic converter with no conversion ability. In both cases the measured actual values of the output signal of the downstream sensor are greater than the expected values that are based on a still efficient catalytic converter.

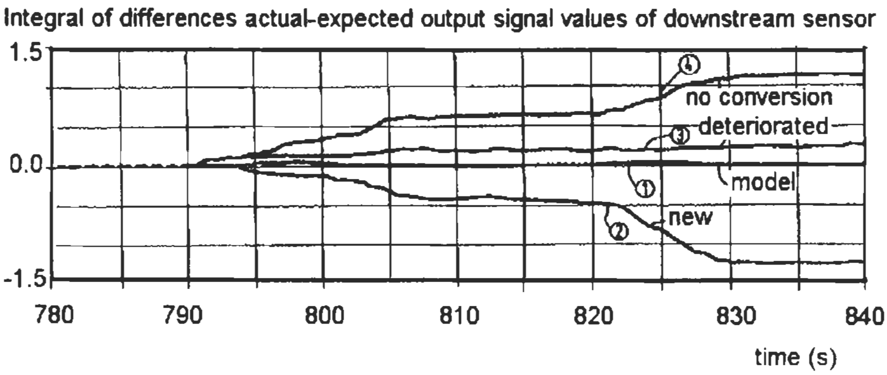


Fig. 26 (from DE19623335)

Chapter 1.2

Daimler-Benz AG

In **DE3443649 (1986)** a workshop test method is proposed. At constant operating conditions, a controlled slight oscillation of the engine air/fuel ratio around the stoichiometric one with a certain frequency is imposed. First the upstream probe is used as the control probe and the corresponding frequency indication f_1 is determined. Then the downstream probe is used as a control probe for the same operating conditions and the corresponding frequency of the control f_2 is determined (two-point closed loop control). The quotient of these two controlled frequencies is formed

$$AZ = \frac{f_1}{f_2}$$

and compared with a given required value range of quotients. If the quotient falls out of this range then the catalytic converter is considered as exhausted. This range is predefined once for the actual type of vehicle or catalytic converter. It obviates the need for road testing.

In **US4622809 (1986)** at predefined operating conditions the engine air/fuel ratio forcibly oscillates with a certain frequency. The corresponding output voltages of the upstream (control) and downstream (test) probes are shown in fig. 27a.
B is the maximum permissible amplitude of the downstream probe signal. If this limit is

exceeded (fig. 27b), the catalytic converter should be replaced, because the smaller the amplitude of this signal, the more complete has been the conversion of the exhaust gases in the catalytic converter. The averaged value of the downstream probe is also determined and it should fall in a predefined range A (fig. 27). In the case where the averaged signal does not fall in this range A (fig. 27c), the operating point of the control system is changed for such a length of time until the downstream probe has reached a desired value.

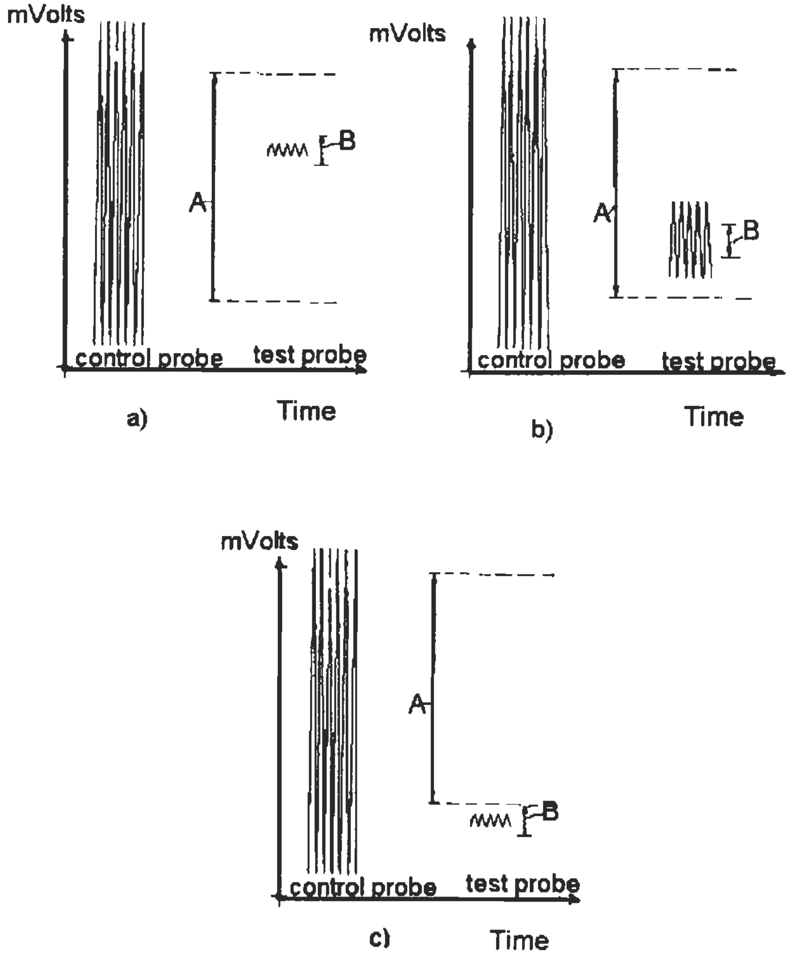


Fig. 27 (from US4622809)

In **GB2178857 (1987)** another workshop test method is applied. At idling or fast idling conditions, a forced switch of the engine air/fuel ratio from rich to lean and the opposite takes place. By introducing a delay element (RC element or a low pass filter) in the control circuit of the λ probe located upstream of the catalytic converter, the switch is retarded by 10 to 5000 msec (preferably 50 to 200 msec). The amount of measured remaining combustible constituents in the exhaust gases after the catalytic converter is a measure of its condition.

In **GB2225860 (1990)** two oxygen probes are installed in a catalytic converter (fig. 28) in its axial direction. The catalytic converter volume between the two probes is equal to 10-30% of the total catalyst volume. A sinusoidal forced oscillation of the engine air/fuel ratio (from rich to lean and the opposite) takes place. The time delay (phase shift) between a respective signal of each of the exhaust oxygen probes is evaluated in the control unit (not shown) to provide a measure of the state of the aging of the catalytic converter.

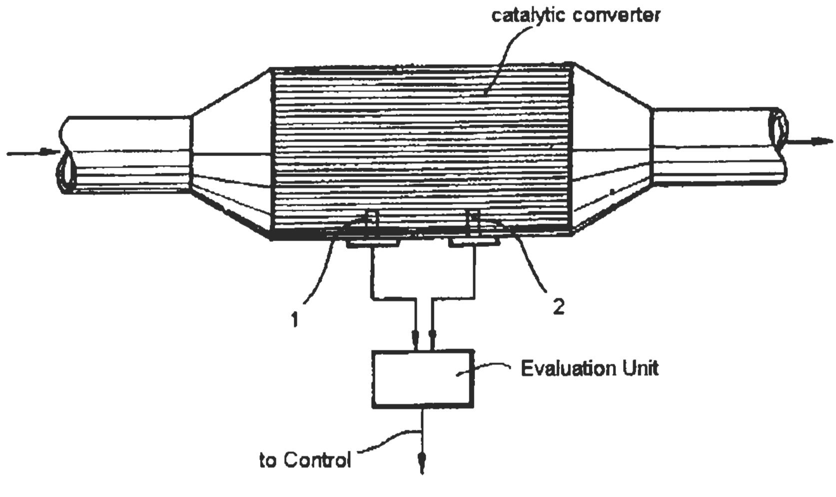


Fig. 28 (from GB2225860)

Chapter 1.3

Ford Motor Co. - Ford France SA - Ford Werke AG - Ford Motor Co. Canada - Ford Motor Co. Ltd.

Ford has presented since 1992 a significant number of methods concerning diagnostic methods of deterioration of catalytic converters. Most of these methods, except otherwise mentioned, have been applied for the engine layout of fig. 29 (see **EP0619420 (1994)**).

The controller is shown in the block diagram of fig. 29 as a conventional microcomputer including: microprocessor unit, input ports, output ports, read-only memory (ROM) for storing the control program, random access memory (RAM) for temporary data storage which may also be used for counters or timers, keep-alive memory for storing learned values and a conventional data bus.

The controller is shown receiving various signals from sensors coupled to the engine including: measurement of inducted mass airflow from a mass airflow sensor, engine coolant temperature from a temperature sensor, and indication of engine speed (rpm) from a tachometer.

The output signal V_1 from a conventional exhaust gas oxygen sensor 1, positioned upstream of catalytic converter, is compared to a reference value associated with stoichiometry in a comparator for providing a compared output signal V_1. Compared signal V_1 is a two-state signal which is a predetermined high voltage when exhaust gases are rich of stoichiometry and a predetermined low voltage when exhaust gases are lean of stoichiometry. Both compared and non-compared signals are coupled to the controller.

Another conventional exhaust gas oxygen sensor 2 is shown coupled to the exhaust manifold downstream of the catalytic converter and provides signal V_2 to the controller which is related to oxygen content in the exhaust gases. Output signal V_2 is also compared to a reference value associated with stoichiometry in the comparator for providing two-state output signal V_2 to the controller. The two-state output signal V_2 is preselected high voltage when exhaust gases downstream of the catalytic converter are rich of stoichiometry and a low preselected voltage when such exhaust gases are lean of stoichiometry.

The intake manifold of the engine is shown coupled to a throttle body having primary throttle plate positioned therein. The throttle body is also shown having a fuel injector coupled thereto for delivering liquid fuel in proportion to the pulse width of a signal from the controller. Fuel is delivered to the fuel injector by a conventional fuel system including fuel tank, fuel pump, and fuel rail.

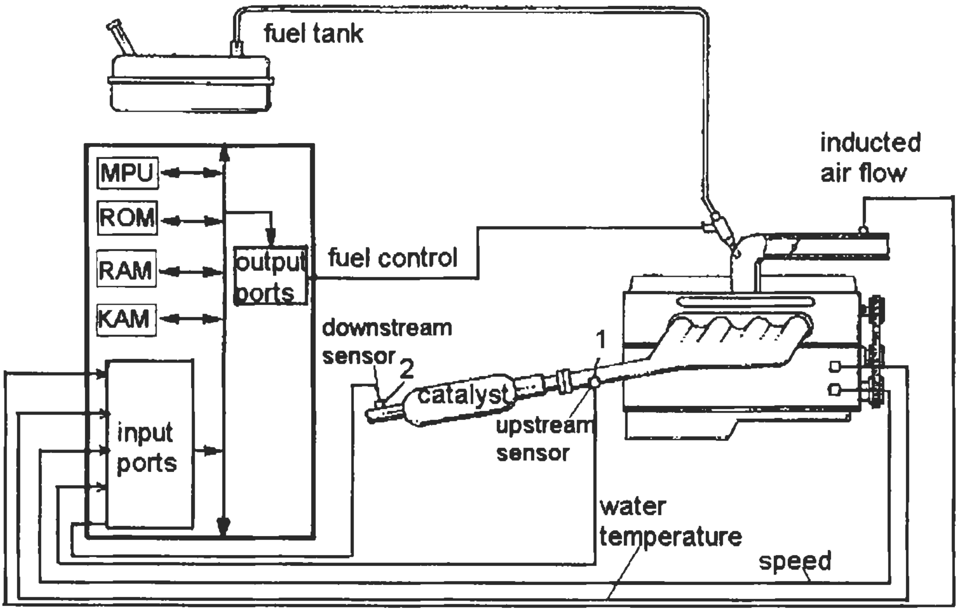


Fig. 29 (from EP0619420)

In **EP0466311 (1992)** a forced modulation (from rich to lean and vice versa) of frequency and/or amplitude of the engine air/fuel ratio takes place. The diagnosis is initiated when the engine is operating in closed-loop feedback mode and the engine is in steady state speed condition. The frequency and the amplitude of the modulation must fulfill certain conditions. During this modulation the catalytic converter is considered as degraded, when it is determined that there is an absence of substantial change between events in the downstream sensed air/fuel characteristic. This change can be

1) a change in degree of frequency and/or amplitude of downstream A/F characteristic
   or
2) a change in time for the downstream sensor to return to cyclical operation.

In Fig. 30 an example of an artificial amplitude modulation is presented. The left part corresponds to a good catalyst, the middle part corresponds to a good catalyst with low oxygen storage while the right part corresponds to a degraded catalyst. At time instant T_0, the CPU imposes a A/F modulation signal and determines whether or not the downstream sensor output exceeds a particular threshold ε during a predetermined time interval ΔT (timed window). In the right hand portion of fig. 30 the voltage of the downstream sensor passes over threshold ε before the expiration of ΔT, so the catalytic converter is considered as degraded.

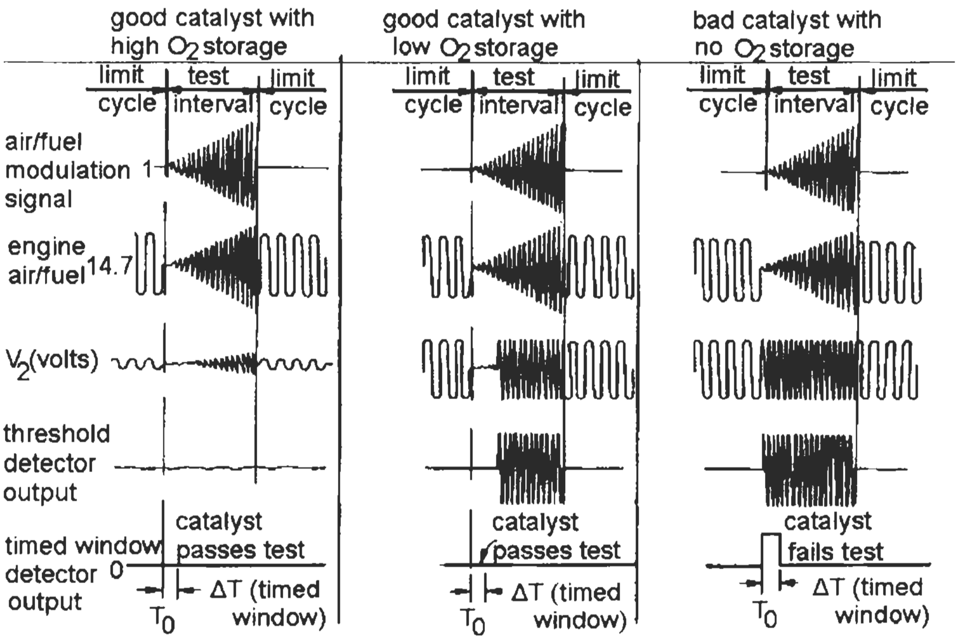


Fig. 30 (from EP0466311)

In fig. 31a an example of artificial frequency modulation of the engine air/fuel ratio is presented. The artificial frequency modulation is initiated at a high frequency at the beginning of the interrogation period and progressively reduced to below the normal limit cycle frequency of the closed-loop feedback system at termination of the interrogation period. During the interrogation period the amplitude of the oscillation is set higher than the amplitude of a normal limit cycle. For an efficient catalytic converter, the downstream sensor does not detect any modulation breakthrough until the A/F frequency has reached some low value. For faulty catalytic converters this breakthrough appears at a much higher air/fuel ratio frequency. "Breakthrough" is defined herein to mean that the oxygen storage capacity of the catalytic converter has been exceeded, and the modulation signals pass through the converter.

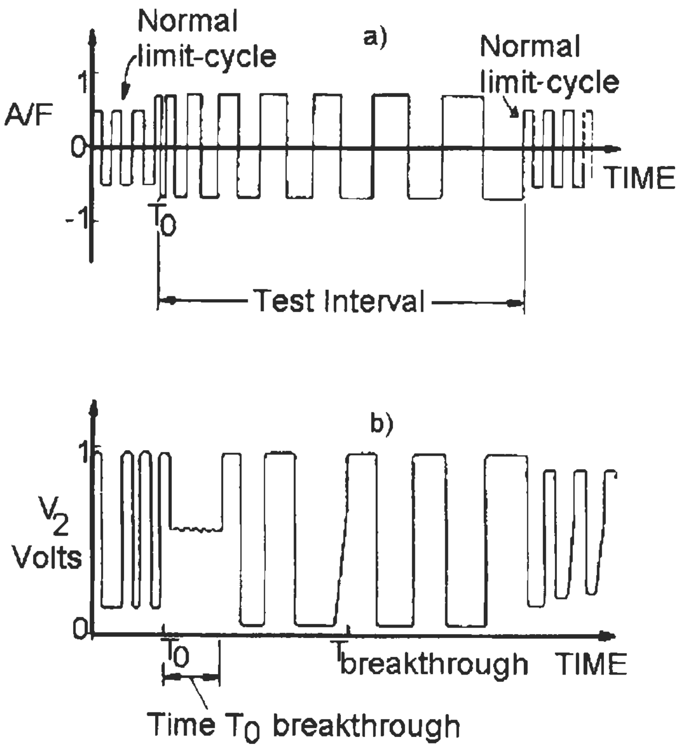


Fig. 31 (from EP0466311)

For linear decrease in time of the A/F modulation frequency, the oxygen storage can be determined by measuring the time that it takes for the downstream sensor to start switching after the test cycle has begun.

The downstream sensor might be an EGO or a hydrocarbon sensor.

In **US5099647 (1992)** an UEGO sensor and a HEGO sensor are installed respectively upstream and downstream of the catalytic converter. The outputs of the two sensors are coupled to a complementary filter set characterized by a crossover frequency.

The output of the upstream sensor is applied to a high pass filter, while the output of the downstream sensor is applied to a low pass filter. A summer receives inputs from each of the high and low pass filter sections and provides an output to a feedback controller which in turn controls a fuel metering system applying fuel to the engine. The method comprises three embodiments:

1) A low crossover frequency is established. The catalytic converter is then considered as exhausted when the measured amplitude of the downstream sensor is less than a predetermined amplitude, or
2) the crossover frequency can be increased until the catalyst monitoring signal reaches a predetermined amplitude. The crossover frequency that achieves this predetermined amplitude is then determined. The catalytic converter is considered as aged when this crossover frequency is greater than a predetermined one, or
3) the crossover frequency increases until the engine control means reaches air/fuel ratio limit cycle operation. The crossover frequency that achieves this limit cycle operation is then determined. The catalytic converter is considered as exhausted when this frequency of air/fuel limit operation is greater than a stored frequency.

A *limit cycle* is defined as the cycle of variation in air/fuel ratio control signal from a rich limit to a lean limit and back to the rich limit again.

In **US5157919 (1992)** the control system operates in a limit cycle mode, and frequencies of the limit cycles are changed by changing parameters of a system controller. Parameters of the catalytic converter are defined based on such limit cycle frequencies. These parameters are matched with experimentally developed functions to estimate catalytic converter efficiency.
The method comprises the following steps:

1) initiation of a closed loop air/fuel ratio control system using the downstream EGO probe
2) measuring the frequency of the limit cycle
3) changing one or more times, operating or structural parameters of a system controller to generate different limit cycle frequencies
4) measuring the frequency of each limit cycle
5) solving a system of equations which relate the limit cycle frequencies to the catalytic converter parameters and

6) determining the catalytic converter efficiency from a predetermined catalytic converter efficiency characterized as function of a transport time delay and time constants

The equations of step 5 are formed as follows: The exhaust is described as a transport delay time T_d (due to time from fuel delivery to engine cylinder till exhaust gas reaches the EGO sensor) and a set of first order low pass filters connected in series (due to catalytic converter oxygen storage damping of exhaust fluctuations, response of EGO, physical mixing and chemical reactions of the exhaust gases in the exhaust pipe).

In a form of Laplace transform, the transfer function $W_{sys}(s)$ of the system is

$$W_{sys}(s) = e^{T_d s} \cdot \prod_{i=1}^{n} \frac{1}{T_{ci} \cdot S + 1}$$

where T_{ci} are the low pass filter constants.
T_{ci} and T_d are unknown parameters which are to be determined during a test.
A controller with transfer function in Laplace form

$$W_{contr}(s) = H + G/s$$

can be used, where H is the calibratable gain (jumpback) and G is the controller ramp.

The limit cycle period T_{li} of the controller can be calculated from the following system of n+1 equations with (n+1) unknown parameters

$$G\frac{T_{li}}{4} - GT_d + \sum_{i=1}^{n} c_i(1-(1-th(\frac{T_{li}}{4T_{ci}}))) \cdot e^{\frac{T_d}{T_{ci}}}) = 0$$

where:
c_i is a known function of the controller jumpback H and the time constants T_{ci}.

The set of equations is formed by changing G, H or both of them n times. Additionally, (n+1) limit cycles T_{li} corresponding to each controller parameter setting should be measured. Then the set of (n+1) algebraic equations may be solved using any known numerical method. The catalytic converter efficiency is then determined from a predetermined catalytic converter efficiency characterized as a function of the calculated transport time delay and the calculated time constants.

In **US5159810 (1992)** the downstream EGO sensor is used for the engine closed loop air/fuel control during monitoring of the catalytic converter. The measured limit cycle frequency at various engine speed/load conditions is compared to stored benchmark limit cycle frequencies as functions of engine speed/load conditions. If the measured frequency is higher than the stored one, the catalytic converter is considered to be degraded.

In **WO9303358 (1993)** two differentially catalyzed EGO sensors replace the conventional EGO sensor downstream of the catalytic converter (fig. 32). One of the sensors is highly-catalyzed while the other one is low or non-catalyzed. As it can be noticed from fig. 32, there is an important change of the downstream highly-catalyzed sensor signal depending on whether the catalytic converter is good or bad.

The low or non-catalyzed sensor signal shows smaller amplitude variations, because the sensor cannot equilibrate the gases in the case of a bad converter and the sensor is consequently saturated.

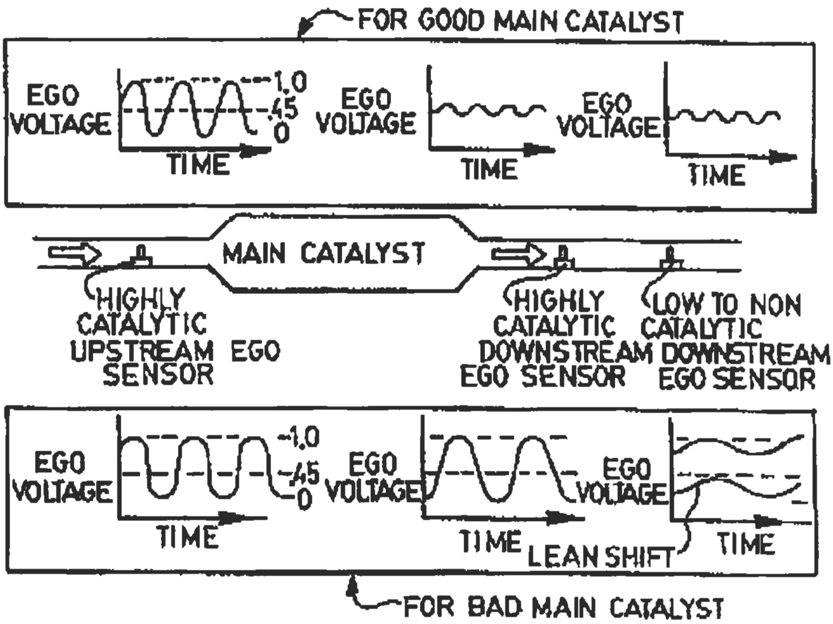


Fig. 32 (from WO9303358)

fThe engine is operated under closed-loop control by making use first of the downstream highly-catalyzed sensor and then by making use of the downstream low or non-catalyzed sensor and the change in the engine air/fuel ratio feedback signal is observed while doing so. Since the two sensors will produce the same output voltage at a different air/fuel ratio value, there will be a difference in the air/fuel feedback signal of the engine depending on which sensor is in control. The magnitude of the change in air/fuel feedback signal is used as an indicator of the condition of the catalytic converter.

In fig. 33 a preferred embodiment of the current method is presented. The feedback signal of air/fuel ratio using a low or non-catalyzed downstream sensor, gradually increases to a new higher level over a period 5-10 sec in the case of a degraded catalytic converter. This period is enough for an accurate, clear comparison of the signals to be made. In case of a good catalytic converter this signal remains essentially the same as for the highly-catalyzed sensor. The method does not require any comparisons to pre-stored data for the evaluation of the condition of the catalytic converter.

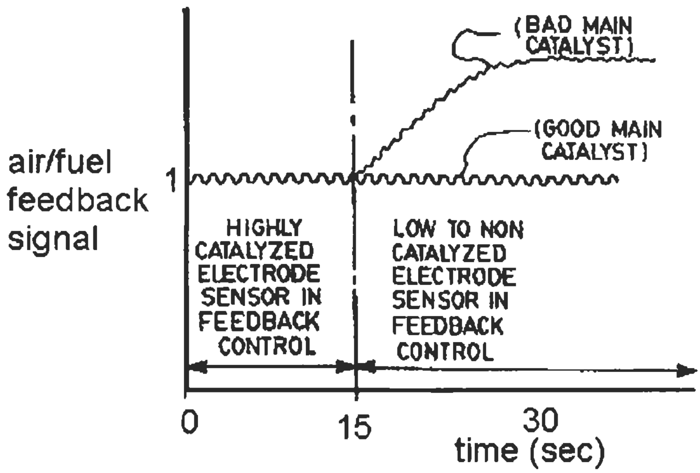


Fig. 33 (from WO9303358)

The oxygen sensors used in the method of **WO9303358 (1993)** are described in detail in **WO9303357 (1993)**.

In **EP0521641 (1993)** and **US5313791 (1994)** the *feedback gain* of the feedback loop control is the parameter that defines the exhaustion of a catalytic converter. The rate at which the controller system increases or decreases the engine air/fuel ratio for a step change in the downstream HEGO sensor output is defined as the ***gain*** of the post-catalytic converter air/fuel feedback system. The engine is operated under closed-loop control with the downstream HEGO probe controlling the air/fuel ratio. Three embodiments of this method are presented:

1) The gain of the downstream air/fuel feedback loop is set at a low value during test. Low value means that when the catalytic converter conversion efficiency is high enough then no definite limit cycle oscillation is produced. Any degradation of the catalytic converter is detected by looking for a decrease in the amplitude of the HEGO sensor output fluctuations compared to the value measured with a good catalytic converter. Temperature corrections to the HEGO control signal may also be applied.
2) The gain of the feedback loop is automatically adjusted to maintain the amplitude of the HEGO sensor output at a particular value. As the catalytic converter conversion efficiency decreases, the gain would automatically increase. When the gain exceeds some preset level then the catalytic converter is considered as exhausted.
3) The feedback gain is increased from an initial low value until it is high enough to produce a relatively clean limit cycle oscillation. At that point, the gain is held constant and the limit cycle frequency is measured. A low gain is used initially to prevent overdriving the catalytic converter, which could result in a multiplicity of limit cycle frequencies. Thus, indication of catalytic converter degradation is based on a combination of the feedback gain required to produce a limit cycle oscillation and the value of the limit cycle frequency.

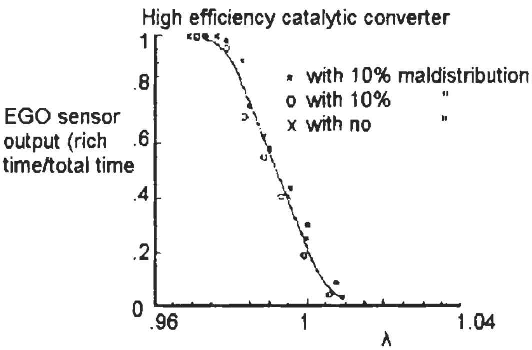


Fig. 34a (from US5265416)

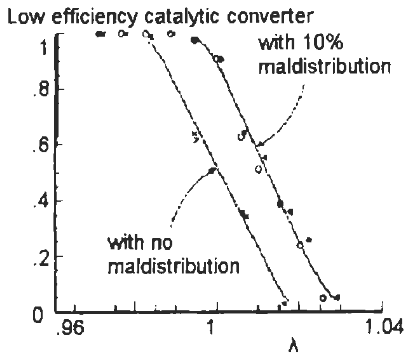


Fig. 34b (from US5265416)

In **US5265416 (1993)** the air/fuel ratio fed to the engine is perturbed on a cylinder-to-cylinder basis above and below a mean or average air/fuel ratio. That is, individual cylinders are fed, in their firing sequence, alternately rich and lean air/fuel mixtures with no overall rich or lean shift of the fuel mixture (maldistribution). The output signal of the downstream of the catalytic converter installed EGO sensor during the perturbation is compared to the corresponding signal measured a time period either immediately preceding or immediately following this perturbation. As it can be seen from fig. 34a, the EGO sensor output is substantially unaffected for both cases of perturbed and non-perturbed engine air/fuel ratio and for the case of an efficient catalytic converter. The EGO sensor output is measurably affected by cylinder-to-cylinder maldistribution in the case of low efficiency converter (fig. 34b). In both figures the EGO sensor output is shown as the portion of time the output signal is on the rich side of the EGO sensor switch-point. The difference of the EGO outputs for the cases of cylinder-to-cylinder air/fuel ratio maldistribution and non-maldistribution is a measure of catalytic converter efficiency.

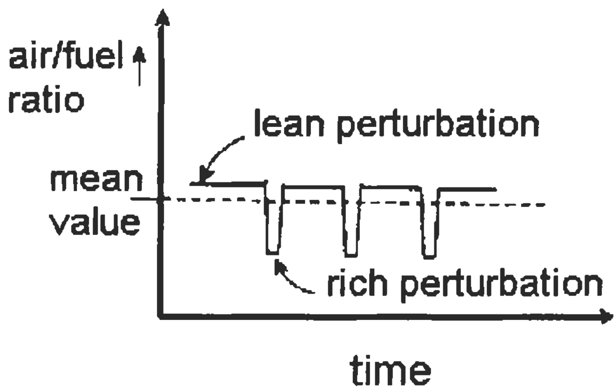


Fig. 35 (from US5272872)

In **US5272872 (1993)** the test period starts at steady state conditions of the engine, during which the closed loop fuel control of the engine is carried out by using only the output signal of the upstream EGO sensor. Air/fuel ratio perturbations are generated comprising establishment of an initial lean interval of the air/fuel ratio higher than the stoichiometric one, followed by a series of rich intervals alternating with lean intervals (fig. 35).
The lean intervals are of a small amplitude and long duration whereas the rich intervals are of high amplitude and short duration. The average air/fuel remains equal to the stoichiometric one. The number of perturbations sensed by the upstream sensor is compared to the number of perturbations detected by the downstream EGO sensor following the initial lean interval. An efficiency value of the catalytic converter is then determined on the basis of this comparison.

This value is then compared to a pre-determined, stored value of the catalytic converter efficiency in order to determine if the converter is within an acceptable efficiency range.

In **US5289678 (1994)** a dual closed loop air/fuel ratio control system is used with two EGO sensors installed upstream and downstream of the catalytic converter. The number of times the downstream EGO sensor switches from rich to lean and vice versa is compared to the corresponding number of times the upstream EGO sensor switches during normal system operation over the course of a test period.

The ratio of the switching frequencies is calculated and compared to a pre-determined, stored value in order to draw conclusions about the efficiency of the catalytic converter. Typically, for a well functioning catalytic converter, the upstream sensor may switch ten times for each downstream sensor switch. As the catalytic converter degrades the ratio moves closer to one-to-one. A normalization of the frequency ratio calculation allows the reduction of dependence of engine speed and load on the downstream sensor.

In **US5319921 (1994)** the test of the catalytic converter takes place at steady operating conditions. During test mode, a test signal is produced, which has a total variation of zero mean value. The test signal is a periodic function having a frequency higher than the natural frequency of the limit-cycle of the downstream EGO sensor. The control of the fuel in the engine takes place by means of a control signal produced from this test signal and the signal of the downstream EGO sensor (e.g. by summing the two signals). After a certain number of cycles the controlling system locks up the test signal i.e. the output signal from downstream EGO sensor and the controller of the system oscillate with the same frequency as the test signal. Then a value of the downstream output signal is compared to a stored value corresponding to a minimum acceptable efficiency of the catalytic converter. This output can be the integral, over a test interval, of an absolute value of the downstream output signal deviation from stoichiometry ($\lambda=1$), divided by the integral over the test interval of the fuel flow control signal deviation from stoichiometry. A failure signal is produced when the measured efficiency is lower than an acceptable value.

In **US5351484 (1994),** the efficiency of a light-off catalytic converter installed upstream of a main catalytic converter is monitored. Two EGO sensors are installed upstream and downstream of the light-off catalytic converter. The monitoring is activated when the mass of the air flow into the engine is such that the space velocity is sufficiently low and the catalytic converter monitoring is not saturated. The ratio of the frequencies of the downstream EGO switching to the upstream EGO switching is used then as criterion of degradation of the catalytic converter.

In **US5353592 (1994)** an attempt is made to provide a catalytic converter monitoring method while concurrently maintaining air/fuel control. Two EGO sensors upstream and downstream of the catalytic converter are used. The measured inducted flow of air to the engine (further called simply "air flow") is used as a criterion of the catalytic converter degradation. The method consists of the following steps:

1) adjusting the engine air/fuel ratio in response to the feedback signal derived from the upstream EGO output
2) accumulating one of a plurality of air flow values upon each transition in output states of the downstream EGO sensor output, each of the air flow values being related to one of a plurality of inducted air flow ranges inducted into the engine and said air flow value which is accumulated upon the downstream sensor output transition is related to the air flow range in which the downstream sensor output transition occurred
3) averaging the accumulated air flow values over a test period e.g. by dividing said air flow values accumulated over said test period by an accumulation of said downstream sensor transitions over said test period
4) and providing an indication of converter degradation when the average falls below a pre-selected average.

The test period is completed when the engine has operated for at least a minimum pre-selected number of upstream sensor output transitions per air flow range. The transitions in the upstream and downstream EGO sensors are generated by comparing each sensor output to a reference.

In **EP0619420 (1994)** a ratio of the transition frequency of the downstream EGO sensor over the transition frequency of the upstream EGO defines the criterion of efficiency of the catalytic converter. The method consists of the following steps:

1) defining a number of inducted engine air flow ranges
2) separately counting the number of transitions from lean air/fuel ratio to rich and vice versa of the upstream EGO sensor in each of the inducted air flow ranges
3) limiting each of the separate upstream sensor counts to one of a corresponding plurality of pre-selected maximum values for each of the air flow ranges
4) generating a separate test period for each of the flow ranges when the upstream sensor reaches the corresponding maximum value of transitions
5) counting the corresponding transitions of the downstream sensor output for each separate test period
6) summing all transition counts of the downstream sensor output for air flow ranges for at least the test period corresponding to each of the flow ranges
7) summing all transition counts of the upstream sensor output for air flow ranges for at least the test period corresponding to each of the flow ranges
8) forming the ratio of the sum of step 6 over the sum of step 7
9) concluding that the catalytic converter is degraded when this ratio exceeds a predetermined ratio

The method also includes the steps of controlling fuel delivered to the engine in response to a feedback of the upstream sensor output and trimming this output in response to a trim signal derived from the downstream sensor output.

In **US5363646 (1994)** the following steps are applied:

1) integrating an output of the upstream oxygen sensor to generate a feedback variable
2) controlling fuel delivery to the engine in response to this feedback variable
3) providing a test period each time the engine has completed operation within each of a plurality of inducted air flow ranges for at least a minimum duration in each of said air flow ranges. Said minimum duration comprises a pre-selected number of transitions of the feedback variable per air flow range.
4) generating a monitoring ratio related to a ratio of frequency of transitions in the feedback variable to frequency of transitions from the downstream sensor output for each of said test periods
5) providing a weighted average of the monitoring ratio over a plurality of test periods
6) indicating degradation in efficiency of the converter when the weighted average of step 5 exceeds a predetermined value (for a pre-selected number of times).

The weighted average of the monitoring ratio of step 5 is reset to the monitoring ratio itself after the monitoring ratio exceeds the weighted average by a pre-selected amount Δ.

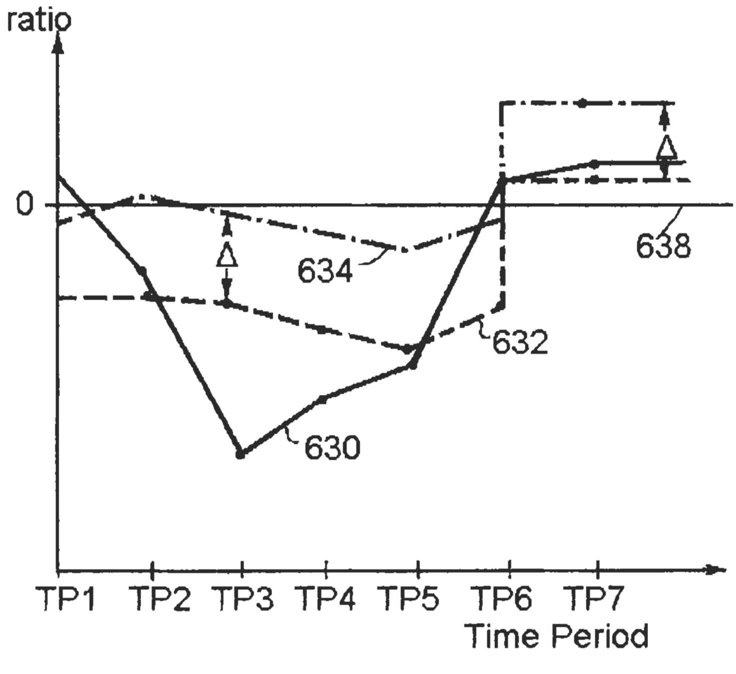


Fig. 36 (from US5363646)

This operation is described in fig. 36, where TP1 to TP7 correspond to 7 test periods. Lines 630, 632, 634 and 638 correspond to a hypothetical selected monitoring ratio, a corresponding weighted average ratio, a deviation Δ from the weighted average ratio and a reference ratio indicating a faulty catalytic converter respectively. Selected ratios are shown at the end of each test period.
At the end of TP1 the selected ratio (line 630) is higher than the reference ratio (638). This seems to be a casual fluctuation and is not an indication of catalytic converter failure because the corresponding weighted average ratio (line 632) is below reference line 638. At the end of TP6 the selected ratio (line 630) exceeds weighted average ratio (line 632) by more than Δ. Accordingly, the weighted average ratio (line 632) is reset to selected ratio (line 630) as shown at TP6. The reset weighted average (line 632) at TP6 exceeds reference line 638 indicating a degraded catalytic converter.

In **US5381656 (1995)** the following mentioned steps are followed:
1) generating a feedback variable by integrating an output of the upstream oxygen sensor
2) trimming said integration by a signal derived from the output of the downstream oxygen sensor
3) cycling the above mentioned variable above and below a nominal value
4) adjusting fuel delivered to the engine by the feedback variable
5) generating a first test signal by squaring the peak amplitude of said feedback variable for each cycle of a plurality of cycles of step 3 and summing the squares
6) generating a second test signal by squaring the peak amplitude of the downstream sensor output for each cycle of a plurality of cycles of step 3 and summing the squares
7) completing a test cycle generated when the engine has operated during a plurality of inducted air flow ranges each for a predetermined duration. This duration comprises a pre-selected number of cycles of the feedback variable.
8) after completion of test cycle, indicating degraded catalytic converter when a ratio of the second test signal over the first test signal exceeds a predetermined ratio

In **US5386693 (1995)** the following steps are applied:
1) integrating an output of the upstream oxygen sensor to generate a feedback variable
2) controlling fuel delivery to the engine in response to this feedback variable
3) providing a test period each time the engine has completed operation within each of a plurality of inducted air flow ranges for at least a minimum duration in each of said air flow ranges. Said minimum duration comprises a pre-selected number of transitions of the feedback variable per air flow range.
4) generating a first monitoring ratio related to a ratio of frequency of transitions in the feedback variable to frequency of transitions from the downstream sensor output for each of said test periods
5) generating a second monitoring ratio related to a ratio of amplitude of transitions in the feedback variable to amplitude of transitions from the downstream sensor output for each of said test periods

6) indicating degradation in efficiency of the converter when at least both said first monitoring ratio and said second monitoring ratio are beyond pre-selected values during said test period
7) by further generating a third monitoring ratio related to a ratio of an integration of said feedback variable to an integration of the downstream exhaust gas oxygen sensor output during this test period and wherein said indicating step 6 is also responsive to said third monitoring signal.

In **US5404718 (1995)** the method consists of the following steps:
1) providing a test cycle each time the engine has completed operation within each of a plurality of inducted air flow ranges for at least a minimum duration in each of said air flow ranges. Said minimum duration comprises a pre-selected number of transitions from a first state to a second state of the output signal of the upstream sensor while the engine operates in one of said flow ranges.
2) integrating an output of the upstream oxygen sensor over said test cycle to generate a feedback variable
3) controlling fuel delivery to the engine in response to this feedback variable
4) integrating an absolute value of the feedback variable over said test cycle to generate a first control signal
5) integrating a rectified output of the downstream sensor over said cycle to generate a second control signal
6) calculating a ratio of said second control signal to said first control signal to determine catalytic efficiency by comparing this ratio to a predetermined one.

In **US5390490 (1995)** the method follows the steps mentioned below:
1) detecting the oxygen content of the exhaust gases by means of the upstream sensor
2) detecting the oxygen content downstream of the catalytic converter by means of the downstream sensor
3) maintaining the air/fuel mixture fed to the engine at a first bias value
4) calculating a first time value, which is indicative of the time required for the upstream sensor to detect the exhaust gas produced from the combustion of the air/fuel mixture maintained at the first bias value
5) calculating a second time value, which is indicative of the time required for the downstream sensor to detect the exhaust gas produced from the combustion of the air/fuel mixture maintained at the first bias value
6) estimating the efficiency of the catalytic converter from pre-stored data by making use of these first and second time values. If the efficiency is outside a predetermined range then the catalytic converter is considered as exhausted.

Additionally, the method allows a repetition of steps 4 and 5 for calculating a third and a fourth time value when the exhaust gas produced from the combustion of the air/fuel mixture is maintained at a second bias value. Then the efficiency of the catalytic converter is additionally responsive to said second bias value and to said third and fourth time values. In this case the air/fuel mixture is altered abruptly from the first to the second bias value.

The method of **US5499500 (1996)** comprises the following steps:
1) adjusting the fuel delivered to the engine (responsive to the upstream oxygen sensor) to maintain the engine air/fuel ratio at a desired value
2) pumping electric current at a gradually increasing amplitude into an electrode of the downstream exhaust gas oxygen sensor having a non-catalytic electrode until the output of the sensor changes output states
3) providing an indication of the converter efficiency in relation to the pumping current amplitude occurring at the change of the downstream sensor output state

The method also allows checking of the condition of the downstream sensor and to retard the engine ignition timing when the efficiency of the catalytic converter is less than a predetermined efficiency.

The method of **US5522219 (1996)** allows the monitoring of the condition of an auxiliary catalytic converter installed in a bypass channel upstream of the main catalytic converter and the monitoring of the main catalytic converter as well (fig. 37).

The exhaust gases are enabled to flow through the auxiliary catalytic converter when the temperature of the exhaust gases is lower than a predetermined value and the exhaust gases are enabled to flow only through the main catalytic converter when the temperature is over the predetermined value. This switching of the exhaust gases flow takes place by means an electronic control of two bypass valves, one installed in the bypass channel and one installed in the main channel. The method comprises the following steps:
1) establishing test conditions based on the air flow inducted to the engine (see the description of any of the methods mentioned above)
2) adjusting the engine air/fuel ratio in response to a feedback variable derived from the oxygen sensor installed upstream of the main catalytic converter
3) correcting the feedback variable in response to a correction signal derived from the oxygen sensor downstream of the main catalytic converter
4) allowing flow of the exhaust gas through the main catalytic converter at high temperatures of the gases
5) providing a first ratio of transitions in outputs of exhaust gas oxygen sensors respectively positioned downstream and upstream of the main catalytic converter
6) allowing flow of the exhaust gas through the auxiliary catalytic converter at low temperatures of the gases
7) providing a second ratio of transitions in outputs of exhaust gas oxygen sensors respectively positioned downstream and upstream of the auxiliary catalytic converter
8) indicating degraded operation of the main catalytic converter when the first ratio exceeds a first predetermined ratio
9) indicating degraded operation of the auxiliary converter when both the second ratio exceeds a second predetermined ratio and an indication of the air flow inducted into the engine exceeds a predetermined air flow

The method of patent **US5544481 (1996)** comprises the following steps:

1) delivering fuel to the engine in proportion to a fuel signal
2) adjusting the fuel signal with a feedback variable derived from a comparison of a reference amplitude to an output amplitude of the upstream exhaust gas oxygen sensor
3) biasing the fuel signal in relation to a biasing signal derived from a comparison of a reference value to an output amplitude of the downstream exhaust gas oxygen sensor
4) generating a difference in amplitude of the downstream sensor output amplitude between two successive sample periods
5) storing the downstream sensor output amplitude as a peak amplitude each sample period when the downstream sensor amplitude difference changes signs thereby providing a stored peak value
6) indicating a downstream sensor transition when the downstream sensor difference between the stored peak value and the peak value stored during a previous change in said sign of the downstream sensor amplitude exceeds a predetermined value
7) indicating catalytic converter efficiency from a ratio of transitions of the downstream sensor transitions to transitions of the upstream signal derived from the upstream sensor output amplitude

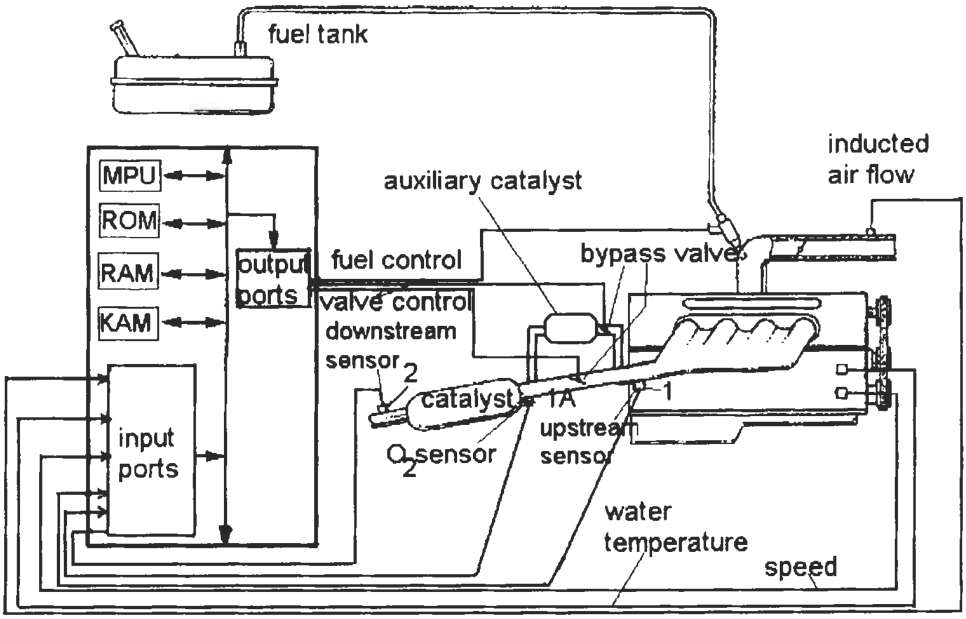


Fig. 37 (from US5522219)

Engines with multiple cylinder groups

The following methods refer to the case of an engine with two banks of cylinders comprising a catalytic converter at the common pipe section of the two banks (fig. 38).

Referring to fig. 38, an engine has two exhaust pipes (left and right), one for each bank of the engine which are joined together in a common exhaust pipe which is applied to a catalytic converter. From the catalytic converter an exhaust pipe passes the exhaust gas to the outside. An exhaust gas oxygen sensor 1a is located in the left bank exhaust pipe, an exhaust gas oxygen sensor 1b is located in the right bank exhaust pipe, an exhaust gas oxygen sensor 1 is located upstream of the converter and an exhaust gas oxygen sensor 2 is located downstream of the converter. The exhaust gas oxygen sensor 1a is a typical air fuel ratio amplitude signal versus time characterizing the exhaust gas carried in left bank exhaust pipe. The exhaust gas oxygen sensor 1b is an air fuel ratio amplitude signal versus time characterizing the exhaust gas carried in the right bank exhaust pipe. A catalytic converter monitoring control module is coupled to exhaust gas oxygen sensors 1 and 2 to sense a switching rate of sensors 1 and 2 and to determine when monitoring of the catalytic converter can occur. The control module is also coupled to exhaust gas oxygen sensors 1a and 1b to sense switching signals used for air/fuel ratio control.

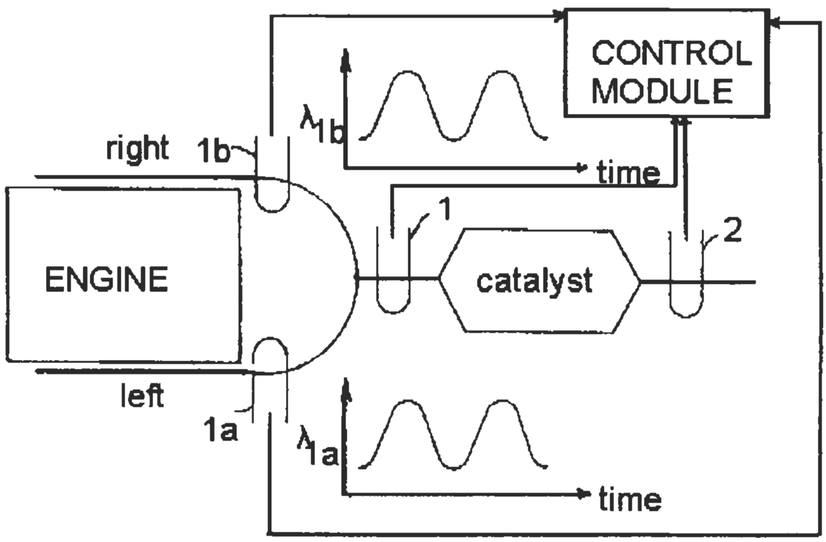


Fig. 38 (from US5357753)

In **US5357753 (1994),** a method for detecting deterioration of a catalytic converter is presented for a layout similar to this of fig. 38.
If the air/fuel ratios in the two branches are out of phase, then the air/fuel ratio upstream of the catalytic converter is substantially constant (fig. 39a) and monitoring is disabled. Monitoring is made possible when a forced variation of the air/fuel ratio upstream of the catalytic converter exists and is over a certain threshold (fig. 39b). That means that the air/fuel signals in the two branches are in phase. Then the signals of the upstream sensor (fig. 39c) and the downstream sensor (fig. 39d) are compared and the effectiveness of the catalytic converter is determined. The two sensors placed in the branches are used as feedback elements, whereas the sensors installed upstream and downstream of the catalytic converter are used only for the monitoring.

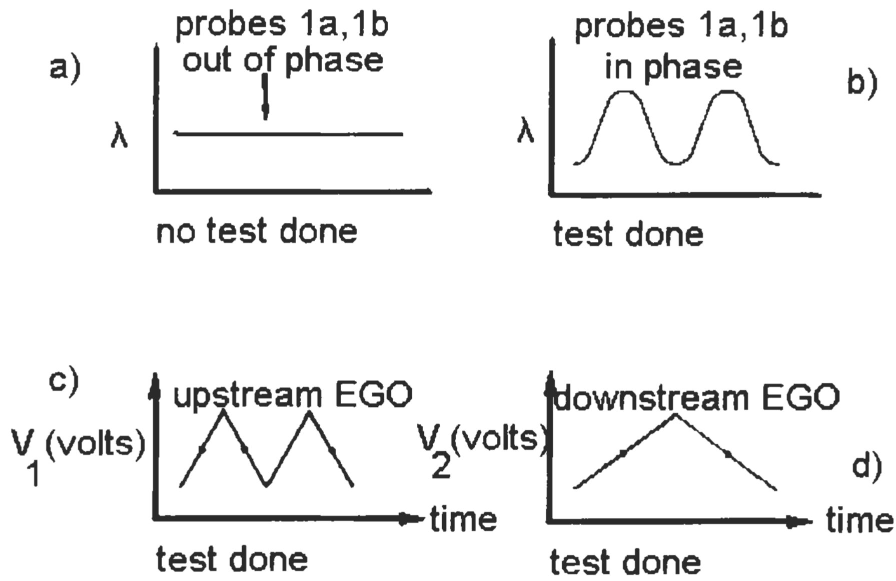


Fig. 39 (from US5357753)

In **US5385016 (1995)** a method to monitor a catalytic converter is presented for an engine with two cylinder banks as the one of **US5357753 (1994).** The arrangement of the sensors is similar to the one of fig. 38 except for the fact that the sensor placed between the junction of the two exhaust gas branches and the catalytic converter is removed. The method consists of the following steps:

1) adjusting the fuel delivered to the left bank of cylinders in response to the upstream sensor placed at the right exhaust branch and in response to the oxygen sensor placed downstream of the catalytic converter
2) adjusting the fuel delivered to the right bank of cylinders in response to the upstream sensor placed at the left exhaust branch and in response to the oxygen sensor placed downstream of the catalytic converter
3) creating an inferred signal by combining output signals from said left and right exhaust oxygen sensors. An inferred signal is an inference of an output from a hypothetical exhaust gas oxygen sensor exposed to a hypothetical blended mixture of exhaust gases from the right and left exhaust manifolds. The inferred signal is extracted from a lookup table in function of the sampled signals of the left and right oxygen sensors
4) indicating converter efficiency in response to a ratio of a count in transitions between output states of the downstream sensor to the count in transitions between output states of said inferred signal. When this ratio exceeds a predetermined one the catalytic converter is considered as degraded

The creation of the inferred signal and indication of the catalytic converter efficiency occur during a test period, which is completed when the engine has completed operation within each of a plurality of inducted air flow ranges for at least a minimum duration in each of said air flow ranges. The minimum duration is determined when the inferred signal has completed a predetermined number of transitions.

The table of inferred signals of step 3 is generated by empirical testing and measurements for many combinations of catalytic converter upstream signals.

Chapter 1.4

Toyota Motor Co. Ltd.

Toyota has presented since 1990 a significant number of methods concerning diagnostic methods of deterioration of catalytic converters. Most of these methods, except otherwise mentioned, have been applied for an engine layout similar to that of fig. 40.

In fig. 40, an air-intake passage of the engine is provided with a potentiometer-type airflow meter for detecting an amount of air drawn into the engine and generates an analog voltage signal proportional to the amount of air flowing through. The signal from the air-flow meter is transmitted to a multiplexer incorporating analog-to-digital (A/D) converter of the control circuit.

Crank angle sensors, for detecting the angle of the crankshaft (not shown) of the engine, are disposed at a distributor. The first of the crank angle sensors generates a pulse signal at every 720 DEG crank angle (CA) and the second crank angle sensor generates a pulse signal at every 30 DEG CA. The pulse signals from the crank angle sensors are supplied to an input/output (I/O) interface of the control circuit. Further, the pulse signal of the second crank angle sensor is then supplied to an interruption terminal of a central processing unit (CPU).

In the air intake passage, a fuel injection valve is provided at an inlet port of each cylinder of the engine, for supplying pressurized fuel from the fuel system to the cylinders of the engine.

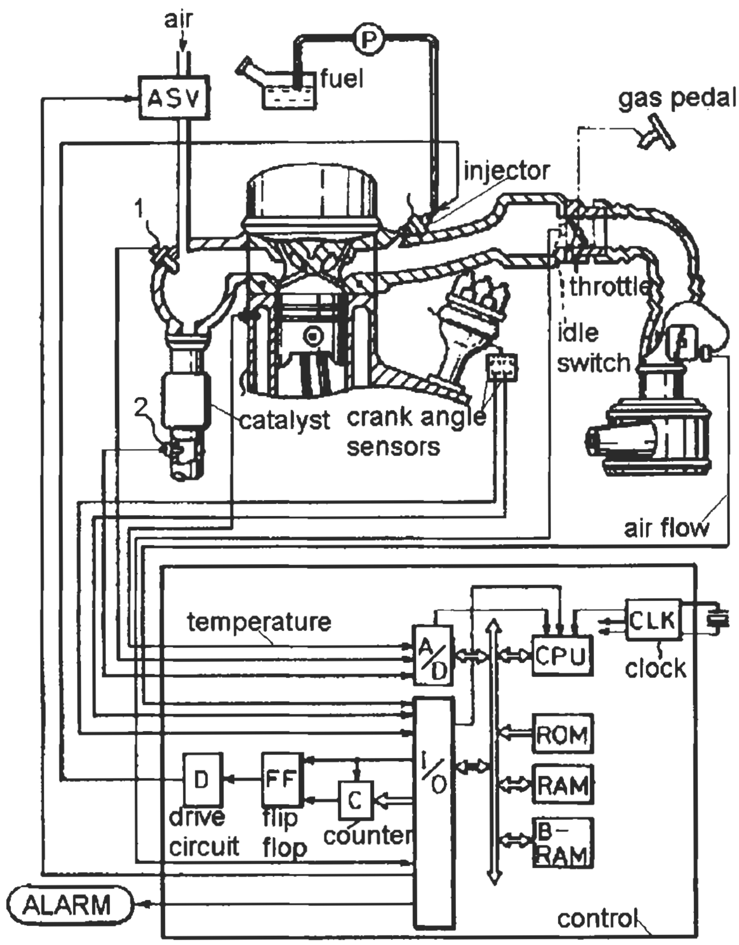


Fig. 40 (from EP0547326)

A coolant temperature sensor for detecting the temperature of the coolant is disposed in a water jacket of a cylinder block of the engine. The coolant temperature sensor generates an analog voltage signal in response to the temperature of the coolant, and transmits this signal to the A/D converter of the control circuit .

In the exhaust system, a three-way reducing and oxidizing catalytic converter is disposed in the exhaust passage downstream of the exhaust manifold. The catalytic converter is able to remove three pollutants in the exhaust gas, i.e., CO, HC and NO_x, simultaneously.

An upstream oxygen sensor 1 is provided at the exhaust manifold , i.e., upstream of the catalytic converter. A downstream oxygen sensor 2 is disposed at an exhaust pipe downstream of the catalytic converter. The upstream oxygen sensor 1 and the downstream oxygen sensor 2 generate output signals corresponding to the concentration of the oxygen component in the exhaust gas. More specifically, the oxygen sensors 1 and 2 generate output voltage signals which are changed in accordance with whether the air-fuel ratio of the exhaust gas is rich or lean, compared with the stoichiometric air-fuel ratio. The signals output by the oxygen sensors 1 and 2 are transmitted to the A/D converter of the control circuit.

The control circuit, which consists of a microcomputer, may further comprise a central processing unit (CPU), a read-only-memory (ROM) for storing a main routine and interrupt routines such as a fuel injection routine, an ignition timing routine and constants, etc., a random-access-memory (RAM) for storing temporary data, a backup RAM (B-RAM), and a clock generator for generating various clock signals. The backup RAM is directly connected to a battery (not shown), and therefore, the content of the backup RAM is preserved even when the ignition switch (not shown) is turned off.

A throttle valve operated by a vehicle driver, is provided in the intake air passage, together with an idle switch for detecting the opening of the throttle valve and generating a signal when the throttle valve is fully closed. This signal is supplied to the I/O interface of the control circuit.

A secondary air supply valve for introducing secondary air to the exhaust manifold is provided to thereby reduce the emission of HC and CO during a deceleration or idling operation of the engine.

An alarm which is activated when it is determined that the catalytic converter has deteriorated.

A down counter, a flip-flop , and a drive circuit are provided in the control circuit for controlling the fuel injection valve.

When a fuel injection amount is calculated, the fuel injection amount is preset in the down counter, and simultaneously, the flip-flop is set, and as a result, the drive circuit initiates the activation of the fuel injection valve. On the other hand, the down counter counts up the clock signal from the clock generator, and finally, a logic "1" signal is generated from the terminal of the down counter, to reset the flip-flop, so that the drive circuit stops the activation of the fuel injection valve, whereby an amount of fuel corresponding to the fuel injection amount TAU is supplied to the cylinders.

Interruptions occur at the CPU when the A/D converter completes an A/D conversion and generates an interrupt signal; when the second crank angle sensor generates a pulse signal; and when the clock generator generates a special clock signal.

The intake air amount data from the airflow meter and the coolant temperature data from the coolant sensor are fetched by A/D conversion routine(s) executed at predetermined intervals, and then stored in the RAM ; i.e., the intake air amount data and the coolant temperature data in RAM are renewed at predetermined intervals. The engine speed is calculated by an interrupt routine executed at 30 DEG CA, i.e., at every pulse signal of the crank angle sensor, and is stored in the RAM.

In **JP2091440 (1990),** at certain conditions of air flow inducted to the engine and of engine load, the air/fuel ratio of the engine oscillates from lean to rich and vice versa. The air/fuel ratio is adjusted in accordance with the outputs of the upstream and downstream oxygen sensors. When the number of oscillations of the downstream sensor exceeds a certain value, the catalytic converter is considered as degraded.

In **JP2030915 (1990)**, **JP2033408 (1990)** and **JP2207159 (1990)** the air/fuel ratio of the engine changes from a lean to a rich state. The time that is needed for the downstream sensor to also change from lean to rich state is measured (*time lag*). When this time is less than a predetermined value then the catalytic converter is considered as degraded.

In **JP3057862 (1991)** the ratio of the reversals of the output signals of the two oxygen sensors during feedback-control is formed and compared to a predetermined threshold. If the threshold is exceeded then the catalytic converter is considered as deteriorated.

In **US5088281 (1992)** the main criterion used for the evaluation of the efficiency of the catalytic converter is also the *time lag* (phase shift) between the time point of a signal switch indicated by the upstream oxygen sensor and the corresponding time point that the downstream oxygen sensor senses this signal switch. The signal switch can be a forced change of the engine air/fuel ratio from stoichiometry to a rich state or from stoichiometry to a lean state or a combination of the two. The catalytic converter is considered as degraded when the measured time lag is lower than a predetermined value.
One embodiment of the method is shown in fig. 41. The engine air/fuel ratio starts at time point T_2 switching forcibly from lean to rich and vice versa according to fig. 41a. Figs. 41b,c and d show the signal of the downstream sensor for the cases of a small, a medium and a large deterioration of the catalytic converter respectively. The time (T_3 - T_2) is long enough to expel all oxygen from the catalytic converter (rich state). The time (T_5 - T_3) corresponds to a lean state and at T_5 oxygen is fully stored in the catalytic converter. T_4 (T_4', T_4") is the time point at which the downstream sensor detects a switch from a rich side to a lean side. T_6 (T_6', T_6") is the time point at which the downstream sensor detects a switch from a lean side to a rich side.

The sum of the time lags $(T_4 - T_3)+(T_6 - T_5)$ is calculated. If this sum is lower than a predetermined value the catalytic converter is considered as degraded.

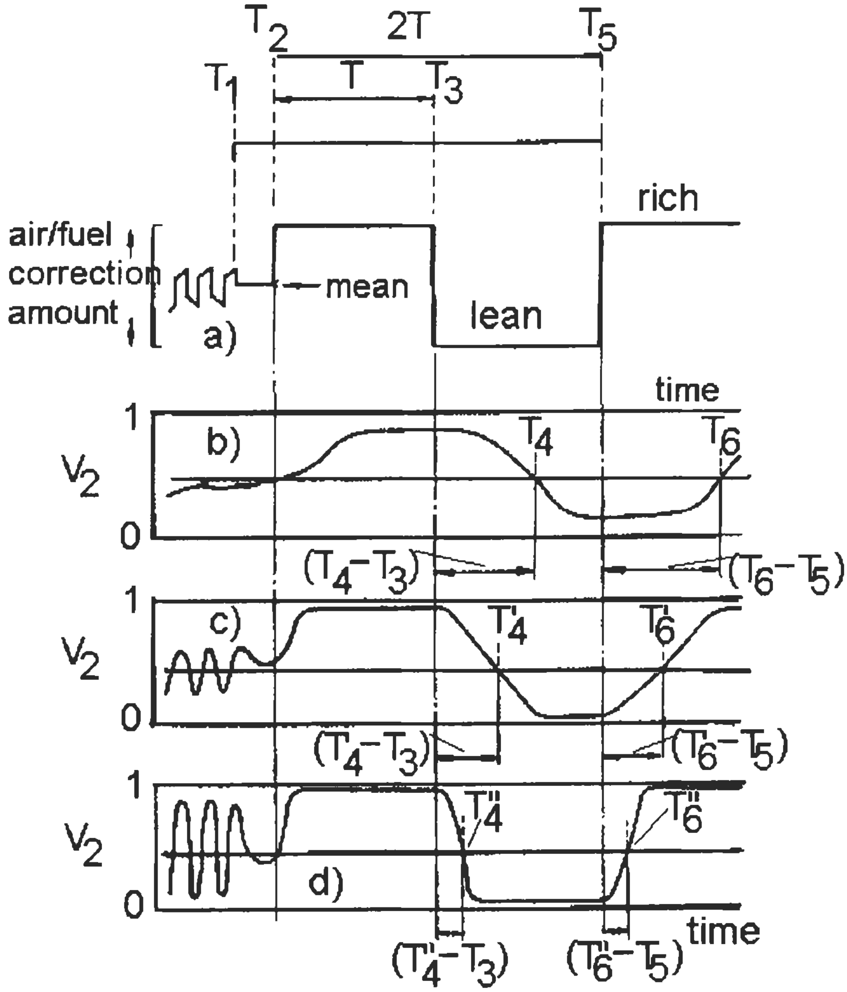


Fig. 41 (from US5088281)

In **US5134847 (1992)** the technique proposed comprises the following steps:

1) adjusting an air/fuel ratio in accordance with the outputs of the upstream and downstream oxygen sensors
2) detecting whether the catalytic converter is deteriorated in accordance with an output of the downstream sensor while the air/fuel ratio is adjusted by an air/fuel correction amount. The criteria of deterioration proposed are:
    a) when the amplitude of the output signal from the downstream oxygen sensor is larger than a predetermined value, or
    b) when the period of the output signal of the downstream oxygen sensor is smaller than a predetermined value, or
    c) when the ratio of periods of the output of the upstream oxygen sensor to the period of the output of the downstream oxygen sensor is larger than a predetermined value.
3) detecting whether the upstream sensor is a normal state in accordance with the output of said sensor
4) prohibiting the detection of state of the catalytic converter efficiency when the upstream oxygen sensor is in an abnormal state.

In **US5165230 (1992)** the following steps are comprised:

1) calculating an air/fuel ratio feedback correction amount in accordance with an output of the upstream sensor. The correction procedure skips down said air/fuel ratio feedback correction amount by a *lean skip* amount when an output of the upstream sensor is switched from a lean side to a rich side, gradually decreases the air/fuel ratio feedback correction amount by a lean integration amount when the output of said upstream sensor is on the rich side, skips up the air/fuel ratio feedback correction amount by a *rich skip* amount when the output of said upstream sensor is switched from the rich side to the lean side, and gradually increases said air/fuel ratio feedback correction amount by a rich integration amount when the output of said upstream sensor is on the lean side. The correction procedure may also include rich and lean delay means for delaying the output of the upstream sensor when switched from lean to rich air/fuel and from rich to lean air/fuel respectively.
2) controlling the air/fuel ratio to a predetermined target air/fuel ratio on the basis of said air/fuel ratio feedback correction amount
3) determining whether or not an engine running state is a predetermined engine running state
4) reducing a rate of change of said air/fuel ratio feedback correction amount when it is determined that the engine running state is said predetermined engine running state. The reduction procedure reduces the lean and rich skip amounts and/or the lean and rich integration amounts by multiplying them with certain coefficients.
5) determining that the condition of the three-way catalyst has deteriorated by utilizing an output of the downstream air/fuel ratio sensor when the engine runs in said predetermined state. The criterion of deterioration is whether the number of reversions of the output of the downstream sensor per unit time is larger than a predetermined number.

As shown in fig. 42 for the case of a slightly deteriorated converter, since the rate of change of the air/fuel ratio feedback correction amount becomes small, the rate of change of the voltage output by the upstream oxygen sensor also becomes small. Accordingly, since the rate of change of the oxygen storage amount becomes small, the time for which the oxygen storage amount is zero becomes short, and thus the voltage output of the downstream sensor is rarely higher than the threshold ε. Accordingly, when a slight deterioration of the condition of the catalytic converter is determined, the frequency of the voltage output by the downstream oxygen sensor is considerably lower than the frequency of the voltage output by the upstream oxygen sensor.

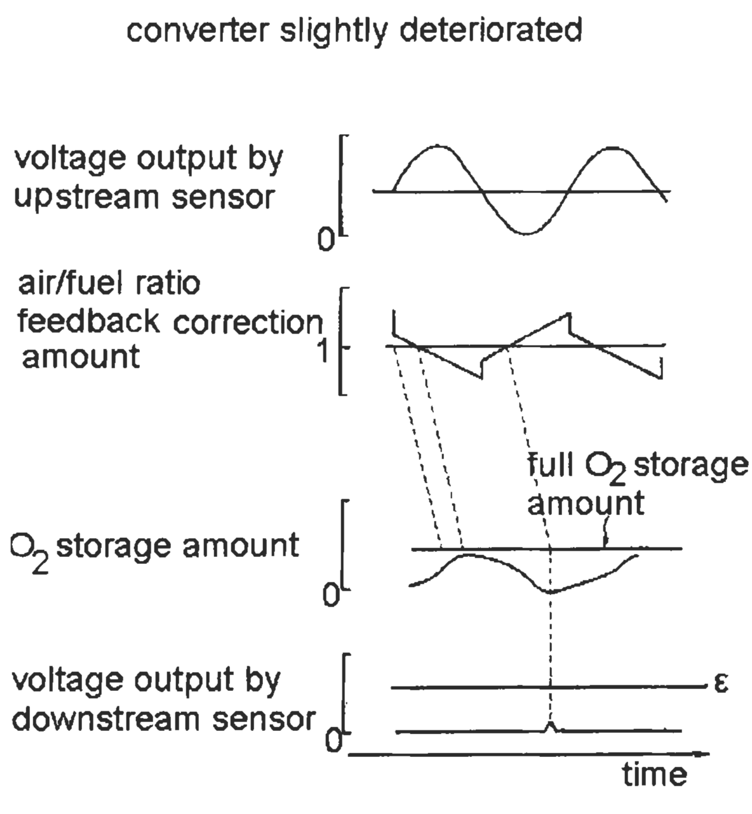


Fig. 42 (from US5165230)

Further, when a considerable deterioration of the catalytic converter is determined (fig. 43), since the full oxygen storage amount becomes lower, the time (T_3 - T_4) for which the oxygen storage amount is zero is increased, and thus the voltage output by the downstream sensor is rarely higher than an increase in the threshold ε. As a result, it can be determined that the condition of the catalytic converter has considerably deteriorated when the ratio of the frequency of the voltage output of the downstream oxygen sensor to the frequency of the voltage output by the downstream oxygen sensor is larger than a predetermined value.

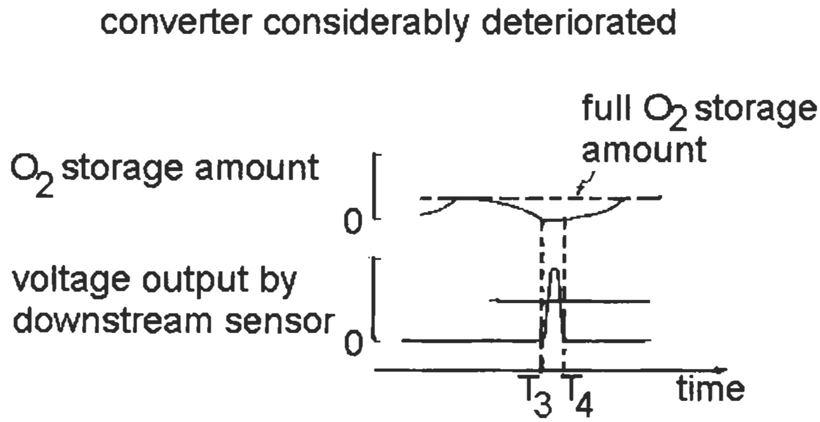


Fig. 43 (from US5165230)

In **EP0536789 (1993)** the criterion of deterioration of the catalytic converter is the ratio of the lengths of the response curves of the output signal of the downstream sensor to the output signal of the upstream sensor when the engine is feedback controlled.
When this ratio is larger than a predetermined value the catalytic converter is considered as degraded. In another embodiment the criterion can be the ratio of the length of the response curve of the downstream sensor to a variable determined by the operating load of the engine during feedback control.

In **DE4234102 (1993)** the following steps are considered:

1) detecting the signal condition that the output signal of the downstream air/fuel ratio sensor is being maintained at either a rich side air/fuel ratio or a lean side air/fuel ratio compared with a stoichiometric air/fuel ratio for more than a predetermined time during the feedback control of the engine by said feedback control means
2) calculating an area surrounded by the output signal response curve of the downstream air/fuel ratio sensor and a predetermined reference value line

3) calculating an area surrounded by the output signal response curve of the upstream air/fuel ratio sensor and a predetermined reference value line
4) forming the ratio of the two areas
5) determining whether or not the three-way catalytic converter has deteriorated in accordance with said area of step 2 or ratio of areas of step 4 when the signal condition detecting means detects that the output signal of the downstream air/fuel ratio sensor is being maintained at either said rich side or said lean side air/fuel ratio for more than said predetermined time.

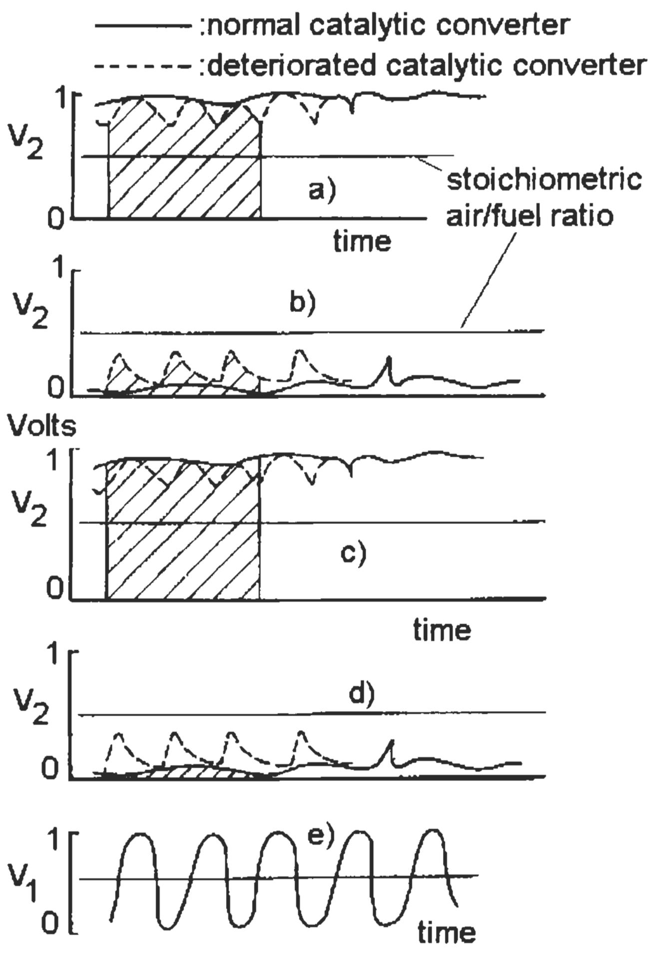


Fig. 44 (from DE4234102)

When only the area of the downstream sensor is used in order to determine the efficiency of the catalytic converter, then the predetermined reference value, based on which said area of the output signal response curve of the downstream air/fuel ratio sensor is calculated, is:

1) a minimum value of the output signal of the downstream air/fuel ratio sensor during each oscillation cycle thereof and the three-way catalyst has deteriorated when said area is more than a predetermined value, or
2) a predetermined constant value, and the three-way catalyst has deteriorated when said area is larger than a predetermined first value and smaller than a predetermined second value

Similar predetermined reference values are calculated for the upstream sensor when the ratio of areas is used as a criterion of efficiency detection.
An embodiment of this method is shown in fig. 44. Fig. 44e shows the forced voltage oscillation around $\lambda=1$ of the upstream sensor from rich to lean and vice versa, whereas figs. 44a-d show the corresponding variations of the downstream sensor for different efficiencies of the catalytic converter. The mean value of the downstream sensor does not oscillate around $\lambda=1$ by influencing the operation characteristics of the sensor or by influencing the fuel injection properties of a certain engine cylinder.
In this case the zero voltage line is considered as the predetermined reference value of step 2. The area under the oscillation line of the sensor becomes maximum when the catalytic converter works normally and the sensor works towards the rich side region (fig. 44c). The area under the oscillation line becomes minimum when the catalytic converter works normally and the sensor works towards the lean side region (fig. 44d). When the catalytic converter is degraded (figs. 44a,b) the area under the oscillation curve always lies between the maximum value of fig. 44c and the minimum value of fig. 44d.

In **EP0547326 (1993)** the following steps are considered:
1) generating an output signal corresponding to an air/fuel ratio of the exhaust gas upstream of the catalytic converter by means of the upstream sensor
2) generating an output signal corresponding to an air/fuel ratio of the exhaust gas downstream of the catalytic converter by means of the downstream sensor
3) feedback controlling the air/fuel ratio of the engine by a feedback control based on the output signal of the upstream air/fuel ratio sensor
4) calculating the lengths of the output signal response curves of the upstream and downstream air/fuel ratio sensors when the engine is feedback controlled
5) forming the ratio of the length of the downstream sensor signal to the length of the upstream sensor signal
6) calculating the areas surrounded by the output signal response curves and reference lines of said upstream and downstream air/fuel ratio sensors when the engine is controlled by said feedback control means
7) forming the ratio of the area of the downstream sensor signal to the area of the upstream sensor signal

8) determining for a given time period whether the catalytic converter has deteriorated when the relationship between the value of said ratio of the lengths and said ratio of the areas satisfy predetermined conditions. These conditions are:

a) the value of said ratio of the lengths is larger than or equal to a predetermined first value, and the value of said ratio of the lengths is smaller than said first value but larger than a predetermined second value while the value of said ratio of the area is smaller than or equal to a predetermined third value

b) a ratio of the value of said ratio of the lengths to the value of said ratio of the areas is larger than a predetermined value

c) I) a ratio of the value of said ratio of the lengths to the value of said ratio of said areas is larger than a first value; and,

II) said ratio of the lengths is larger than a second value.

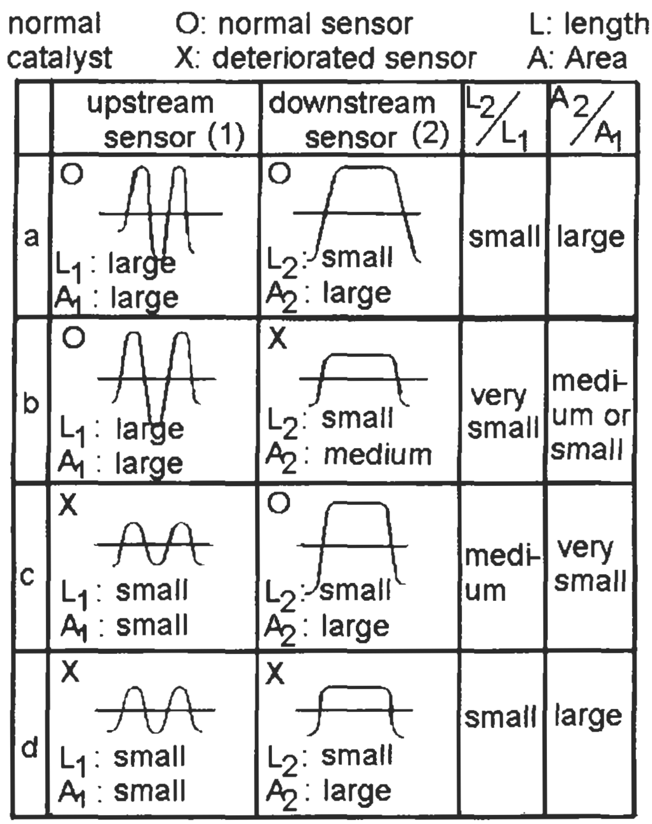


Fig. 45 (from EP0547326)

The method detects accurately the efficiency of a three-way catalytic converter regardless of the deterioration of the oxygen sensors.
In fig. 45 and fig. 46 ratios of signal lengths L and ratios of signal areas A are shown for normal and degraded catalytic converters respectively.

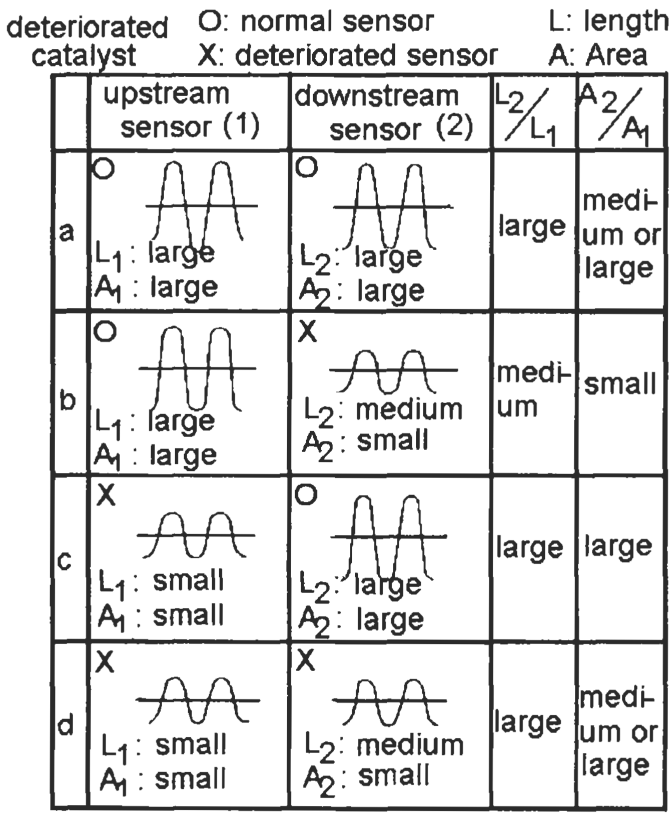


Fig. 46 (from EP0547326)

Upstream oxygen sensor:

a) sensor not deteriorated: Both length L_1 and area A_1 are large regardless of the deterioration of the catalytic converter (figs. 45a,b) and figs. 46a,b)

b) sensor deteriorated: Both L_1 and A_1 are small regardless of the deterioration of the catalytic converter (figs. 45c,d and figs. 46.c,d)

Downstream oxygen sensor:

a) catalytic converter not deteriorated: 1) Length L_2 is small regardless of the deterioration of the downstream sensor (figs. 45a-d) 2) Area A_2 is large for non-deteriorated oxygen sensor (figs. 45a,c) and is medium for deteriorated downstream oxygen sensor (figs. 45b,d)
b) catalytic converter deteriorated: 1) Both L_2 and A_2 are large for non-deteriorated downstream oxygen sensor (figs. 46a,c) 2) L_2 is medium and A_2 is small for deteriorated downstream oxygen sensor (figs. 46b,d)

The ratios of lengths and areas are calculated and shown to the two right columns of fig. 45 and fig. 46. The combination of these ratios gives an accurate estimation of the condition of the catalytic converter.

An embodiment of the method is shown in fig. 47. The hatched area indicates the area in which the catalytic converter is determined to be deteriorated.
For $L_2/L_1 > A$ the catalytic converter is considered as deteriorated.
For $L_2/L_1 < B$ the catalytic converter is considered as non-deteriorated.
For $B < L_2/L_1 < A$ and $A_2/A_1 < C$ the catalytic converter is considered as deteriorated.
The values A, B and C depend on type of catalytic converters and sensors used.

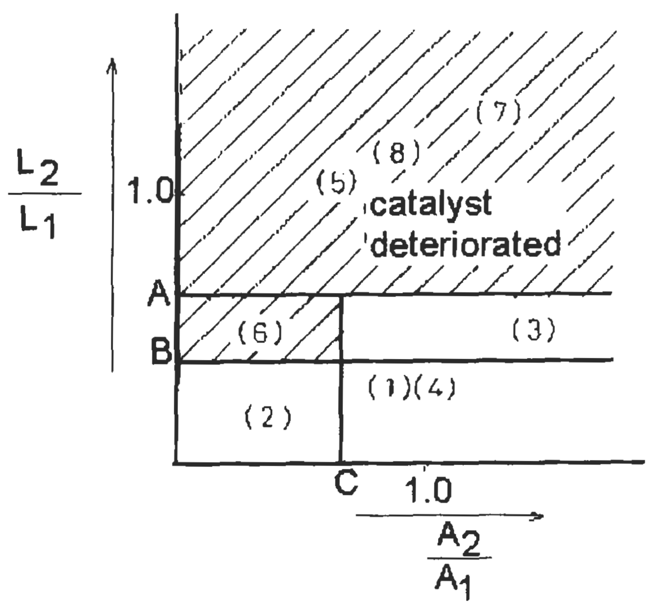


Fig. 47 (from EP0547326)

The method of **JP5179935 (1993)** comprises only one air/fuel sensor installed downstream of a rhodium catalytic converter. The method comprises the following steps:

1) feedback-controlling the engine air/fuel ratio based on the output signal of the downstream air/fuel sensor so as the actual air/fuel ratio corresponds to the stoichiometric one
2) detecting the inversion period of the output signal of the downstream sensor
3) judging deterioration of the catalytic converter when the inversion period detected in step 2 becomes shorter than a predefined threshold.

The method of **JP6159048 (1994)** also comprises only one air/fuel sensor installed downstream of the catalytic converter. The method comprises the following steps:

1) detecting fuel-cut of the internal combustion engine
2) making air/fuel ratio rich when the fuel supply is found to have been suspended for a specified period of time
3) computing the oxygen adsorption capacity of the catalytic converter based on the detected values of the downstream air/fuel ratio sensor and the engine intake air
4) assessing the degradation of the catalytic converter based on the computed oxygen adsorption capacity

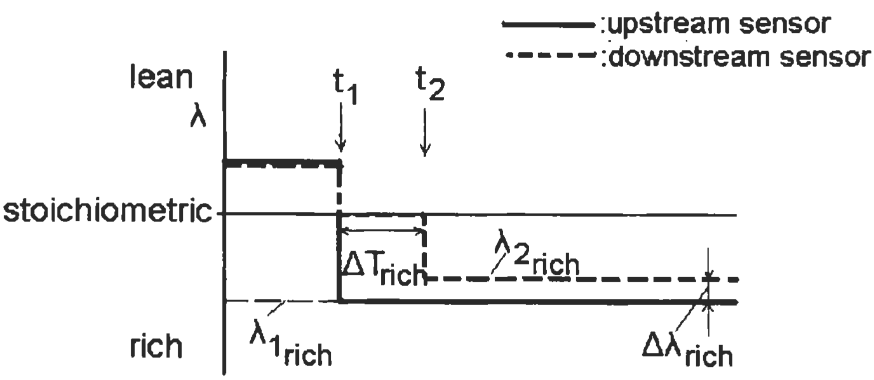


Fig. 48 (from US5279115)

The method of US5279115 **(1994)** consists of the following steps:

1) measuring the air/fuel ratio upstream of the catalytic converter by means of an upstream sensor

2) measuring the air/fuel ratio downstream of the catalytic converter by means of a downstream sensor
3) feedback controlling the air/fuel ratio of the engine by a feedback control based on the output signal of the upstream air/fuel ratio sensor
4) changing over the air/fuel ratio of the exhaust gas flowing into the catalyst, from a lean air/fuel ratio to a rich air/fuel fuel ratio λ_{1rich} (fig. 48)
5) calculating a length of time ΔT_{rich} which is necessary for the catalyst to release the oxygen stored therein after the air/fuel ratio is changed over to said rich air/fuel ratio. During time ΔT_{rich} the air/fuel ratio of the downstream sensor is maintained at the stoichiometric value $\lambda_2=1$ (fig. 48)
6) determining a degree of deterioration of the catalyst after said length of time has elapsed
7) determining said degree of deterioration of the catalyst from a difference $\Delta\lambda_{rich}$ between the air/fuel ratio λ_{1rich} detected by said first air/fuel ratio sensor and the air/fuel ratio λ_{2rich} detected by said second air/fuel ratio sensor when compared to predetermined data

In **US5282383 (1994)** the method comprises the steps of:
1) adjusting an air/fuel ratio correction factor in accordance with the output of the upstream-side air/fuel ratio sensor so that an air/fuel ratio is controlled at a predetermined target air/fuel ratio that is equal to the stoichiometric air/fuel ratio, the air/fuel ratio changing from the rich state to the lean state, or vice versa
2) monitoring fluctuations in the output of the downstream-side air/fuel ratio sensor around a predetermined reference voltage
3) determining that the degree of deterioration of said catalyst is such that a diagnostic procedure is required when the number of these fluctuations during a predetermined interval is greater than a predetermined value
4) shifting the air/fuel ratio that is controlled in accordance with said adjusting step to an air/fuel ratio that is not equal to the stoichiometric air/fuel ratio (e.g. lean)
5) determining whether said catalyst converter has deteriorated in accordance with the output of the downstream-side air/fuel ratio sensor when
    a) the number of fluctuations is greater than a predetermined value, or
    b) the difference between the number of upstream-side fluctuations and the number of downstream-side fluctuations, when the number of upstream-side fluctuations is greater than a first predetermined value, is greater than a second predetermined value, or
    c) a ratio of the number of downstream-side fluctuations to the number of upstream-side fluctuations is greater than a predetermined value, which is about "1".

The adjusting step 1 comprises the step of:

a) increasing the air/fuel ratio correction factor when the air/fuel ratio changes from the lean state to the rich state, and decreasing the air/fuel ratio correction factor when the air/fuel ratio changes from the rich state to the lean state, or

b) gradually increasing the air/fuel ratio correction factor while the air/fuel ratio remains in the rich state, and gradually decreasing the air/fuel ratio correction factor while the air/fuel ratio remains in the lean state, or
c) delaying a time at which the air/fuel ratio changes from the rich state to the lean state by a predetermined lean delay time, and a time at which the air/fuel ratio changes from the lean state to the rich state by a predetermined rich delay time.

The corresponding shifting step 4 comprises respectively the step of: a),b) varying said correction factor or c) varying said lean delay time and said rich delay time.

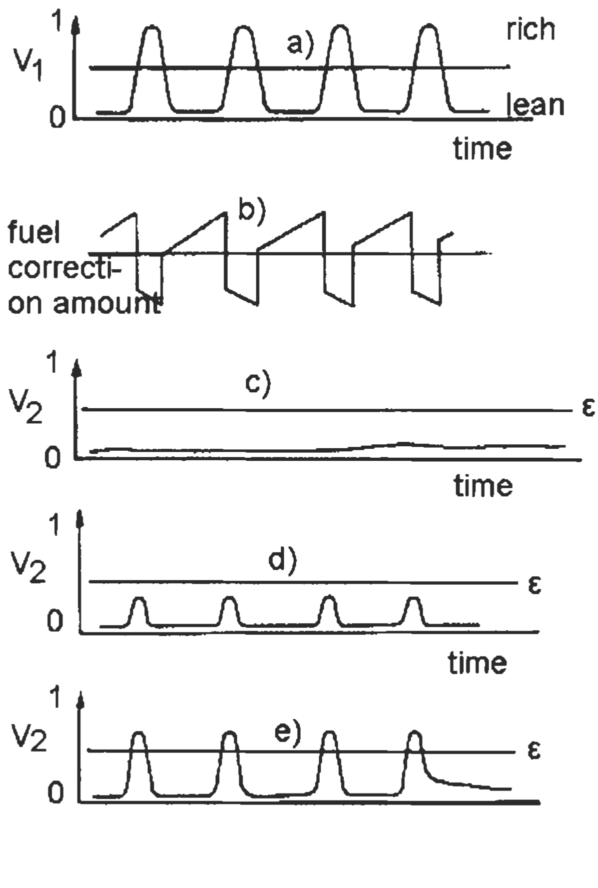


Fig. 49 (from US5282383)

The method can be better explained by making use of fig. 49. In fig. 49a the upstream oxygen sensor output is denoted while in fig. 49b the corresponding air/fuel correction amount is presented that is changed in order to shift the actual air/fuel ratio to the lean side. Figs. 49c,d and e correspond to the voltage signal of the downstream sensor for the cases of a normal converter, a 20% deteriorated converter and a 50% deteriorated converter respectively. In the case of fig. 49e the number of reversals per unit time period of the downstream sensor output is larger than in the cases of figs. 49c and d and can be easily distinguished.

The method of **EP0602468 (1994)** comprises the steps of:

1) detecting an air/fuel ratio of the exhaust gas upstream of the catalytic converter
2) detecting the air/fuel ratio of the exhaust gas downstream of the catalytic converter
3) controlling the air/fuel ratio of the engine by a feedback control based on the output of the upstream air/fuel ratio sensor
4) calculating the ratio of the length of the output signal response curve of the downstream air/fuel ratio sensor and the length of the output signal response curve of the output signal response curve of the upstream air/fuel ratio sensor, when the engine is controlled by said feedback control means
5) calculating the ratio of the area bounded by the output signal response curve of the downstream air/fuel ratio sensor and a reference line thereof and the area bounded by the output signal response curve of the upstream air/fuel ratio sensor and a reference line thereof
6) determining the degree of transition of the operating condition of the engine and correcting the value of said ratio of areas of the output signal response curves in accordance with said degree of transition of the operating condition of the engine
7) detecting deterioration of the catalytic converter based on the ratio of the lengths, the corrected ratio of the areas and the degree of transition of the operating condition of the engine. The catalytic converter has deteriorated when the relationship between said ratio of the lengths of the output response curves and said corrected value of the ratio of the areas satisfies predetermined conditions.

The determination of transition of step 6 comprises:

a) detecting the number of reversals between a rich air/fuel ratio side and a lean air/fuel ratio side of the output signal of said upstream air/fuel ratio sensor over a predetermined time, and determining the degree of transition in such a manner that the degree of transition becomes larger as said number of reversals decreases, or
b) detecting whether the number of occurrences of
   - the rate of change of the pressure in the intake manifold, or
   - the rate of change of the intake air flow, or
   - the rate of change of the degree of opening of the throttle valve, or
   - the rate of change of the traveling speed of the vehicle driven by the engine

exceeds a predetermined rate or not over a predetermined time and determining the degree of transition in such a manner that the degree of transition becomes larger as said number of occurrences increases.

The method is also applicable in transient operation states of the engine (deceleration or acceleration) and it is an improvement of the method of **EP0547326 (1993)**.

The method of **JP7269330 (1995)** uses the time delay difference in response of the upstream and downstream sensors to judge the deterioration of the catalytic converter. This difference is calculated from a time at which the output signal of the upstream sensor becomes lower than a predetermined value to another time at which the output signal of the downstream sensor becomes lower than the predetermined value. Half the maximum voltage output of the sensor is used as a predetermined value.

The method of **US5412941 (1995)** prevents accuracy errors during determination of the condition of a catalytic converter and comprises the steps of:

1) detecting an air/fuel ratio of the exhaust gas upstream of the catalytic converter
2) detecting the air/fuel ratio of the exhaust gas downstream of the catalytic converter
3) controlling the air/fuel ratio of the engine by a feedback control based on the output of the upstream air/fuel ratio sensor
4) determining whether the engine operating conditions are not appropriate to determine the deterioration of the three-way catalyst, in which a period of a cycle of said feedback control of the air/fuel ratio becomes larger than a value appropriate for the determination of the deterioration of said three-way catalytic converter
5) prohibiting the determination of the deterioration of the three-way catalytic converter when it is determined that the engine operating conditions are not appropriate
6) calculating lengths of the output signal response curves of said upstream and downstream air/fuel ratio sensors
7) calculating areas surrounded by the output signal response curves and reference value lines of said upstream and downstream air/fuel ratio sensors
8) calculating a ratio of said length of the output signal response curve of said upstream air/fuel ratio sensor to said length of the output signal response curve of said downstream air/fuel ratio sensor
9) calculating a ratio of said area of the output signal response curve of said upstream air/fuel ratio sensor to said area of the output signal response curve of said downstream air/fuel ratio sensor
10) determining whether said three-way catalytic converter has deteriorated in accordance with said ratio of the lengths and said ratio of areas (see method of **EP0547326 (1993)**).

The condition determining step 4 comprises:

a) detecting the interval of reversals between a rich air/fuel ratio side and a lean air/fuel ratio side of the output signal of the upstream air/fuel ratio sensor, and determining that the engine operating conditions are not appropriate for said determination of the deterioration of the three-way catalyst when said interval of reversals of the output of the upstream air/fuel ratio sensor becomes longer than a predetermined value, or

b) detecting an amount of intake air flow of the engine, and determining that the engine operating conditions are not appropriate for said determination of the deterioration of the three-way catalyst when said amount of intake air flow of the engine becomes smaller than a predetermined value.

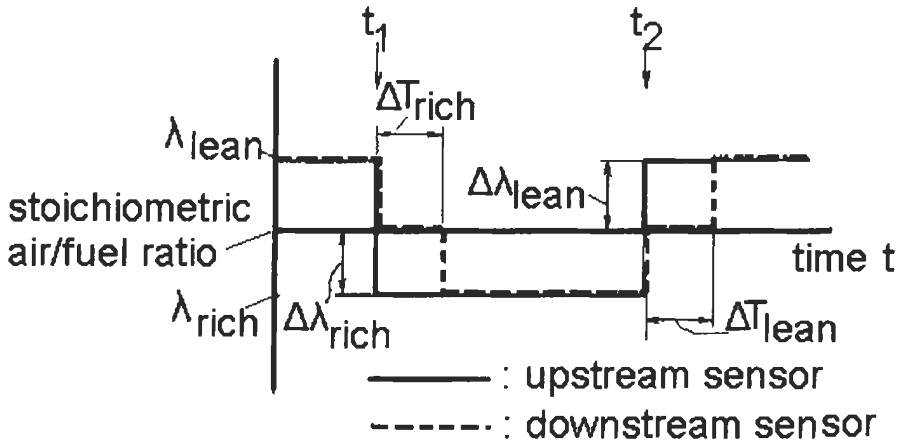


Fig. 50 (from US5414996)

The method of **US5414996 (1995)** comprises the steps of:

1) changing over the air/fuel ratio at an upstream side of the catalyst between a predetermined rich air/fuel ratio λ_{rich} and a predetermined lean air/fuel ratio λ_{lean} (fig. 50)
2) detecting the air/fuel ratio λ_1 of the exhaust gas upstream of the catalytic converter
3) detecting the air/fuel ratio λ_2 of the exhaust gas downstream of the catalytic converter
4) detecting the amount of the engine intake air $\dot{Q}_{air}$ (as a measure of the exhaust gas passing through the catalytic converter) during a time ΔT from when the air/fuel ratio is changed over from one of said predetermined rich air/fuel ratio λ_{rich} and said predetermined lean air/fuel ratio λ_{lean} to the other predetermined air/fuel ratio to when the air/fuel ratio detected by the downstream air/fuel sensor becomes approximately equal to the air/fuel ratio detected by the upstream air/fuel ratio sensor (fig. 50)
5) calculating the amount of oxygen stored in the catalyst from said amount of the engine intake air and a difference $\Delta\lambda$ between the stoichiometric air/fuel ratio ($\lambda=1$) and the air/fuel ratio detected by the upstream air/fuel ratio sensor. The amount of oxygen stored is calculated from the formula

$$V_{O2m} = \alpha \cdot \Delta\lambda \cdot \dot{Q}_{air} \cdot \Delta T$$

where α = ratio of the amount of oxygen contained in air

6) determining a degree of deterioration of the catalyst on the basis of said calculated amount of oxygen stored in the catalyst.

The method of **JP8210126 (1996)** describes a catalytic converter deterioration discrimination device, which inhibits the deterioration judgment when a value of the constant used for the feedback control of the engine air/fuel ratio reaches a predetermined threshold. The feedback control is based on the output signal of the upstream oxygen sensor. The method prevents judgment error due to a leak in the exhaust pipe.

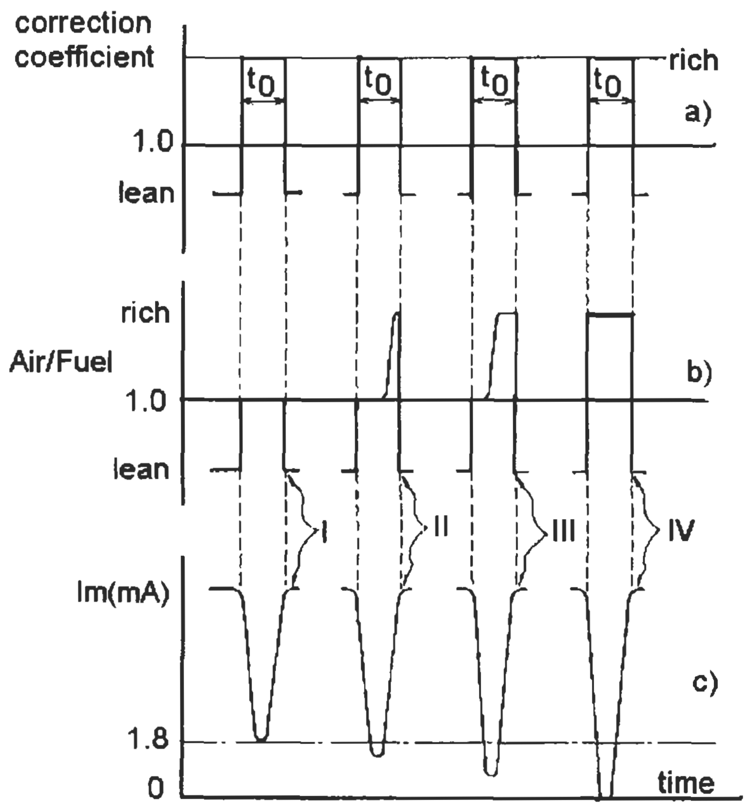


Fig. 51 (from EP0690213)

The method of **EP0690213 (1996)** comprises the following steps:

1) temporarily changing the air/fuel ratio of the exhaust gases from rich to lean for a predetermined fixed time t_0
2) detecting the variation of the air/fuel ratio of the exhaust gases by means of an oxygen concentration sensor installed downstream of the catalytic converter
3) detecting a peak value of the level of the output of the downstream oxygen sensor within the predetermined fixed time during which the air/fuel ratio of the exhaust gases flowing into the catalytic converter is temporarily maintained at a lean or at a rich air/fuel ratio
4) judging a degree of deterioration of the catalytic converter on the basis of the peak value of the output of the downstream sensor

Fig. 51a shows the feedback fuel correction coefficient for a predetermined fixed time t_o, that is, when the air/fuel ratio is made rich for the predetermined fixed time t_o. Figs. 51b and c show the corresponding measured air fuel ratio and current I_m (mA) of the downstream sensor for the cases of a new (I), a slightly deteriorated (II), a much deteriorated (III) and a completely deteriorated (IV) catalytic converter. The higher the deterioration of the catalytic converter the shorter the time during which the air/fuel ratio of the exhaust gases is maintained substantially at the stoichiometric air/fuel ratio (fig. 51b).

The corresponding peak of the current I_m becomes smaller the larger the degree of deterioration of the catalytic converter (fig. 51c). The value of current I_m becomes zero for a completely deteriorated converter (case IV).
The method is also applied to NO_x adsorbents.

In the method of **EP0743433 (1996)** the following steps are considered:

1) detecting the air/fuel ratio upstream of the catalytic converter by means of an upstream sensor
2) detecting the air/fuel ratio downstream of the catalytic converter by means of a downstream sensor
3) feedback controlling the engine air/fuel ratio between a rich and a lean value by means of the upstream sensor
4) calculating the amount of oxygen released from the catalytic converter when the air/fuel ratio of the exhaust gas flowing into the catalytic converter is rich, based on the value obtained by a temporal integration of the amount of the deviation of the air/fuel ratio flowing into the catalytic converter from the stoichiometric air/fuel ratio
5) controlling the length of the time period in which the air/fuel ratio of the exhaust gas flowing into the catalytic converter becomes a rich air/fuel ratio in such a manner that the amount of oxygen released from the catalytic converter becomes a predetermined value

In a first embodiment of the method the following further steps are considered:

a) controlling the length of the output signal response curve of the downstream air/fuel sensor
b) determining the degree of deterioration of the catalytic converter based on this length of the output signal response curve of the downstream air/fuel sensor

In a second embodiment of the method the following further steps are considered:

a) calculating a first integral value obtained by a temporal integration of the difference between the maximum and minimum values in each cycle of fluctuation of the output signal of the upstream air/fuel sensor
b) calculating a second integral value obtained by a temporal integration of the difference between the maximum and minimum values in each cycle of fluctuation of the output signal of the downstream air/fuel sensor
c) calculating lengths of the output signal response curves of the two sensors
d) estimating the length of the output signal response curve of the downstream sensor in an imaginary condition in which the catalytic converter is considered to be removed from the exhaust pipe by multiplying the length of the output of the upstream sensor (step (c)) and the ratios between the calculated first and second integral values (steps (a) and (b))
e) calculating the degree of deterioration of the catalytic converter based on the estimated length of the output signal of the downstream sensor and the length of the output signal of the downstream sensor as calculated in step (d).

The method of **EP0748927 (1996)** comprises the following steps:

1) detecting the air/fuel ratio upstream of the catalytic converter by means of an upstream air/fuel sensor
2) detecting the air/fuel ratio downstream of the catalytic converter by means of a downstream air/fuel sensor
3) feedback controlling the engine air/fuel by means of the output of the upstream sensor in such a manner, that the air/fuel ratio of the exhaust gas flowing into the catalytic converter becomes a predetermined ratio
4) determining the deterioration of the catalytic converter based on the output signal of the downstream air/fuel sensor during the feedback control
5) detecting the flow rate of the intake air drawn to the engine
6) inhibiting the operation for determining the deterioration of the catalytic converter of step 4 when the flow rate of intake air drawn to the engine is out of a predetermined allowable range
7) setting the allowable air flow range in accordance with:
    a) the temperature of the catalytic converter, or
    b) the engine speed

In this way the method takes into account the fact that a catalytic converter has different oxygen storage capacities at e.g. different temperatures of the catalytic converter.

The method of **EP0756072 (1997)** comprises the following steps:

1) grasping an ability value in relation with a current purification ability of the catalytic converter. The ability value can be based a) on a current oxygen storage ability or b) on a current HC purification ability of the converter
2) grasping a varying amount of the ability value grasped in step 1. The varying amount of the ability value can be expressed

a) as a ratio of a varying amount of the ability value to a varying amount of time or
b) as a ratio of a varying amount of the ability value to a varying amount of the temperature of the catalytic converter

3) determining that the catalytic converter is deteriorated when said varying amount grasped in step 2 is smaller than a predetermined value

The test takes place when the temperature of the catalytic converter is within a predetermined state and/or the engine operation is steady and/or when an amount of intake air is within a predetermined range.

The method of **EP0756073 (1997)** comprises the following steps:

1) feedback-controlling the air/fuel ratio of the exhaust gases flowing into the catalytic converter so that the air/fuel ratio of the exhaust gases fluctuates around a center value on the lean air/fuel ratio side compared to the stoichiometric air/fuel ratio (fig. 52a)
2) determining whether the catalytic converter has absorbed oxygen to its maximum oxygen storage capacity (saturation) during the period in which the air/fuel ratio of the exhaust gas flowing into the catalytic converter is on a lean side (step 1) (figs. 52b,d)
3) prohibiting the determination of deterioration of the catalytic converter when the determination of step 2 does not indicate a saturated catalytic converter whereas allowing the determination of deterioration of the catalytic converter when the determination of step 2 indicates a saturated catalytic converter
4) calculating the amount of CO and HC in the exhaust gas flowing into the catalytic converter based on the output of the upstream air/fuel sensor, when the air/fuel ratio of the exhaust gas is feedback-controlled
5) calculating the amount of CO and HC in the exhaust gas flowing out from the catalytic converter based on the output of the downstream air/fuel sensor, when the air/fuel ratio of the exhaust gas is feedback-controlled
6) determining the deterioration of the catalytic converter based on the inflow and outflow amounts of HC and CO as calculated in steps 4 and 5

The curves of figs. 52b,c illustrate the change in the amount of oxygen stored in the catalytic converter and the response of the output V_2 of the downstream air/fuel sensor, respectively, when the converter is normal. The curves of figs. 52d,e illustrate the change in the amount of oxygen stored in the catalytic converter and the response of the output V_2 of the downstream air/fuel sensor, respectively, when the converter is deteriorated.
As shown in curves of figs. 52b,d, the converter absorbs oxygen up to its saturation point. When the air/fuel ratio of the exhaust gases temporarily largely fluctuates to the rich side (point A, fig. 52a), the catalytic converter releases all the absorbed oxygen (point B, fig. 52b). Therefore the reversal of V_2 occurs even though the catalytic converter is normal (point C, fig. 52c). However, if the portion A of the curve of fig. 52c is compared with the portion B of the curve of fig. 52e, the amount of fluctuation of V_2 to the rich side and the length of the period in which V_2 stays on the rich side become smaller for the case of a normal converter than that of a deteriorated converter (point E, fig. 52e). Namely, even if the air/fuel ratio of the exhaust gas flowing into the catalytic converter fluctuates to the rich side in the same manner, the

fluctuation of V_2 changes in accordance with the amount of oxygen stored in the catalytic converter (saturation). As explained above, the amount of oxygen stored in the catalytic converter can be calculated from the rich gas inflow amount (the amount of HC and CO in the exhaust gas flowing into the converter) and the rich gas outflow amount (the amount of HC and CO in the exhaust gas flowing out from the converter). Therefore, the rich gas inflow and outflow amounts in each cycle are calculated in accordance with the outputs V_1 and V_2, respectively, and the deterioration of the catalytic converter is determined by comparing the rich gas inflow amount and the rich gas outflow amount.

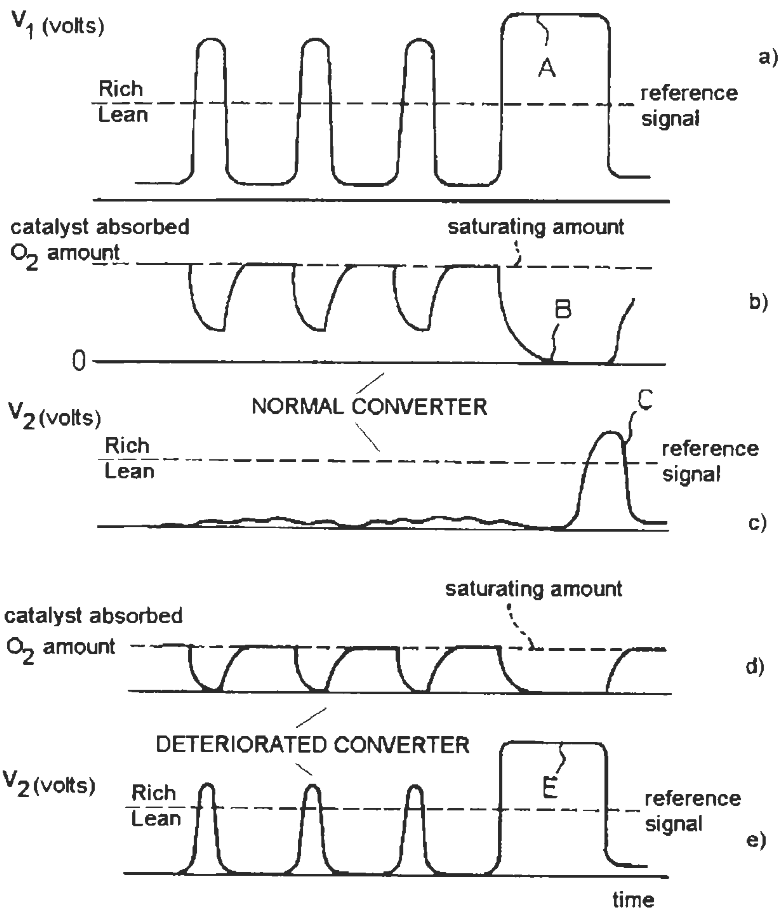


Fig. 52 (from EP0756073)

The method of **EP0770767 (1997)** comprises the following steps:

1) detecting the air/fuel concentration of the exhaust gases upstream of the three-way catalytic converter by means of an upstream air/fuel sensor
2) detecting the oxygen concentration of the exhaust gases downstream of the three-way catalytic converter by means of a downstream oxygen sensor
3) feedback-controlling the engine air/fuel ratio based on the output signal of the upstream sensor. The feedback correction amount consists of
    a) a proportional term to achieve the stoichiometric air/fuel ratio and
    b) an integral term for bringing an integrated value of an error between the actual air/fuel ratio and the stoichiometric air/fuel ratio to zero
4) determining deterioration of the three-way catalytic converter on the basis of
    a) the length of a response curve that the output of the downstream sensor describes during the time that the air/fuel ratio is feedback-controlled, or
    b) the ratio of the response curve of the output signal of the downstream sensor with a deterioration determination reference value during the time that the air/fuel ratio is feedback-controlled.

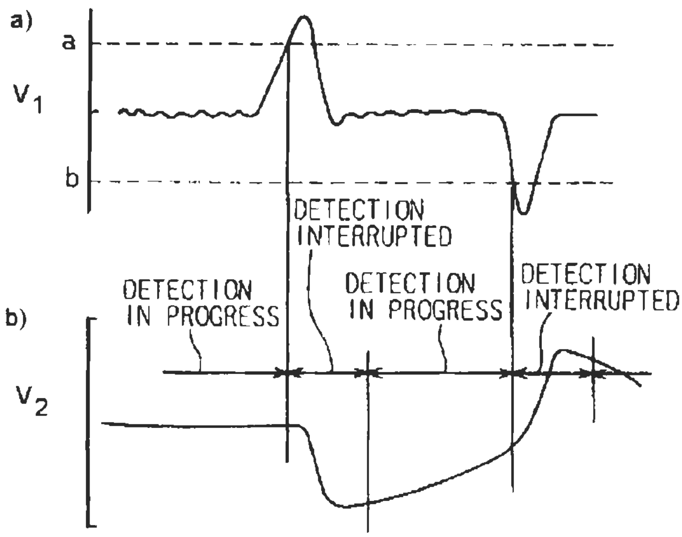


Fig. 53 (from EP0770767)

The method further comprises the steps:

5) interrupting the calculation of the response curve length of step 4 for a predetermined length of time when the output of the upstream sensor or the amount of change of said output exceeds a preset value, or/and
6) imposing an upper limit on an absolute value of the integral term or on a gain of the integral term of step 3 during the deterioration determination, or/and
7) inhibiting the correction of the output of the upstream sensor (step 3) when the determination of deterioration takes place, or/and
8) imposing a limit so that the determination of deterioration is carried out only when the response curve length or variation amplitude of the output of the upstream sensor is within a prescribed range, or/and
9) changing the deterioration determination reference value according to the response curve length or variation amplitude of the output of the upstream sensor.

Fig. 53 shows the principle of embodiment i). If the output V_1 of the upstream sensor exceeds a limit value (limits "a", "b", fig. 53a) that can cause an excessive response of the output of the downstream sensor, then the summation of data for determination of the deterioration of the catalytic converter is interrupted for a prescribed duration of time considering the distance between the two sensors (the time required until the gas detected by the upstream sensor reaches the downstream sensor) (fig. 53b).

The method of **EP0793009 (1997)** comprises the following steps:
1) measuring the oxygen content of the exhaust gas upstream of the catalytic converter by means of an upstream oxygen sensor
2) measuring the oxygen content of the exhaust gas downstream of the catalytic converter by means of a downstream oxygen sensor
3) feedback-controlling the engine air/fuel ratio so as to bring the engine air/fuel ratio to a target air/fuel ratio on the basis of a difference between an output of the upstream oxygen sensor and a target output corresponding to said target air/fuel ratio
4) determining the lengths of the response curves of the output signals of the upstream and downstream oxygen sensors respectively for a prescribed period during the air/fuel ratio feedback control of step 3
5) calculating
   a) an amplitude of the output of the upstream sensor, measured in reference to the target output
   b) a period from the time the output of the upstream sensor crosses the target output to the time this output returns to the target output, each time an inversion occurs in the output of the upstream sensor with respect to the target output during the air/fuel ratio feedback control
6) correcting on the basis of the calculated amplitude and period in step 7 the output response curve length of the upstream sensor
7) judging deterioration of the catalytic converter on the basis of the lengths of the response curves of the output signals of the two sensors determined in steps 4 and 6.

The method of **EP0796985 (1997)** comprises the following steps:

1) detecting the oxygen content of the exhaust gases upstream of the catalytic converter by means of an upstream air/fuel sensor
2) detecting the oxygen content of the exhaust gases downstream of the catalytic converter by means of a downstream air/fuel sensor
3) feedback-controlling the engine air/fuel ratio to a target air/fuel ratio in accordance with at least the output signal of the upstream sensor
4) estimating a center of the air/fuel ratio of the catalytic converter based on a moving average of the output of the downstream sensor
5) converting the output of the upstream oxygen sensor into a converted output in accordance with a relationship between the difference between the output of the upstream air/fuel sensor and the target air/fuel ratio and
    a) the difference between the output of the downstream air/fuel sensor and the target air/fuel ratio, or
    b) the center estimated in step 4
6) calculating a length of the response curve of the converted output of the upstream air/fuel ratio sensor converted at step 5 and a length of the response curve of the downstream sensor when the engine is controlled as in step 3
7) detecting deterioration of the catalytic converter in accordance with the upstream and downstream lengths of step 6
8) estimating an upper and a lower limit in accordance with the center of the air/fuel ratio estimated in step 4
9) inhibiting detection of the deterioration of the catalytic converter when the output of the upstream sensor departs from the range between the upper limit and the lower limit determined in step 9.

The detecting accuracy is improved by compensating for aberration of the balance between the oxygen absorbing power and the oxygen releasing power of the converter. When there is no balance between the power for storing oxygen and the power for releasing oxygen, there is no accuracy in detecting the efficiency of the catalytic converter. This can be better explained by means of fig. 54.

Fig. 54a shows the output of the upstream air/fuel sensor and fig. 54b shows the output of the downstream oxygen sensor. In this figure, the output of the oxygen sensor is kept at the rich state before time t_3 and thus turns from the rich state to the lean state at time t_3. When the air/fuel ratio of the exhaust gas supplied to the converter deviates largely to the lean state at time t_1, the length of the response curve of the output of the oxygen sensor becomes long because the output of the oxygen sensor also deviates largely to the lean state from the rich state.

Conversely, when the air/fuel ratio of the exhaust gas supplied to the converter deviates largely to the rich state at time t_2, the length of the response curve of the oxygen sensor is not largely influenced by this deviation because the output of the oxygen sensor becomes saturated. Similarly, when the air/fuel ratio of the exhaust gas supplied to the converter deviates largely to the lean state at time t_4, the length of the response curve of the oxygen sensor is not largely influenced by this deviation because the output of the oxygen sensor becomes saturated.

Conversely, when the air/fuel ratio of the exhaust gas supplied to the converter deviates largely to the rich state at time t_5, the length of the response curve of the oxygen sensor becomes long because the output of the oxygen sensor also deviates largely to the rich state from the lean state.

That is, the accuracy for detecting the deterioration of the converter may become worst because the deviation of the oxygen sensor is affected by the fluctuation of the air/fuel ratio of the exhaust gas exhausted from the converter, even when the fluctuation of the exhaust gas supplied to the converter is kept constant.

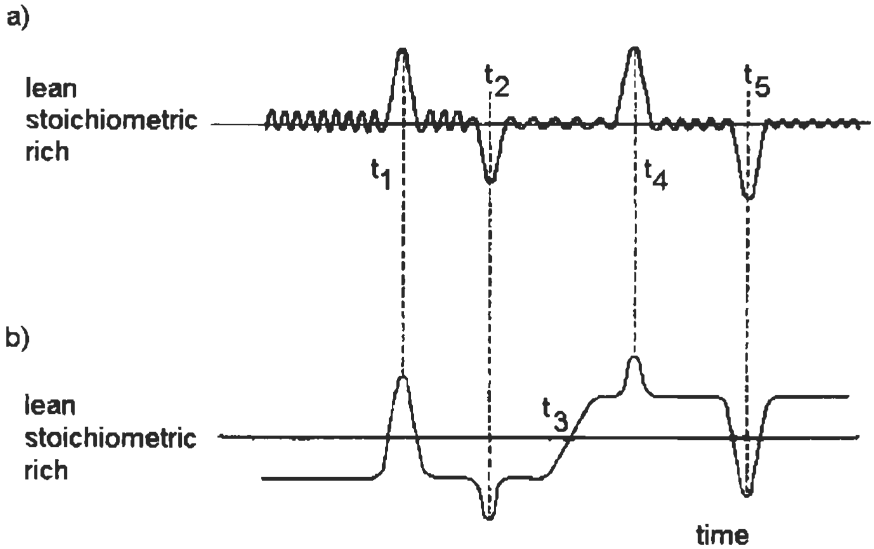


Fig. 54 (from EP0796985)

The object of the method of **EP0801215 (1997)** is to avoid misjudgment of a catalytic converter deterioration detection even though the balance between the oxygen absorbing and releasing power disappears. The method comprises the following steps:

1) feedback-controlling the amount of fuel supplied to the engine at least in accordance with the output of the upstream air/fuel sensor

2) estimating a balance between the oxygen absorbing power and the oxygen releasing power of the catalytic converter. This estimation comprises the following sub-steps:
   a) calculating a difference between a target amount of fuel required to maintain the air/fuel ratio of the engine at the stoichiometric air/fuel ratio and an actual amount of fuel calculated at the air/fuel ratio feedback control step 1
   b) detecting the change of the downstream air/fuel sensor. This change detecting step has a hysteresis characteristic between a threshold used for a change from a rich state to a lean state and a threshold used for a change from said lean state to said rich state.
   c) integrating a fuel difference calculated at step 2a to estimate the oxygen balance from the time when a first change of the output of the downstream air/fuel sensor is detected at step 2b to the time when a second change is detected at step 2b
3) detecting deterioration of the catalytic converter at least in accordance with the output of the downstream air/fuel sensor. The deterioration of the catalytic converter is detected in accordance with:
   a) the length of the response curve of the output of the upstream air/fuel sensor and the length of the response curve of the downstream air/fuel sensor, or
   b) the frequency of deviations of the fuel difference integral integrated at step 2c from a fixed upper limit or a fixed lower limit
4) inhibiting the detection of the deterioration degree of the catalytic converter (step 3) when the balance estimated at step 2 deviates from at least one fixed threshold
5) restraining from inhibiting the detection until a fixed interval is elapsed after the change of the output of the downstream air/fuel sensor is detected at step 2b though the fuel difference integral integrated at step 2c deviates from a fixed upper limit or a fixed lower limit

The problem of inhibiting misjudgment is explained in fig. 55. Fig. 55a denotes the output of the downstream sensor and fig. 55b denotes the balance between the oxygen absorbing power and the oxygen releasing power.

The downstream sensor detects the rich state before time t_2, and its output changes from the rich state to the lean state between time t_2 and t_3. It detects the lean state between time t_3 and t_5, and its output changes from the lean state to rich state between time t_5 and t_6. It detects the rich state between time t_6 and t_8, and its output changes from the rich state to the lean state between time t_8 and t_9.

Therefore, the converter absorbs oxygen before time t_3, releases it between time t_3 and t_6, absorbs it between t_6 and t_9, and releases it after time t_9. The amount of oxygen stored in the converter increases gradually before time t_3, the amount of oxygen stored in the converter decreases gradually between time t_3 and t_6, and the oxygen absorbing power increases gradually after time t_9.

Because the amount of oxygen stored in the converter, however, is limited (limit levels are shown by one point chain lines in fig. 55b), misjudgment may be caused when the balance between the oxygen absorbing power and the oxygen releasing power falls beyond the limits, that is, between time t_1 and t_3, between time t_4 and t_6 and between time t_7 and t_9.

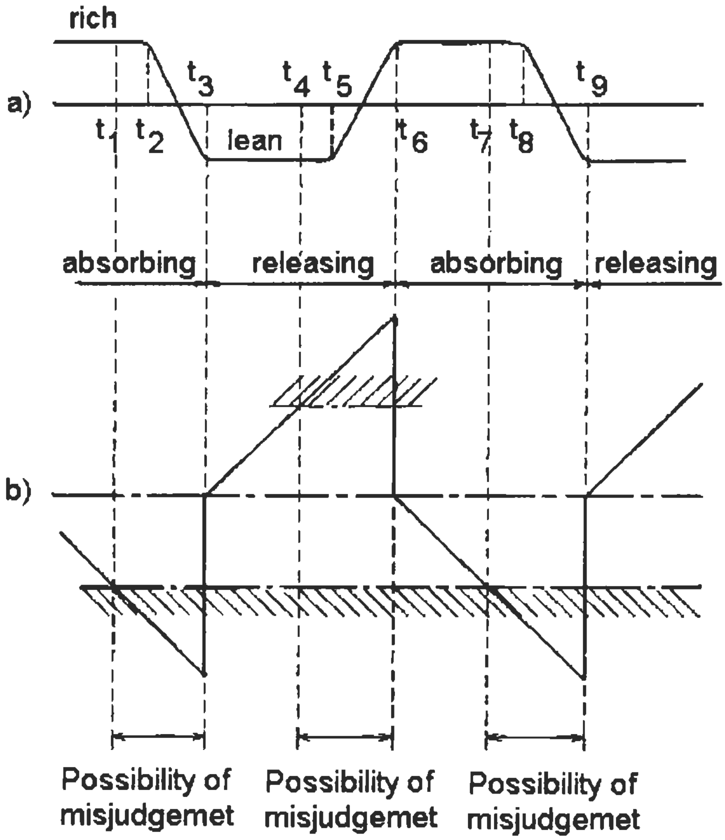


Fig. 55 (from EP0801215)

Other methods presented by Toyota Motor Co Ltd. are described in **JP7139400 (1995)**, **JP8291740 (1996)** and **JP8291741 (1996)**.

Engines with multiple cylinder groups

The following three methods proposed by Toyota refer to the case of an engine with multiple cylinder groups, where there is an auxiliary catalytic converter in each individual exhaust passage of each cylinder group. A main three-way catalytic converter is also installed in the common exhaust pipe section of all cylinder groups (fig. 56). An oxygen sensor is installed upstream of each auxiliary catalytic converter (1a, 1b, etc.) and an oxygen sensor (2) is installed downstream of the main catalytic converter. The layout of the engine as well as the electronic module used for monitoring the efficiency of the main catalytic converter for all three methods is shown in fig. 56. For simplicity, only two cylinder groups will be considered named as left and right bank.

The auxiliary converters are three-way catalytic converters and have a small volume in order to be activated rapidly after the engine is started. The main converter is also a three-way catalytic converter.

Secondary air is injected in both exhaust branches in order to reduce the emission of HC and CO during deceleration or idling of the engine.

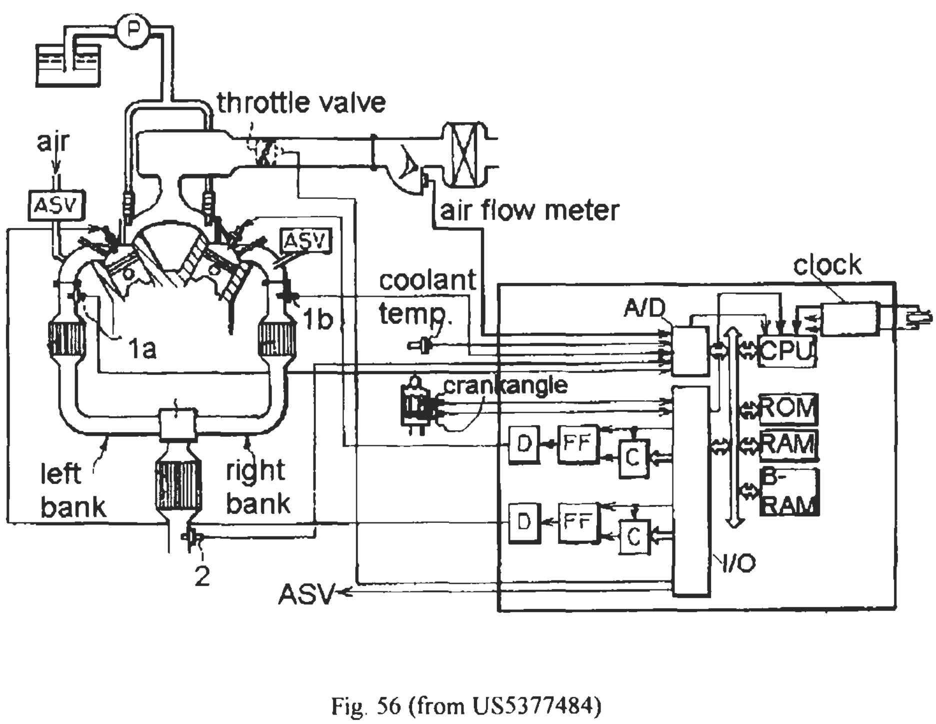


Fig. 56 (from US5377484)

Two fuel injection valves are installed, one for each bank. The control of the fuel injection is similar to this of fig. 40. The difference is that there are two control units, each comprising a down counter, a flip-flop and a drive circuit. Each of these control units controls one of the fuel injection valves.

The method of **US5207057 (1993)** comprises the following steps:

1) individually controlling the air/fuel ratio of each cylinder group in accordance with the output of the upstream air/fuel ratio sensor corresponding to the respective cylinder group
2) controlling the air/fuel ratio of all cylinder groups simultaneously, in accordance with an output of one of the upstream sensors, when the engine is operated under a predetermined operating condition. The output of said one of the upstream air/fuel ratio sensors alternates between a rich air/fuel ratio side and a lean air/fuel ratio side periodically, compared with the stoichiometric air/fuel ratio.
3) determining whether or not said catalyst converter has deteriorated, when the ratio of periods of the oscillating outputs of said upstream sensor and said downstream sensor becomes larger than a predetermined value.

The method of **EP0595044 (1994)** comprises the following steps:

1) individually controlling the air/fuel ratio of each cylinder group in accordance with control parameters defined from the output signals of the upstream air/fuel ratio sensors so that the air/fuel ratio of each cylinder group oscillates periodically between a rich air/fuel ratio and a lean air/fuel ratio
2) detecting phases of the air/fuel ratio oscillations of exhaust gases flowing into said common exhaust passage from said respective individual exhaust passages
3) determining whether or not conditions in which the above mentioned phases of air/fuel ratio oscillations spontaneously synchronize, are satisfied. A spontaneous synchronization can exist due to slight differences of the periods of the cycle of the air/fuel ratio feedback controls in the respective cylinder groups. The conditions for the spontaneous synchronization of these phases are satisfied when
    a) the phases of the air/fuel ratio oscillations of the respective cylinder groups synchronize, or
    b) the differences in the phases of the air/fuel oscillations of the respective cylinder groups become predetermined time periods (e.g. constant time periods regardless of the operating conditions of the engine)
4) determining the condition of the catalytic converter based on the output signal of the downstream sensor, when the conditions for the spontaneous synchronization of these phases are satisfied. Three different methods are used to determine the deterioration of the catalytic converter by using
    a) the number of reversals of the output signal of the downstream oxygen sensor, or

b) the lengths of the output signal of the downstream sensor, or
c) the lengths and areas of the output signal response curves of the upstream and downstream oxygen sensor.

The use of a spontaneous synchronization instead of a forced one has the big advantage of not provoking extra pollution to the atmosphere.

The method of **US5377484 (1995)** comprises the steps:

1) estimating the air/fuel ratio of a mixture of the exhaust gases from the individual exhaust passages flowing into the common exhaust passage based on the output signals of the upstream sensors. The estimation step comprises:
   a) calculating a mean value of the air/fuel ratio of the exhaust gases detected at the same time by the upstream sensors and determining that said mean value is the air/fuel ratio of the mixture of the exhaust gases, or
   b) calculating a mean value of the air/fuel ratios detected by the upstream sensors at a predetermined interval, and determining that said mean value is the air/fuel ratio of the mixture of the exhaust gases.
2) determining whether or not the three-way catalytic converter has deteriorated based on the output signal of the downstream air/fuel sensor and the estimated air/fuel ratio of the mixture of the exhaust gases flowing into the common exhaust passage. The method of **EP0547326 (1993)** is then used to determine the condition of the catalytic converter, where the measured air/fuel ratio of the upstream sensor is replaced by the estimated air/fuel ratio of the mixture of the exhaust gases from the individual exhaust passages flowing into the common exhaust passage. Ratios of lengths and bounded areas of the downstream signal to the estimated upstream signal are calculated and depending on the relationship of these ratios, conclusions are drawn about the condition of the catalytic converter.

Chapter 1.5

Nippon Denso Co.

The methods proposed by Nippon Denso Co. have been applied, except otherwise mentioned, for an engine layout similar to that of fig. 40.

In **JP2136538 (1990)** a deceleration state of the engine is detected during which the fuel supply to the engine is stopped. When the fuel supply starts again, a clock measures the time elapsed for the oxygen content of the exhaust gases downstream of the catalytic converter to fall below a predetermined threshold. If this elapsed time is shorter than a predetermined one, the catalytic converter is considered as degraded.

The methods of **DE4101616 (1991)** and **US5154055 (1992)** comprise the following steps:

1) measuring the air/fuel ratio of the exhaust gases upstream and downstream of the catalytic converter by means of the upstream and downstream sensor
2) detecting a first delay time difference T_x between the inversion time of an output of the upstream air/fuel ration sensor and the inversion time of an output of the downstream air/fuel ratio sensor (fig. 57) when a rotational speed of the engine is within a first predetermined range and a load of the engine is within a second predetermined range

3) detecting a second delay time difference T_s' between the inversion time of an output of the upstream air/fuel ration sensor and the inversion time of an output of the downstream air/fuel ratio sensor (fig. 57) when the rotational speed is within a second predetermined range and the engine load is within a second predetermined range
4) detecting the oxygen storage volume capability of said catalytic converter on the basis of a deviation $\Delta T = T_s - T_s'$ between said first and second response delay time differences respectively. A feedback correction coefficient of a fuel injection time determining element is changed in accordance with an output value of said upstream air/fuel ratio sensor. The period in which said feedback correction coefficient is changed is increased to be longer than a period at the time of ordinary emission control, during which the purification factor of said catalyst is measured.

The response delay time T_1 of the upstream oxygen sensor to a change of the engine air/fuel ratio from a rich to a lean state is given by the equation:

$$T_1 = t_1 + D_1$$

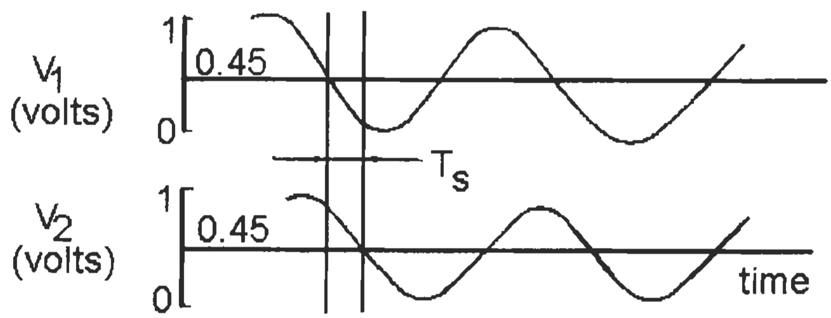


Fig. 57 (from DE4101616)

where
t_1: time needed for exhaust gas after it leaves the engine to approach the upstream sensor
D_1: response time of upstream sensor

The response delay time T_2 of the downstream oxygen sensor is given by the equation

$$T_2 = t_1 + t_2 + \frac{V_{O2}}{\dot{Q}_{O2}} + t_3 + D_2$$

where
t_2: time needed for exhaust gas after it leaves the upstream sensor to approach the catalytic converter
t_3: time needed for exhaust gas after it leaves the catalytic converter to approach the downstream sensor
D_2: response time of downstream sensor
$\dot{Q}_{O2}$: oxygen volume content of exhaust gases,
V_{O2}: oxygen storage volume of the catalytic converter.
The ratio of the oxygen storage volume over the oxygen volume content of exhaust gases represents a time which is elapsed before the oxygen storage volume reaches a maximum limit thereof.

The first delay time difference T_s is calculated as

$$T_s = T_2 - T_1 = \frac{V_{O2}}{\dot{Q}_{O2}} + (D_2 - D_1) + (t_2 + t_3)$$

The second delay time difference T_s' is calculated similarly. The deviation then is calculated as:

$$\Delta T = T_s - T_s' = V_{O2}\left(\frac{1}{\dot{Q}_{O2}} - \frac{1}{\dot{Q}'_{O2}}\right) + (t_2 + t_3) - (t_2' + t_3')$$

The oxygen volume content of the exhaust gases is represented as

$$\dot{Q}_{O2} = k \cdot \dot{Q}_{air\ in}$$

where
k: constant representing concentration of oxygen in engine inducted air flow $\dot{Q}_{airin}$.

Accordingly the oxygen storage volume can be calculated by the following equation:

$$V_{O2} = k \cdot \frac{\Delta T - (t_2 + t_3) + (t_2' + t_3')}{\frac{1}{\dot{Q}_{air\ in}} - \frac{1}{\dot{Q}'_{air\ in}}}$$

In **JP3246456 (1991)** the average frequency f_0 of the air/fuel ratio oscillation is measured downstream of the catalytic converter during a time interval T_1, when certain operating conditions hold. During the same diagnostic period, the exhaust gases bypass the catalytic converter and pass through a fresh reference catalytic converter. The average frequency f_1 of the air/fuel ratio oscillation is then measured downstream of the reference catalytic converter during a time interval T_2. The catalytic converter is considered as deteriorated when

$$\frac{f_0}{f_1} > \varepsilon ,$$

where ε is a preset threshold.

In **JP4066748 (1992)** the air/fuel ratio of the engines starts oscillating around the stoichiometric value. The time elapsed between a maximum and a minimum value as well as the number of turnover cycles of the variation of the output of the downstream sensor in a specific period are detected. When the number of cycles is higher than a predetermined number and the elapsed time is lower than a predetermined time, then the catalytic converter is considered as degraded.

In **JP4081540 (1992)** the air/fuel ratio of the engines starts oscillating around the stoichiometric value. The upstream and downstream oxygen sensors detect the phase difference of the two signals upstream and downstream of the catalytic converter and an average phase difference is calculated within a specified time. When the average value is judged to be less than a predetermined value the catalytic converter is considered as degraded.

The method of **JP4321744 (1992)** detects deterioration of catalytic converters even in the case of a deteriorated upstream oxygen sensor. The engine air/fuel ratio is corrected according to the output signal of the upstream sensor in order to achieve the theoretical engine air/fuel ratio. The deterioration of the catalytic converter is based on the delay time length between a change in the corrected air/fuel ratio of the engine and the corresponding change in the output signal of the downstream sensor. The catalytic converter is considered as deteriorated when the delay time length becomes shorter than a predetermined threshold.

The method of **EP0475177 (1992)** and **US5220788 (1993)** is based on a change of the feedback control of the engine air/fuel ratio period to a value different from the feedback period (responsive to the upstream sensor) that occurs during normal air/fuel ratio control operation. Two methods are presented for changing the feedback period:

1) the period is set to a predetermined (target) value such so to ensure optimum accuracy of detecting the purification factor, i.e. accuracy of determining whether the purification factor is above a certain reference level or accuracy of measuring the value of the purification

factor. This can be achieved by adding a constant delay time interval to the normal feedback control period. The purification factor can then be judged by detecting

a) the amplitude of the downstream sensor and checking whether it exceeds a predetermined threshold value or
b) the phase difference between the output signals of the upstream and downstream sensor

2) the period is changed by successive small amounts, and it is detected when the amplitude ΔV_2 of the output signal of the downstream oxygen sensor reaches a predetermined threshold voltage. The value of feedback period at which that threshold voltage is reached is then measured, and the purification factor of the catalytic converter can then be obtained based on a known relationship between values of feedback period at which the threshold voltage is reached.

Fig. 58 shows said relationship between the feedback period and the output signal amplitude ΔV_2 of the downstream sensor, with the purification factor of the catalytic converter as a parameter. By using that characteristic, it becomes possible to measure the purification factor of the catalytic converter, based on the specific feedback period at which the amplitude ΔV_2 is found to exceed the threshold value, which in this example is 0.7 Volts. The relationship between values of feedback period and values of the purification factor is stored beforehand, in a memory map. If the detected purification factor is lower than a reference value the catalytic converter is considered as degraded.

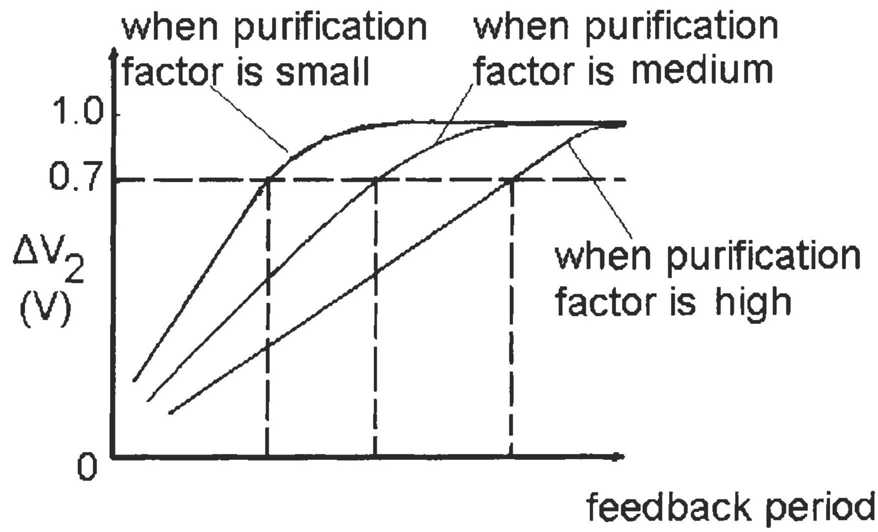


Fig. 58 (from EP0475177)

The method of **US5097700 (1992)** allows accurate detection of the catalytic converter irrespective of the deterioration of the downstream oxygen sensor itself. This can be achieved as follows:
1) detecting a concentration of oxygen of the exhaust gas by means of the downstream sensor
2) comparing a predetermined judgment threshold with an amplitude of the output signal therefrom to detect, on the basis of the comparison result, whether the catalytic converter is in a deteriorated state
3) relatively correcting said predetermined judgment threshold with respect to the output signal from said gas concentration sensor means I) on the basis of the output signal therefrom under a predetermined rich or lean air/fuel ratio state or II) on the basis of the difference between the output signal therefrom under the condition that an air/fuel ratio for said internal combustion engine is in a predetermined rich state and the output signal therefrom under the condition that the air/fuel ratio is in a predetermined lean state.

The predetermined rich state is taken when an output of the internal combustion engine is increasing and the predetermined lean state is taken when supply of a fuel to said internal combustion engine is stopped.

In the method of **DE4322341 (1994)** the saturation of a gas (e.g. CO or HC) entering the catalytic converter is checked and comprises the following steps:
1) monitoring the exhaust gases with an oxygen sensor installed downstream of the catalytic converter
2) driving the engine with a λ sensor installed upstream of the catalytic converter. The sensor drives the engine with a correction feedback amount in a given direction away from the stoichiometric value ($\lambda=1$)
3) increasing the correction feedback amount and/or the correction feedback time interval, in order to execute a variation process of the air/fuel ratio towards saturation of the catalytic converter
4) judging whether the catalytic converter is saturated and when saturation is detected by means of the downstream sensor then
5) calculating the saturation amount of a gas absorbed from the catalytic converter (e.g. CO or HC) and checking if this saturation amount is out of a predefined range indicating the need of replacement of the catalytic converter

The method of **US5280707 (1994)** comprises the steps:
1) measuring the air/fuel ratio of the exhaust gases upstream of the catalytic converter
2) measuring the air/fuel ratio of the exhaust gases downstream of the catalytic converter
3) calculating, in accordance with an output signal from the upstream and/or downstream oxygen sensors, an air/fuel ratio correction coefficient with which the air/fuel ratio is corrected so as to be in the neighborhood of the theoretical air/fuel ratio

4) performing control of the internal combustion engine by using the air/fuel ratio correction coefficient in such a manner that the air/fuel ratio is made to be equal to the theoretical air/fuel ratio
5) calculating an average air/fuel ratio correction coefficient of the air/fuel ratio correction coefficient when the air/fuel ratio is changed from a rich side to a lean side and the air/fuel ratio correction coefficient when the air/fuel ratio is changed from the lean side to the rich side
6) discriminating the deterioration of the catalytic converter in accordance with a response delay time from a moment an output signal from the upstream oxygen sensor has been changed to a moment an output signal from the downstream oxygen sensor has been changed in the same direction, and the catalytic converter is considered as deteriorated when the response delay time is smaller than a predetermined value
7) permitting the catalyst deterioration detection when the internal combustion engine is in idling state and when the air/fuel ratio has been converged to the neighborhood of the theoretical air/fuel ratio in accordance with the value of the average air/fuel ratio correction coefficient.

The method of **US5412942 (1995)** comprises the following steps:
1) deriving a main air/fuel ratio correction coefficient based on an output of the upstream-side oxygen sensor. The main air/fuel ratio correction coefficient is derived for correcting an air/fuel ratio of an air/fuel mixture to be fed to the engine so as to be near the stoichiometric air/fuel ratio
2) controlling the air/fuel ratio to be fed to the engine so as to be near the stoichiometric air/fuel ratio, using said main air/fuel ratio correction coefficient
3) deriving a high-frequency amplitude of an output of the downstream-side oxygen sensor by calculating a difference between maximum and minimum values of the output of said downstream-side oxygen sensor. The maximum and minimum values are derived at every period of the main air/fuel ratio correction coefficient
4) deriving a low-frequency amplitude of the output of the downstream-side oxygen sensor. The mean value of maximum and minimum values of the output of the downstream oxygen sensor at every period of the main air/fuel ratio correction coefficient is derived and the amplitude of the low-frequency component is calculated by the difference between maximum and minimum values of said mean values during a preset time period
5) determining that the catalytic converter is deteriorated when said high-frequency amplitude is greater than a preset value and said low-frequency amplitude is smaller than a preset value.

The method can be better explained with the help of figs. 59a,b,c, where the voltage variation of the upstream sensor V_1 and the downstream sensor V_2 are shown for the cases of a high purification rate, a medium purification rate and a low purification rate of a catalytic converter respectively. The dashed lines represent the low frequency variation of the output signal of the downstream sensor, which is generated due to the air/fuel ratio feedback control. As can be noticed from fig. 59, as the purification factor of the catalytic converter decreases, the high frequency amplitude becomes larger and the low frequency amplitude becomes smaller. The deterioration of the catalytic converter is determined when the high frequency amplitude of the output of the downstream sensor is large and the low frequency amplitude thereof is small.

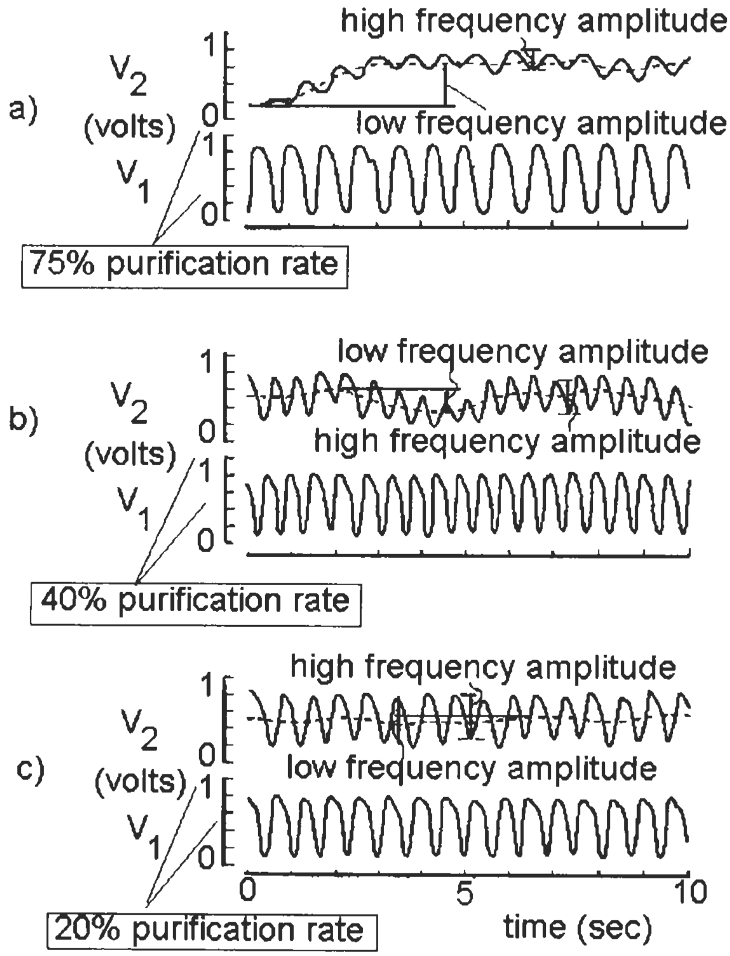


Fig. 59 (from US5412942)

The method of **EP0668438 (1995)** takes into consideration the differences in performance of the air/fuel ratio sensors and comprises the following steps:

1) measuring the air/fuel ratio upstream and downstream of a catalytic converter by means of two sensors with different responsiveness. The responsiveness of the downstream sensor is lower than the responsiveness of the upstream sensor by a range from 20% exclusive to 100% inclusive
2) forming the locus ratio LR of the locus lengths L of the output wave forms of the two sensors

$$LR = \frac{L_2}{L_1} = \frac{\int_{t0}^{tN} \sqrt{1 + (V_2'(t))^2}\, dt}{\int_{t0}^{tN} \sqrt{1 + (V_1'(t))^2}\, dt}$$

where $V(t)$ is the output voltage of a sensor, t_0 is the time at which a period of this wave form begins and t_N is the time at which a period of this wave form ends
3) detecting the degradation of the catalytic converter when the locus ratio is out of a predetermined range.

The ratio of opening area of the air holes of the downstream sensor to the opening area of the air holes of the upstream sensor is an additional parameter for detecting the degradation of the catalytic converter.

The method of **JP8246854 (1996)** also uses a locus ratio of the output signals of the upstream and downstream sensor to assess the efficiency of the catalytic converter. The locus ratio is based on the frequencies of the two signals.

The method of **JP7103039 (1995)** comprises the following steps:
1) feedback-controlling the engine air/fuel ratio based on the output signal of the upstream oxygen sensor, to continuously fluctuate the air/fuel ratio of the exhaust gas introduced in the catalytic converter at a specific amplitude and period
2) correcting either the amplitude or the period of the air/fuel ratio fluctuation of the exhaust gas introduced in the catalytic converter by increasing its value
3) detecting the air/fuel ratio of the exhaust gases by means of the downstream sensor. When the output signal of the downstream sensor does not fluctuate despite the increase of either the amplitude or the period of the air/fuel ratio fluctuation of the exhaust gas introduced in the catalytic converter, then the increase range of either the amplitude or period of the fluctuation is further increased till the downstream output signal starts fluctuating
4) assessing the efficiency of the catalytic converter from the necessary increase of either the amplitude or period of the air/fuel ratio fluctuation of the exhaust gas introduced in the catalytic converter till the downstream output signal starts fluctuating.

The method of **US5528898 (1996)** comprises the following steps:

1) detecting whether an air/fuel ratio is rich or lean with respect to the stoichiometric ratio by means of the upstream and downstream oxygen sensors
2) establishing certain conditions of engine operation
3) detecting whether the amplitude of the output signal of the downstream oxygen sensor is higher than a reference value
4) determining whether deterioration of the catalytic converter is likely to be present on the basis of the amplitude detection results of step 3 and then
5) adjusting the response of the upstream sensor to a preset value by adjusting the air/fuel feedback control frequency to a target setting (slower response than the one at non-testing conditions)
6) summing a response delay time occurring within a specified period in the downstream sensor after adjusting the response of the upstream sensor
7) finally determining whether deterioration is present in the catalytic converter by comparing the sum of step 6 with a reference value

The method of **GB2297847 (1996)** comprises the following steps:
1) feedback-controlling the engine air/fuel ratio by means of the upstream λ sensor
2) checking whether the period of inversion of the downstream oxygen sensor exceeds a predetermined time and determining then from this check that the three-way converter is activated
3) estimating the quantity of heat required from the start-up of the engine to the time of activation of the catalytic converter. The quantity of heat is obtained from the accumulated engine intake air quantity during the period of step 2 or from the quantity of fuel injected
4) determining whether the catalytic converter has deteriorated from the calculated quantity of heat

The method of **US5622047 (1997)** comprises the following steps:
1) detecting the air/fuel ratio upstream of the catalytic converter by means of an upstream air/fuel sensor
2) detecting the air/fuel ratio downstream of the catalytic converter by means of a downstream air/fuel sensor
3) controlling a rate of fuel injection into the engine in response to a result of the detected upstream air/fuel ratio, and varying the air/fuel ratio of the exhaust gas flowing into the catalytic converter around a predetermined air/fuel ratio at an amplitude and a period
4) correcting and increasing at least one of the amplitude and the period of said varying of the air/fuel ratio
5) increasing a degree of said increasing of at least one of the amplitude and the period in cases where the detected downstream air/fuel ratio does not vary although at least one of the amplitude and the period is corrected and increased, and when the detected downstream air/fuel ratio varies
6) determining a condition of deterioration of the catalytic converter in response to the amplitude and the period which occur as result of said variation

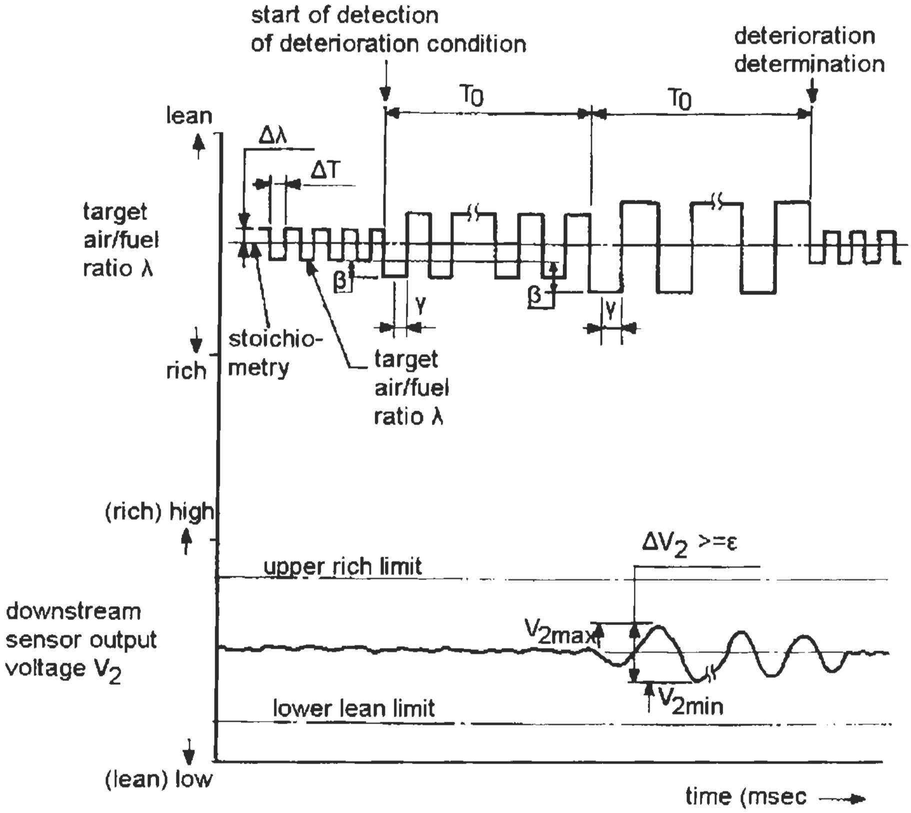


Fig. 60 (from US5622047)

As shown in fig. 60, during deterioration detection of the catalytic converter the target air/fuel ratio of the engine varies at a greater amplitude and a longer period in response to a corrected increased dither amplitude $\Delta\lambda$ and dither period ΔT than the ones during a normal engine operation. The correction takes place according to the expressions:

$$\Delta\lambda = \Delta\lambda + \beta$$
$$\Delta T = \Delta T + \gamma$$

where
β, γ: corrective quantities

The target air/fuel ratio continues to vary at the greater amplitude and the longer period during the preset continuation time T_0. Immediately after the preset continuation time T_0 elapses, it is determined whether or not the catalytic converter is saturated. When the catalytic converter is not saturated, the dither amplitude $\Delta\lambda$ and the dither period ΔT are further corrected and increased. Therefore, as shown in fig. 60, the target air/fuel ratio varies at a further greater amplitude and a further longer period. The target air/fuel ratio continues to vary at the further greater amplitude and the further longer period during the next preset continuation time T_0.

Immediately after the next preset continuation time T_0 elapses, it is determined whether or not the catalytic converter is saturated. Such processes are reiterated until the saturation of the catalytic converter is detected. It should be noted that variation of the target air/fuel ratio at a greater amplitude and a longer period causes the catalytic converter to be more easily and surely saturated. The detection of saturation of the catalytic converter is based on the fact that, as shown in fig. 60, the difference ΔV_2 between the maximum value V_{2max} and the minimum value V_{2min} of the output voltage V_2 of the downstream oxygen sensor is equal to or greater than a predetermined reference value ε when the catalytic converter is saturated.

When saturation of the catalytic converter is determined, the degree of deterioration of the catalytic converter is determined in response to the current deterioration detection corrective values β and γ which are components of the current dither amplitude $\Delta\lambda$ and the current dither period ΔT. Low values of β, γ to achieve saturation of the catalytic converter mean great deterioration of the converter.

The degree of deterioration of the catalytic converter is detected each time the distance traveled by the vehicle body increases by 2,000 km. The degree of deterioration of the catalytic converter may be detected when the total time of travel of the vehicle body increases by each preset time or when the total time of operation of the engine increases by each preset time.

Other methods of Nippon Denso Co.: see **JP8338286 (1996)**

Engines with multiple cylinder groups

The method of **US5279114 (1994)** is applied to the case of a multiple cylinder bank engine with an air/fuel sensor installed in each cylinder bank exhaust pipe upstream of the catalytic converter and an air/fuel sensor installed in the common exhaust pipe section downstream of the catalytic converter. The general layout is this of fig. 56. The method comprises the steps:

1) executing a feedback control of the air/fuel ratio of each cylinder bank in accordance with the results of detected output signals performed by the plurality of upstream air/fuel ratio sensors and the downstream air/fuel ratio sensor
2) discriminating the deterioration state of the catalytic converter in accordance with results of detected output signals performed by the upstream air/fuel ratio sensor corresponding to a predetermined cylinder bank and the downstream air/fuel ratio sensor
3) adjusting the air/fuel ratio control quantity at the time of feedback-controlling the air/fuel ratio so as to eliminate an influence of exhaust gas emitted from cylinder banks except for said predetermined cylinder bank of a plurality of said cylinder banks. This elimination of influence can be achieved by one of the following methods:
    a) reducing air/fuel correction coefficients of all cylinder banks except for the predetermined cylinder bank at the time of feedback-controlling the air/fuel ratio, or
    b) using an air/fuel ratio correction coefficient of the predetermined cylinder bank as the air/fuel ratio correction coefficients for the other cylinder banks at the time of feedback-controlling said air/fuel ratio so as to cause the phases of the upstream air/fuel ratio sensors to be synchronized with one another, or
    c) subjecting all cylinder banks except for the predetermined cylinder bank to a dither control in which the air/fuel ratio is changed relative to a target air/fuel ratio

Fig. 61 illustrates changes of the wave forms of the air fuel ratio for the case of left and right bank upstream sensors with coinciding phase (fig. 61a), with non-coinciding phase (fig. 61b) and with a reduced air/fuel correction coefficient for the right bank sensor (fig. 61c). The left cylinder bank is considered to be the predetermined cylinder bank mentioned above. The case of fig. 61a is an ideal one where the output signal of the downstream sensor results in a high amplitude oscillation, but in reality the phases of the two upstream sensors never coincide because they are independently feedback-controlled. The case of fig. 61b results in an almost flat signal output of the downstream sensor and no real detection of the catalytic converter can take place. In the case of fig. 61c the amplitude of the right cylinder bank is considerably decreased, so it does not influence the total variation of the output signal of the downstream sensor and the deterioration of the catalytic converter can take place by comparing the output signals of the left cylinder bank air/fuel sensor and of the downstream air/fuel sensor.

The case of fig. 61d corresponds to a dither control of the air/fuel ratio of the upstream sensor placed in the right cylinder bank. The air/fuel correction coefficient for this sensor swings slightly while traversing a point at which the air/fuel ratio λ=1. As a result, the period of the wave form of the right air/fuel ratio sensor in which the rich state and the lean state are inverted is lengthened. Hence, the influence of the exhaust as shown from the right bank is eliminated considerably, and therefore the wave form detected by the downstream sensor is able to show the change at the left bank. Therefore, the catalytic converter deterioration discrimination can be accurately performed.

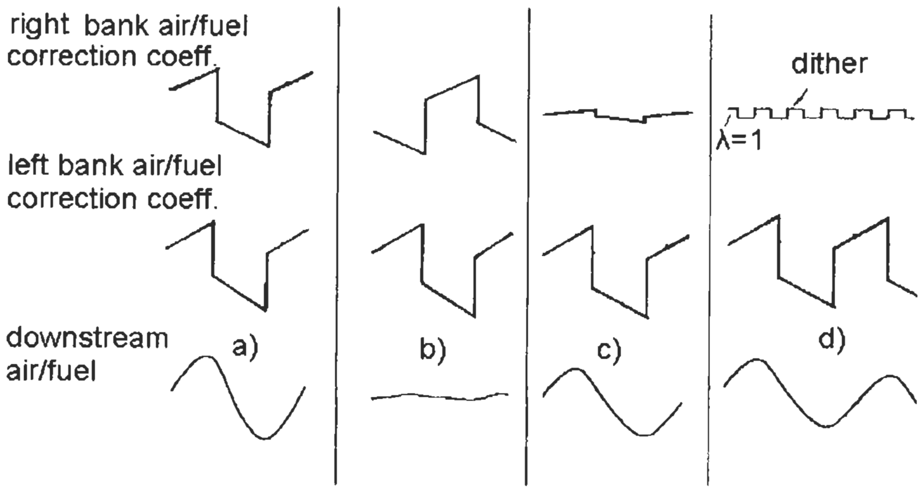


Fig. 61 (from US5279114)

Chapter 1.6

Honda Motor Co. Ltd.

The methods proposed by Honda have been applied, except where otherwise mentioned, for an engine layout similar to that of fig. 62.

Connected to the cylinder block of the engine is an intake pipe across which is arranged a throttle body accommodating a throttle valve therein. A throttle valve opening (θ) sensor is connected to the throttle valve for generating an electric signal indicative of the sensed throttle valve opening and supplying same to an electronic control unit (hereinafter called "the ECU").

Fuel injection valves, only one of which is shown, are inserted into the interior of the intake pipe at locations intermediate between the cylinder block of the engine and the throttle valve and slightly upstream of respective intake valves, not shown. The fuel injection valves are connected to a fuel pump, not shown, and electrically connected to the ECU to have their valve opening periods controlled by signals therefrom.

On the other hand, an intake pipe absolute pressure sensor is provided in communication with the interior of the intake pipe through a conduit at a location immediately downstream of the throttle valve for supplying an electric signal indicative of the sensed absolute pressure within the intake pipe to the ECU. An intake air temperature sensor is inserted into the intake pipe at a location downstream of the intake pipe absolute pressure sensor for supplying an electric signal indicative of the sensed intake air temperature to the ECU.

An engine coolant temperature sensor, which may be formed of a thermistor or the like, is mounted in the cylinder block of the engine, for supplying an electric signal indicative of the sensed engine coolant temperature to the ECU. An engine rotational speed sensor and a cylinder-discriminating sensor are arranged in facing relation to a camshaft or a crankshaft of the engine, neither of which is shown. The engine rotational speed sensor generates a pulse as a TDC (top dead center) signal pulse at each of predetermined crank angles whenever the crankshaft rotates through 180 degrees, while the cylinder-discriminating sensor generates a pulse at a predetermined crank angle of a particular cylinder of the engine, both of the pulses being supplied to the ECU

A three-way catalyst is arranged within an exhaust pipe connected to the cylinder block of the engine for purifying noxious components such as HC, CO, and NO_x. Oxygen sensors as air-fuel ratio sensors are mounted in the exhaust pipe at locations upstream and downstream of the three-way catalyst, respectively, for sensing the concentration of oxygen present in exhaust gases emitted from the engine and supplying electric signals in accordance with the output values V_1, V_2 thereof to the ECU. Further, a catalyst temperature sensor is mounted on the three-way catalyst for detecting the temperature of same and supplying a signal indicative of the detected catalyst temperature to the ECU.

A vehicle speed sensor is connected to the ECU for detecting the vehicle speed V and supplying a signal indicative of the detected vehicle speed V to the ECU. Further connected to the ECU is an LED (light emitting diode) for raising an alarm when deterioration of the three-way catalyst has been detected by the present method in a manner described in detail herein below.

The ECU comprises an input circuit having the functions of shaping the wave forms of input signals from various sensors, shifting the voltage levels of sensor output signals to a predetermined level, converting analog signals from analog-output sensors to digital signals, and so forth, a central processing unit (hereinafter called "the CPU"), memory means storing various operational programs which are executed in the CPU and for storing results of calculations therefrom, etc., and an output circuit which outputs driving signals to the fuel injection valves and the LED.

The CPU operates in response to the above mentioned signals from the sensors to determine operating conditions in which the engine is operating, such as an air-fuel ratio feedback control region in which the fuel supply is controlled in response to the detected oxygen concentration in the exhaust gases, and open-loop control regions including a region in which fuel supply should be increased under a high load condition of the engine, and a fuel cut region, and calculates, based upon the determined operating conditions, the valve opening period or fuel injection period over which the fuel injection valves are to be opened in synchronism with inputting of TDC signal pulses to the ECU.

In **JP4017758 (1992)** the air/fuel ratio is switched to a rich state and the output signals of the upstream and downstream sensors are detected and compared. The fuel supply is then cut off for a certain time and the output signals of the two sensors are detected again. From the four in total detected signals useful conclusions about the condition of the catalytic converter can be drawn without any influence of the physical characteristics of the two sensors to be involved.

In the method of **US5158059 (1992)** an amount of residual fuel in the tank is compared with a predetermined value and when the residual fuel is below a predetermined value, an abnormality detection of the catalytic converter is inhibited. The detection method comprises the steps of:

1) obtaining a first signal and a second signal based on respective signal outputs from the upstream and downstream air/fuel ratio sensors when the fuel supply to the engine is increased (high load)
2) obtaining a third signal and a fourth signal based on respective signals outputs from the upstream and downstream air/fuel ratio sensors when the fuel supply to the engine is interrupted (fuel cut)

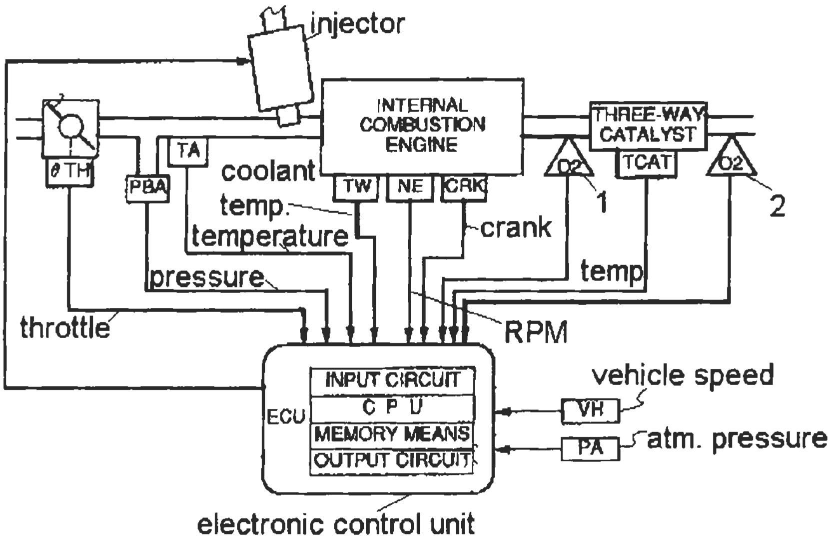


Fig. 62 (from US5381657)

3) comparing a wave form of a signal output from the upstream air/fuel ratio sensor with a wave form of a signal output from the downstream air/fuel ratio sensor, based on said first to fourth signals while the engine is in a predetermined stable operating condition
4) determining from a result of this comparison whether or not the three-way catalyst is deteriorated.

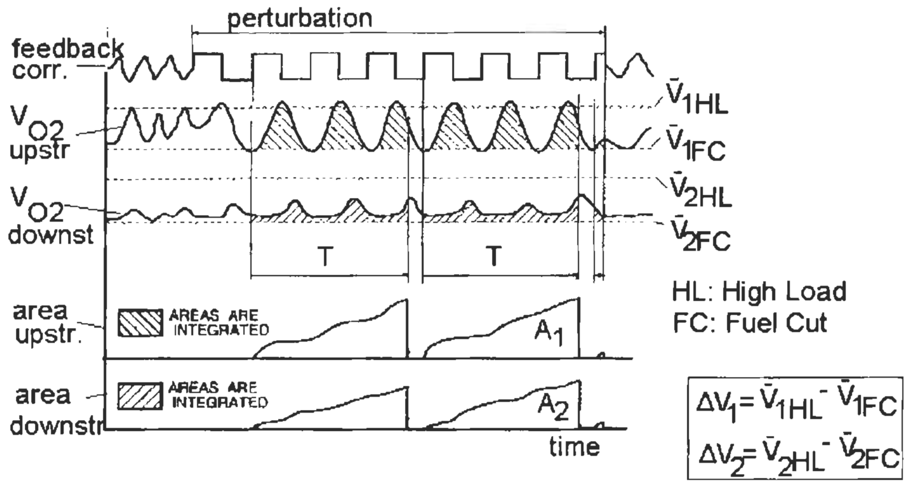


Fig. 63 (from US5158059)

The method can be explained with the help of fig. 63. When the engine is in a predetermined operating condition, the air/fuel ratio feedback correction coefficient is subjected to a perturbation. This change of oxygen concentration V_{O2} in the exhaust gases is sensed by the upstream and downstream sensors. The area A_1 between the output signal V_{O2} of the upstream sensor and the average values $\overline{V}_{1HL}$ and $\overline{V}_{1FC}$ (corresponding to a high load and a fuel cut condition respectively) is formed during a time period T. Similarly, the area A_2 between the output signal V_{O2} of the downstream sensor and the average values $\overline{V}_{2HL}$ and $\overline{V}_{2FC}$ (corresponding to a high load and a fuel cut condition respectively) is formed during a time period T. The area A_2 is then corrected by using the expression

$$A_2' = A_2 \cdot \frac{\Delta V_1}{\Delta V_2}$$

where

$$\Delta V_1 = \overline{V}_{1HL} - \overline{V}_{1FC} \quad \text{and}$$

$$\Delta V_2 = \bar{V}_{2HI} - \bar{V}_{2FC}$$

In this way, any differences or variations between the two sensors are eliminated. If the difference between the areas A_1 and A_2' is smaller than a predetermined limit, the catalytic converter is considered as degraded.

The method of **US5191762 (1993)** comprises the following steps:
1) starting to cut off the fuel supply to the engine when the engine is decelerated having the throttle valve substantially fully closed (fig. 64)
2) resuming the fuel supply to the engine when the rotational speed of the engine has become lower than a predetermined value. This resumption of fuel supply comprises resuming feedback control, in which the air/fuel ratio of a mixture supplied to the engine is controlled to a predetermined value in response to a signal of the upstream sensor
3) measuring the time Δt which the output from the downstream air/fuel ratio sensor has required to reach a predetermined reference value V_{ref} (fig. 64) after the resumption of the fuel supply to the engine. This carrying out of time measurement takes place when I) the temperature of the engine is higher than a predetermined value, or II) after a predetermined time period has elapsed after transition of the engine from starting mode to normal mode
4) determining that the three-way catalyst is deteriorated when said measured time Δt is shorter than a predetermined time period (fig. 64).

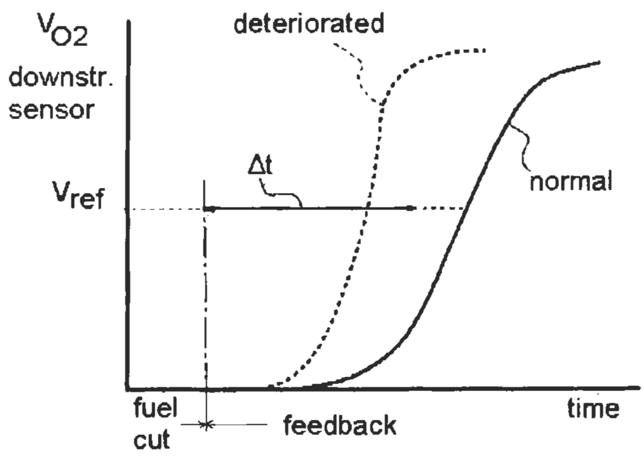


Fig. 64 (from US5191762)

The method of **US5325664 (1994)** comprises the following steps:

1) sensing concentration of oxygen contained in exhaust gases emitted from the engine by means of an upstream sensor
2) sensing concentration of oxygen contained in the exhaust gases downstream of the catalytic converter by means of a downstream sensor
3) controlling the air/fuel ratio of a mixture supplied to the engine by means of an air/fuel ratio feedback correction value, the control being responsive to the outputs of the upstream and downstream sensors (first control)
4) controlling the air/fuel ratio of the mixture by means of the air/fuel ratio feedback correction value, the control being responsive to the output of the downstream sensor (second control)
5) detecting the temperature of the catalytic converter by means of a temperature sensor mounted inside the catalytic converter body, or estimating the temperature of the catalytic converter from an amount of intake air supplied to the engine or from a rotational speed and a load on the engine
6) effecting changeover from the first air/fuel ratio control to the second air/fuel ratio control for controlling the air/fuel ratio of the mixture, when the detected temperature or the estimated temperature of the catalytic converter falls outside a predetermined range
7) determining whether the output from the downstream oxygen sensor has been inverted from a lean side to a rich side or vice versa with respect to a stoichiometric air/fuel ratio
8) measuring a first time period elapsed from the time the second air/fuel ratio control causes a change in the value of the air/fuel ratio feedback correction value from the rich side to the lean side to the time the output from the downstream oxygen sensor is inverted from the rich side to the lean side, after the changeover has been effected
9) measuring a second time period elapsed from the time the second air/fuel ratio control causes a change in the value of the air/fuel ratio feedback correction value from the lean side to the rich side to the time the output from the second oxygen concentration sensor is inverted from the lean side to the rich side, after the changeover has been effected
10) comparing the sum of the first and second time periods or an average value thereof with a predetermined time period and determining that the catalytic converter is deteriorated, when the sum or the average value is shorter than the predetermined time period. The predetermined time period is extracted from a table as function of the in oxygen storage capacity (OSC) and the temperature of the catalytic converter.

Fig. 65 shows the change in oxygen storage capacity (OSC) of the catalytic converter with respect to the temperature of the converter for a new, a qualified and a deteriorated converter. For new converters the oxygen storage capacity reaches the maximum value at approximately 300 °C, and at higher values of catalytic converter temperatures, it remains unchanged. For a progressively degraded converter the oxygen storage capacity becomes smaller. The qualified and the deteriorated converters show a change in the oxygen storage capacity within a temperature range A-B defined between 300 and 550 °C.

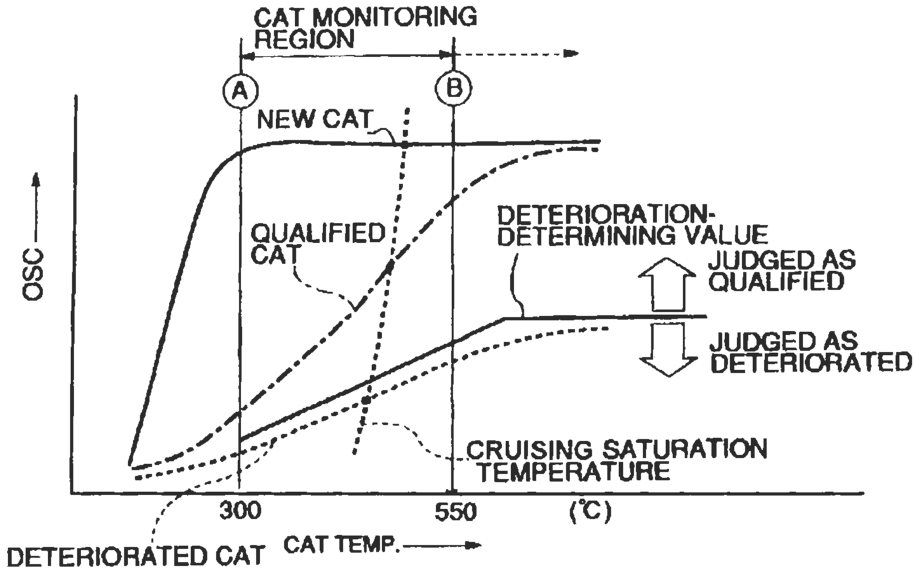


Fig. 65 (from US5325664)

In the case of a used converter, an erroneous determination can take place within range A-B. Additionally, if point B (550 °C) is used as the lower temperature limit, a deteriorated converter cannot be determined to be deteriorated at higher temperatures, or there is a possibility that the catalytic converter temperature does not rise to the monitoring temperature range, so that the deterioration determination cannot be carried out. For this reason, the predetermined time period of step 10 is corrected in dependence of the catalytic converter temperature falling within the specific catalytic converter temperature region A-B. The predetermined time period is extracted from a table as function of the in oxygen storage

The method of patent application **EP0588324 (1994)** comprises the following steps:

1) detecting the concentration of oxygen upstream and downstream of the catalytic converter by means of oxygen sensors
2) detecting operating conditions of the engine
3) calculating a desired air/fuel ratio mixture supplied to the engine in response to the detected operating conditions of the engine
4) correcting the desired air/fuel ratio based on an output value from the downstream sensor
5) feedback controlling an air/fuel ratio of a mixture supplied to the engine to the corrected desired air/fuel ratio in response to the output signal of the upstream sensor
6) calculating an average value of the output signal of the downstream sensor
7) calculating an output fluctuation width with respect to the calculated average value, based on the output signal of the downstream sensor

8) determining whether the catalytic converter is deteriorated, based on the calculated average value and output fluctuation width

In **JP6193436 (1994)** the engine air/fuel ratio forcibly varies from rich to lean and the opposite with a specific amplitude and frequency. The average engine air/fuel ratio is set leaner than the stoichiometric value during execution of the perturbation. The deterioration judgment of the three-way catalytic converter is then based on the average output signals of the upstream and downstream sensor.

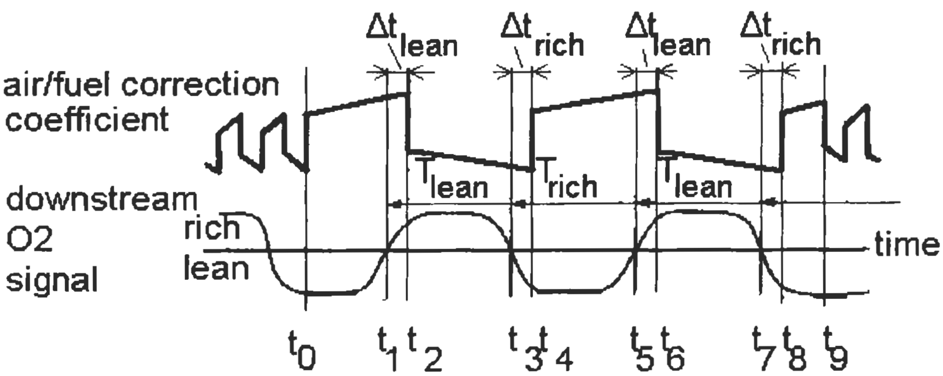


Fig. 66 (from US5381657)

The method of **US5381657 (1995)** comprises the following steps:

1) sensing the concentration of oxygen contained in the exhaust gases downstream of the catalytic converter by means of the downstream sensor (fig. 66 lower part)
2) controlling an air/fuel ratio of a mixture supplied to the engine in relation with the output of the downstream sensor (feedback control) (fig. 66 upper part)
3) comparing the output from the downstream sensor with a predetermined reference value to thereby determine whether the air/fuel ratio of the mixture supplied to the engine is on a rich side or a lean side with respect to a stoichiometric air/fuel ratio
4) changing the air/fuel ratio of the mixture supplied to the engine across the stoichiometric air/fuel ratio upon the lapse of a delay time period Δt_{lean} or Δt_{rich} after the time the inversion of the air/fuel ratio (from rich to lean and vice versa) is detected from the downstream sensor (fig. 66)

5) detecting a value of an inversion period T_{rich} or T_{lean} with which the output from the downstream sensor is inverted from rich to lean and vice versa
6) determining a value of the delay time period Δt_{rich} or Δt_{lean} in function of the flow rate of the exhaust gases e.g. by setting the value of the delay time period to a large value for a large value of the flow rate of the exhaust gases. This happens because normally for large exhaust flow rates the inversion time period becomes shorter causing inaccuracies to the determination of the deterioration of the catalytic converter. So by adjusting the delay time period the inversion time period is also adjusted to make the determination of the catalytic converter deterioration independent from the exhaust gas flow rate
7) comparing between the value of the detected inversion period T_{rich} or T_{lean} and a predetermined value, and determining that the catalytic converter is deteriorated, when the detected value of the inversion period is shorter than the predetermined value.

The method of **US5386695 (1995)** comprises the following steps:
1) calculating an air/fuel ratio correction amount, based on an output from the upstream air/fuel ratio sensor
2) correcting the air/fuel ratio correction amount, based on the output from the downstream air/fuel ratio sensor
3) measuring an inversion period with which the output from the downstream air/fuel ratio sensor is inverted from a rich to a lean state and vice versa
4) detecting deterioration of the catalytic converter, based on the measured inversion period
5) inhibiting deterioration-detecting operation of the catalytic converter when the air/fuel ratio correction amount falls outside a predetermined range
6) permitting the deterioration-detecting operation of the catalytic converter after a predetermined time period elapses from a time the air/fuel ratio correction amount returns into said predetermined range

The method may also comprise a limitation of the air/fuel ratio correction amount within a first predetermined range when the air/fuel ratio correction amount falls outside the first predetermined range, and inhibiting the deterioration detecting operation of the catalytic converter when the air/fuel ratio correction amount falls outside a second predetermined range included within the first predetermined range.

In **US5396766 (1995)** a method is described to detect abnormalities of an internal combustion engine based on the detection of a deterioration of the catalytic converter. The method comprises the following steps:
1) feedback controlling the air/fuel supplied to said engine, in response to the output from the downstream oxygen concentration sensor
2) detecting a repetition period of inversion of the output from the upstream oxygen sensor
3) detecting a degree of deterioration of the catalytic converter, based on: I) detecting a response time lag of the output of the downstream oxygen sensor (a time interval from the moment a predetermined control term is generated during the air/fuel ratio feedback control to the moment the output from the downstream oxygen sensor is correspondingly inverted) or II) detecting a repetition period of inversion of the output of the downstream sensor

4) setting a reference value for determining an abnormality in the engine, based on the degree of deterioration of the catalytic converter e.g. by setting this reference value to a value capable of detecting a lower degree of the abnormality in the engine as the detected degree of deterioration of the catalytic converter is higher
5) comparing between the reference value and a value based on the repetition period of the output of the upstream oxygen concentration sensor detected in step 2.
6) determining the abnormality in the engine, based on a result of said comparison

The method of **US5416710 (1995)** comprises the following steps:
1) obtaining a first signal and a second signal based on respective signal outputs from the upstream and downstream air/fuel ratio sensors when the fuel supply to the engine is increased (high load)
2) obtaining a third signal and a fourth signal based on respective signal outputs from the upstream and downstream air/fuel ratio sensors when the fuel supply to the engine is interrupted (fuel cut)
3) calculating
   a) a first area defined between the waveform of the signal outputted from the upstream air/fuel ratio sensor and the first and third signals with
   b) a second area defined between the waveform of the signal outputted from the downstream air/fuel ratio sensor and the second and fourth signals
4) correcting at least one of the first and second areas by a ratio calculated between a difference between the first and third signals and a difference between the second and fourth signals while the engine is steadily cruising
5) comparing
   a) a difference between the first area and the second area with a predetermined reference value or
   b) a ratio between the first area and the second area with a predetermined reference value
6) determining deterioration of the three-way catalyst when said difference or said ratio of areas are smaller than said predetermined reference values

The explanation of the method is similar to the one of fig. 63.

The method of **US5437154 (1995)** is similar to the one of **US5396766 (1995)** described above. The method detects misfiring (abnormality) of an internal combustion engine based on the detection of a deterioration of the catalytic converter. All steps of **US5395766 (1995)** are also applied in this method so they are not repeated here

In **JP8144744 (1996)** the judgment of deterioration of the catalytic converter is based on the output signal of the downstream oxygen sensor only. A time between a time point at which this output signal is inverted from a lean (rich) side to a rich (lean) side in a prescribed reference voltage and a time point at which this output signal is inverted in a reverse direction, is detected (inversion cycles). The deterioration judgment of the catalytic converter is based on these inversion cycles.

The method described in **JP8144745 (1996)** is based on the phase difference of the output signals of the upstream and downstream sensor during a forced oscillation of the engine air/fuel ratio.

The method of **JP8296482 (1996)** prevents a deterioration misjudgment of a catalytic converter due to sulfur poisoning of the converter. The sulfur poisoning is determined by the fact that the larger the content of sulfur is, the smaller the maximum output of the downstream oxygen sensor becomes. If poisoning is detected then the air/fuel ratio feedback is stopped and the air/fuel ratio is maintained to a rich side for a predetermined time. The sulfur then is discharged as oxygen sulfide. After the predetermined time has passed the ordinary detection of the efficiency of the catalytic converter starts.

The methods of **JP9041952 (1997)**, **JP9041953 (1997)** and **JP9041954 (1997)** interrupt the deterioration judgment of the catalytic converter when respectively

a) an operation parameter of the engine varies beyond a predefined value
b) the amplitude of the output signal of the downstream oxygen sensor is below a predetermined value
c) the density of oxygen in evaporated fuel discharged from a purge tank to the intake suction system is high.

The method of **US5636514 (1997)** comprises the following steps:

1) detecting concentration of oxygen in the exhaust gases by means of an oxygen sensor installed downstream of the catalytic converter
2) feedback-controlling the engine air/fuel ratio amount based on the output of the downstream oxygen sensor
3) detecting deterioration of the catalytic converter based on a value of a catalytic converter deterioration parameter indicative of a degree of deterioration of the catalytic converter, and an amount of variation in the air/fuel ratio control amount. The catalytic converter deterioration parameter is a time period from execution of the proportional term control to inversion of the output from the downstream oxygen sensor. The amount of variation in the air/fuel ratio control amount is:
    a) a cumulative value of a difference between two adjacent values of the air/fuel ratio control amount measured immediately after proportional term control carried out by the air/fuel ratio control means, or

b) an average value of the cumulative value of the difference between two adjacent values of the air/fuel ratio control amount over a predetermined time period

4) deterioration detection-inhibiting means for inhibiting detection of deterioration of the catalytic converter when the amount in variation of the air/fuel ratio control amount exceeds a predetermined value.

The catalytic converter deterioration detection of step 3 is carried out by making use of an amount obtained by subtracting an amount ascribed to the amount of variation in the air/fuel ratio control amount obtained by dividing the cumulative value of the difference between two adjacent values of the air/fuel ratio control amount over the predetermined time period by an integral term applied in the air/fuel ratio control, from an average value of the catalytic converter deterioration parameter over the predetermined time period.

The patent disclosure **US5678402 (1997)** describes an air/fuel ratio control system for an internal combustion engine and a device that can estimate the temperature of the catalytic converter. The deterioration of the converter as well as the temperature of the converter are used as parameters to set this air/fuel ratio control. The method comprises the following steps:

1) calculating a maximum oxygen storage amount indicative of the maximum amount of oxygen that can be stored in the catalytic converter. This is based on at least one of
   a) the temperature of the catalyst of the catalytic converter , or
   b) a degree of deterioration of the catalytic converter
2) forcibly oscillating an air/fuel ratio of a mixture supplied to the engine at a predetermined frequency and a predetermined amplitude
3) changing at least one of the predetermined frequency and the predetermined amplitude at a predetermined rate of change
4) setting the predetermined rate of change of the predetermined frequency and the predetermined amplitude, in dependence on the maximum oxygen storage amount calculated in step 1.

Engines with multiple cylinder groups

The method of **US5394691 (1995)** is applied to the case of a multiple cylinder bank engine with an air/fuel sensor (1a, 1b) installed in each cylinder bank exhaust pipe upstream of the catalytic converter and an air/fuel sensor (2) installed in the common exhaust pipe section downstream of the catalytic converter (fig. 38). The general detection layout is that of fig. 62. The method comprises the steps:

1) when the engine is in a predetermined operating condition then
    - I) controlling the air/fuel ratio of an air/fuel mixture supplied into the left group of cylinders by the use of a first air/fuel ratio control amount based on outputs from the left upstream oxygen sensor and the downstream oxygen sensor and
    - II) controlling the air/fuel ratio of an air/fuel mixture supplied into the right group of cylinders by the use of a second air/fuel ratio control amount based on outputs from the right upstream oxygen sensor and the downstream oxygen sensor
2) when the engine is in an operating condition other than the predetermined condition of the previous step then
    - I) controlling the air/fuel ratio of an air/fuel mixture supplied into one of said left and right groups of cylinders by using a third air/fuel ratio control amount based solely on an output from the downstream oxygen sensor and
    - II) controlling the air/fuel ratio of an air/fuel mixture supplied into the other of said left and right groups of cylinders by using a predetermined value
3) detecting deterioration of the left or the right catalytic converter, based on an inversion time period of the output from the downstream oxygen sensor obtained during operation as described in step 2.

The method of detecting alternately the deterioration of the left or right bank catalytic converters is similar to the one of **US5381657 (1995)** described above.

Chapter 1.7

Hitachi Ltd.

The methods proposed by Hitachi have been applied, except where otherwise mentioned, for an engine layout similar to that of fig. 67.

Fig. 67 shows a catalytic converter, an upstream oxygen sensor 1 and a downstream oxygen sensor 2 which are mounted upstream and downstream of the catalytic converter, respectively, and a fuel injection control means for feedback controlling the air/fuel ratio based upon the outputs of the oxygen sensors.

The upstream and downstream oxygen sensors which include zirconium, titania, etc. are used as air/fuel ratio sensors. Hydrocarbon sensors may be used as the air/fuel ratio sensors. Some hydrocarbon sensors that may be used measure the absorption factor of infra-red rays. Signals derived from the upstream and downstream oxygen sensors 1 and 2 will be hereinafter represented by characters x and y, respectively.

The fuel injection control means comprises fuel injection quantity calculating means, output means and air/fuel ratio feedback calculating means. The fuel injection quantity calculating means determines the fuel-injection quantity from a value detected by a sensor for detecting the load imposed upon an engine (for example, an intake air/fuel quantity) and a value detected by a sensor for detecting the engine speed.

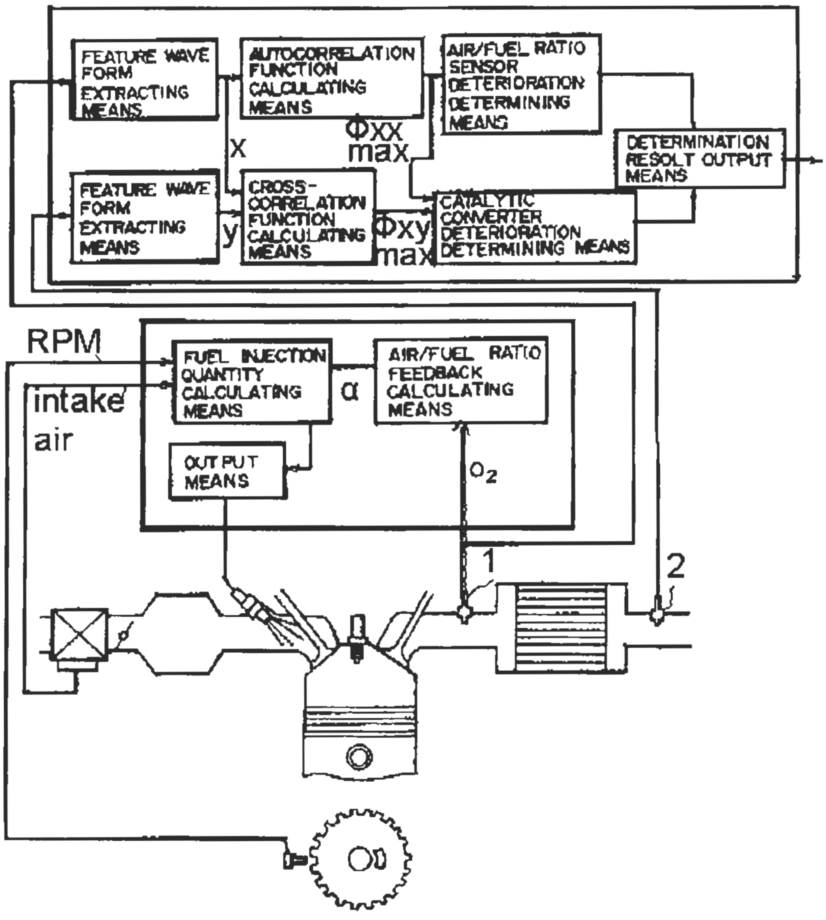


Fig. 67 (from US5341642)

The deterioration diagnosing means is provided for evaluating the similarity in accordance with a correlation function. It mainly comprises a single chip microcomputer having an A/D converter therein, and a high pass filter. The microcomputer is operated in accordance with stored software for achieving functions of the above mentioned means such as auto-correlation function calculating means and the catalytic converter deterioration determining means.

The auto-correlation function of the output signal from the upstream oxygen sensor is calculated by an auto-correlation function calculating means. The cross-correlation function between the output signal x of the upstream oxygen sensor and an output signal y of the downstream oxygen sensor is calculated by the cross-correlation function calculating means.

Determination of whether or not the catalytic converter has deteriorated is carried out by catalytic converter deterioration determining means, which calculates a successive deterioration index and compares the calculated index with a predetermined reference value.

Determination as to whether or not the upstream oxygen sensor deteriorates is made by air/fuel ratio sensor deterioration determining means.

In the method of **DE4209136 (1992)** and **US5237818 (1993)** the catalytic converter conversion efficiency is estimated by comparing a correlation function $\Phi(\tau)$ computed from the output signals of the upstream and downstream sensors with a reference value.

Figs. 68a,d show the variation in time of the output signals of the upstream and downstream sensors respectively, when the air/fuel feedback control of fig. 68c is imposed on the engine. Figs. 68b,e show the corresponding binary code signals (rectangular waves) generated by comparing the output signals of figs. 68a,d to the comparison levels ε_1 and ε_2 respectively. Level ε_1 equals a mean value of the maximum and minimum values of the wave of the upstream air/fuel ratio. The value of the comparison level ε_2 is based on a characteristic of the upstream air/fuel sensor. Symbols y and z (figs. 68b,d) denote an interval in which the correlation function is calculated. The region z containing the space where a rectangular wave is not generated is put equal to a fixed interval of the feedback coefficient of the air/fuel ratio.

The correlation function is then calculated by y and z as follows:

$$\Phi(\tau) = \frac{\int_0^{\tau} \int_{T}^{T} f_1(t)\, f_2\,(t-\tau)\; dt\; d\tau}{2T}$$

where,

f_1, f_2: functions of time, such as the input and output of a communication system,

τ : a time delay parameter

T : is a time interval

The correlation function Φ_j is calculated as

$$\Phi_j = \sum_j y_i \cdot z_{i+j}$$

where,
i : sampling number of y
j : phase difference to i

The complement function of the correlation function Φ_j is calculated according to the following equation:

$$\Phi_j = \sum_j \bar{y}_i \cdot \bar{z}_{i+j}$$

where $\bar{y}$ and $\bar{z}$ are complementary signals of y and z respectively

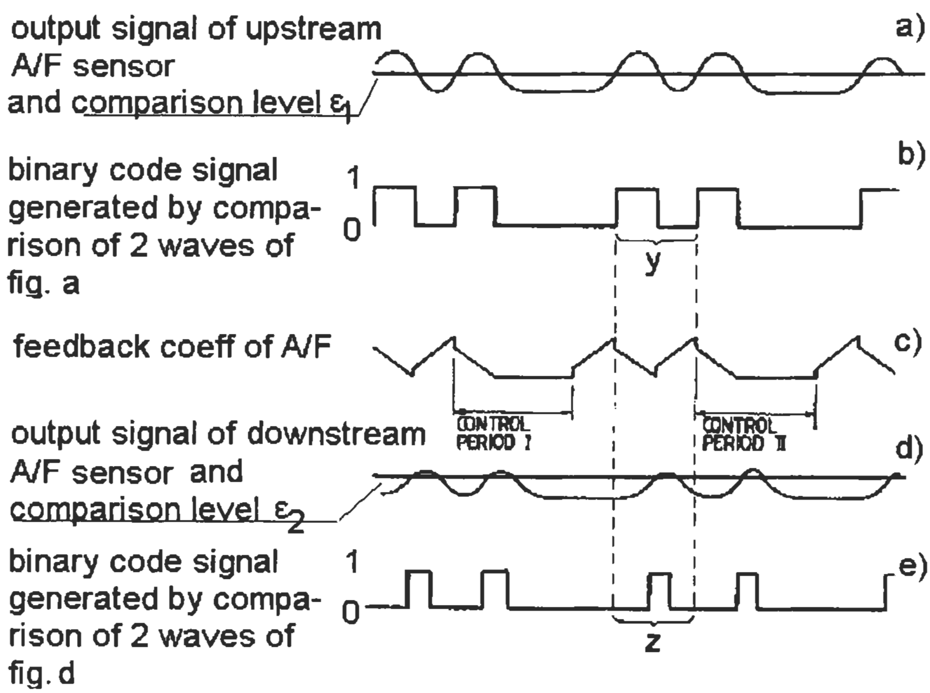


Fig. 68 (from US5237818)

The conversion efficiency CE is calculated by the following equation for compensating an effect of an output ratio between a high level output period and a low level output period of the upstream air/fuel sensor

$$CE \propto \max(\Phi_j) + \max(\overline{\Phi}_j)$$

When the calculated converter efficiency in function of the correlation function falls out of a predetermined region, then the catalytic converter is considered as deteriorated.

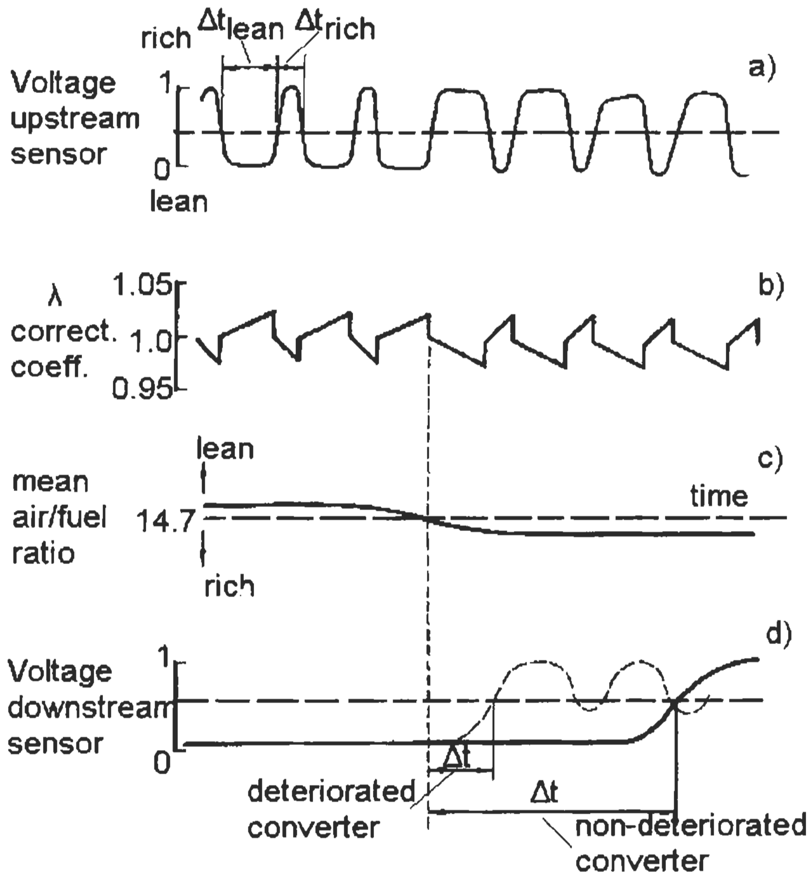


Fig. 69 (from EP0478133)

The method of **EP0478133 (1992)** comprises the following steps:

1) controlling the air/fuel ratio of the air/fuel mixture supplied to each cylinder of the engine to the stoichiometric value ($\lambda=1$)
2) changing the air/fuel ratio supplied to the engine from one predetermined rich value to another predetermined lean value around the stoichiometric one by means of a λ correction coefficient (fig. 69b) in such a way that the mean value is leaner than the stoichiometric one (fig. 69c, left side), then
3) changing the air/fuel ratio supplied to the engine from one predetermined rich value to another predetermined lean value around the stoichiometric one by means of a λ correction coefficient (fig. 69b) in such a way that the mean value is richer than the stoichiometric one (fig. 69c, right side)
4) measuring the response time Δt of the downstream sensor from the moment the mean value of the air/fuel ratio supplied to the engine turns from lean to rich till the moment the signal of the downstream sensor passes from lean to rich respectively (fig. 69d)
5) deciding that the catalytic converter is deteriorated if the response time Δt is lower than a predetermined threshold

In the method of **DE4238807 (1993)** a cross-correlation function of the output signals of the upstream and downstream sensors is calculated in a way similar to the method of **US5237818 (1993)** described above. The correlation coefficient calculated from the two signals is averaged and from this coefficient an averaged conversion efficiency of the catalytic converter is estimated. This value of the conversion efficiency is compared to a predetermined region of values. If the conversion efficiency falls out of this region then the catalytic converter is considered as deteriorated.

The method of **DE4243339 (1993)** and **US5341642 (1994)** comprises the following steps:

1) calculating an auto-correlation function Φ_{xx} of the output signal x from the upstream sensor to output the maximum values of the auto-correlation function at predetermined intervals, each maximum value being in each of the predetermined intervals. Φ_{xx} is calculated as:

$$\Phi_{xx}(\tau)=\int x(t)x(t-\tau)dt$$

where the maximum value is determined by changing the phase τ in an integration region

2) calculating a cross-correlation function Φ_{xy} between the output signal y from the upstream and downstream air/fuel sensors to output the maximum values of the mutual correlation function at predetermined intervals, each maximum value being in each of the predetermined intervals. Φ_{xy} is calculated as:

$$\Phi_{xy}(\tau)=\int x(t)y(t-\tau)dt$$

where the maximum value is determined by changing the phase τ in an integration region

3) calculating the ratios between the maximum values of the cross-correlation function Φ_{xy} and auto-correlation function Φ_{xx} (successive deterioration index Φi)

$$\Phi_i = \frac{\max \Phi_{xy}}{\max \Phi_{xx}}$$

4) determining the deterioration condition of the catalytic converter by comparing the ratio with a predetermined value. If the catalytic converter deteriorates, the successive deterioration index Φ_i increases since there is an increase in similarity between the variations of the air/fuel ratio upstream and downstream of the catalytic converter.

The methods of **DE4404449 (1994)** and **US5400592 (1995)** comprise the following steps:

1) sensing at least one operating parameter of the engine and providing at least one output signal indicative thereof
2) detecting when the at least one output signal falls within a predetermined diagnostic area and generating an enabling signal indicative thereof. In particular the engine must be driven at no less than a predetermined speed, and the temperature of the catalytic converter must be at least 500 °C.
3) detecting when the output signal from the downstream air/fuel ratio sensor varies within predetermined limits proximate to a stoichiometric mixture; when the output signal from the downstream air/fuel ratio sensor is not within the predetermined range, determining whether it varies on a rich side or a lean side of the predetermined limits; and generating a fuel ratio adjustment signal which causes said fuel input control system to adjust an amount of fuel input to the engine to shift the output signal from the downstream air/fuel ratio sensor within the predetermined limits
4) calculating a cross correlation function Φ_{xy} of the output signals x, y of the upstream and downstream air/fuel ratio sensors (see method of **US5341642 (1994)** described above)
5) calculating an auto-correlation function Φ_{xx} of the output x of the upstream air/fuel ratio sensor (see method of **US5341642 (1994)** described above)
6) periodically calculating an instantaneous deterioration index Φ_i based on the ratio of a maximum of the cross correlation function and the calculated auto-correlation function

$$\Phi_i = \frac{\max \Phi_{xy}}{\Phi_{xx}}$$

7) periodically calculating a mean value of a predetermined number N of instantaneous deterioration index values having greatest magnitude to define a final deterioration index I
8) comparing the final deterioration index I with a predetermined deterioration reference level, and activating an output indication when the deterioration index is greater than a deterioration reference level

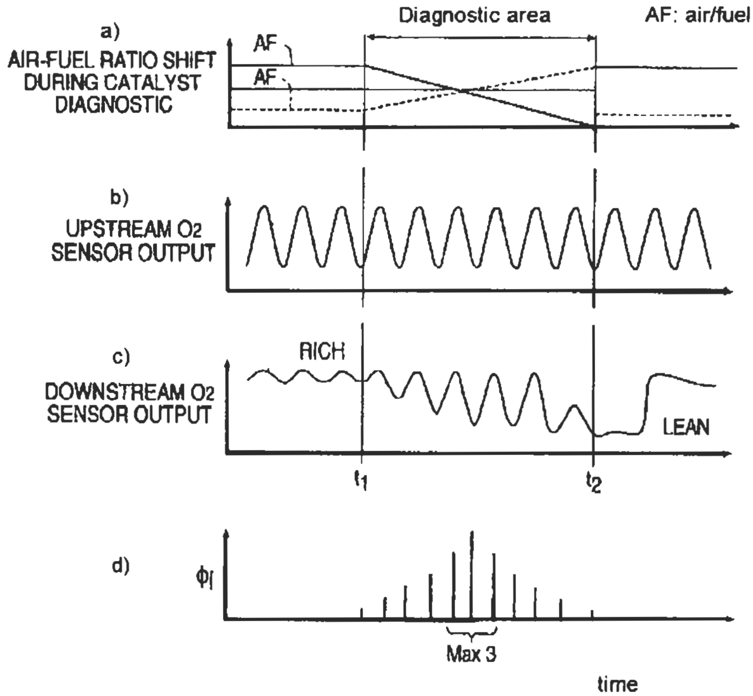


Fig. 70 (from DE4404449)

As shown in fig. 70a, a signal is supplied to the air/fuel ratio feedback calculating means (fig. 67) which causes the output signal of the downstream O_2 sensor to move into proximity with the stoichiometric line by shifting it to the lean side when the air/fuel ratio is on the rich side, and shifting it to the rich side when it is on the lean side in the diagnostic area (from t_1 up to t_2). The correlation function of the output signal of the upstream O_2 sensor shown in fig. 70b with the downstream O_2 sensor shown in fig. 70c can then be calculated accurately.

In a preferred embodiment of the invention, instead of simply taking the mean value of N instantaneous degradation indices as described above, the final deterioration index ***I*** calculation is performed by taking the mean of the M largest values of $\boldsymbol{\Phi}_i$, according to the following formula:

$$I = \frac{1}{M}\sum \max_{M}(\Phi_i)$$

where $\max_M(\Phi_i)$ represents the M largest values of Φ_i within the designated time interval.

This calculation achieves greater diagnostic accuracy than a straight mean value calculation because the maximum deterioration index occurs at a time when the air-fuel ratio, as detected and indicated by the output signal of the downstream O_2 sensor (fig. 70b), varies about the stoichiometric point, as shown in fig. 70d.

In the patent application **DE4412191 (1994)**, a method similar to the one described in **DE4243339 (1993)** is presented in order to assess the performance of a catalytic converter. The main difference between the two methods is that in the current method, the deterioration index Φ_i is corrected for possible abnormalities of the function of the engine. Such abnormalities are provoked by misfiring or malfunctioning of a secondary air supply system. The assessment of the deterioration of the catalytic converter is interrupted in the event of an important abnormality of the function of the engine being logged.

The method of **EP0626507 (1994)** and **US5649420 (1997)** comprises the following steps:
1) estimating the temperature of the catalytic converter in function of an engine physical parameter e.g. the engine intake air mass flow, by means of a map stored in the control unit of the system
2) suspending the decision of judgment on condition that the temperature of the catalytic converter is outside a predetermined range
3) obtaining a value of conversion efficiency of the catalytic converter by means of two oxygen sensors installed upstream and downstream of the catalytic converter
4) correcting the conversion efficiency value to a value in a standard state of the catalytic converter previously set as to the temperature of the catalytic converter estimated in step 1
5) deciding the deterioration state of the catalytic converter by comparing the corrected conversion efficiency value with a threshold value
6) deciding that the catalytic converter is deteriorated when the corrected conversion efficiency value is smaller than the threshold value

The method of **EP0641920 (1995)** diagnoses the degradation of the catalytic converter and the upstream air/fuel sensor with high accuracy. The method comprises the following steps:
1) sampling data of an output signal from the upstream and downstream air/fuel sensors at a rate dependent on engine speed by means of an angular-based data sampler e.g. a sampler sampling data at a constant rotation angle of the crank shaft
2) judging that the conditions of the catalytic converter monitoring zone are satisfied when the rotational speed of the internal combustion engine is higher than or equal to a predetermined rotational speed value, and a catalytic converter temperature estimated from the rotational speed, and intake air flow rate of the internal combustion engine is higher than or equal to a predetermined temperature

3) judging the deterioration of the catalytic converter according to the steps 4 to 8 of the method of **US5400592 (1995)** described above, where the judgment is based on the data sampled by the angular-based sampler in step 1 of the present method
4) sampling an output signal from the upstream air/fuel sensor at every lapse of a predetermined constant time by means of a time-based data sampler e.g. a sampler sampling data at every lapse of a constant time interval
5) judging deterioration of the upstream sensor on the basis of data sampled by the time-based data sampler

The method of **JP7063107 (1995)** uses the output signals of an air quantity sensor, a rotational speed sensor and the oxygen sensors placed upstream and downstream of the catalytic converter to assess the deterioration degrees of an ignition plug, the upstream oxygen sensor and the catalytic converter.

The method of **JP7116469 (1995)** comprises a monolithic catalytic converter with a lot of exhaust gas channels located in the middle of the monolith. Exhaust gas on both upstream and downstream sides of the catalytic converter is introduced to the inside electrode and the outside electrode of an oxygen sensor respectively, which is located close to the exit end face of the monolith (fig. 71). Electromotive force is generated corresponding to the difference in the oxygen concentration of the exhaust gas on the upstream and downstream sides which are in contact with the inside electrode and the outside electrode of the oxygen sensor respectively to be extracted from lead wires as electric output signals. The output signals are compared with predetermined values to diagnose the degree of deterioration of the catalytic converter.

The method of **JP8296428 (1996)** inhibits the deterioration detection of the catalytic converter until the catalytic converter is activated. An initial deterioration index is calculated by means of the output signals of the upstream and downstream oxygen sensors, as described in other methods of this chapter. A final deterioration index is then calculated based on the initial deterioration index and a correction value obtained by a correction value calculating means.

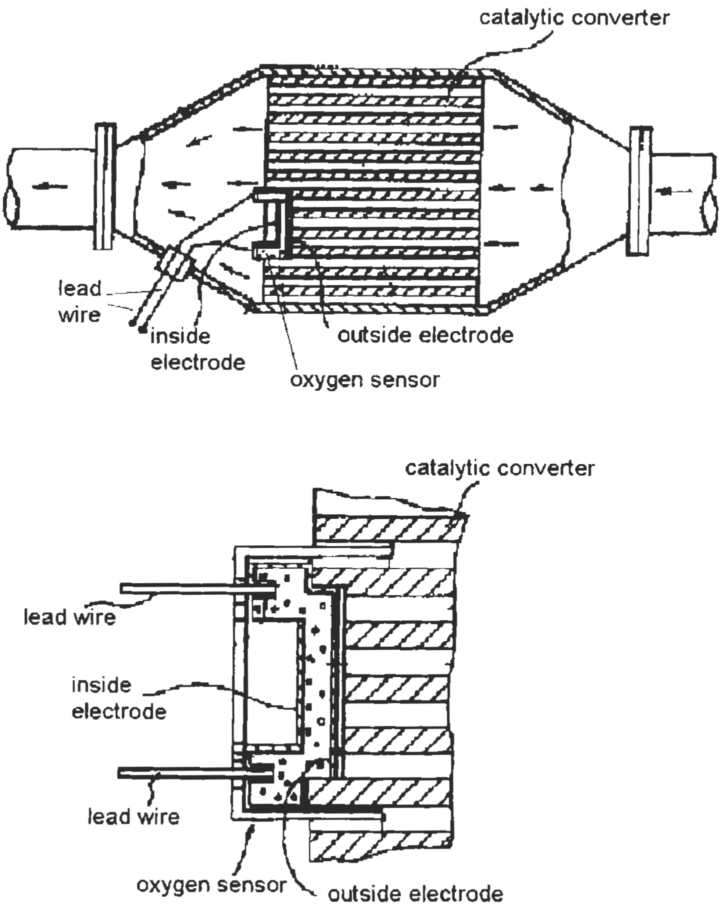


Fig. 71 (from JP7116469)

The method of **EP0719931 (1996)** comprises the following steps:

1) detecting a leak of the gases in the exhaust pipe by means of an exhaust gas oxygen sensor mounted in the exhaust pipe and by means of a specific driving condition of the engine. The leak detection is based on:
    a) a frequency component about a combustion cycle of the output of the exhaust sensor
    b) the output signals of the oxygen sensors mounted upstream and downstream of the catalytic converter

2) when a leak is detected, stopping or correcting
   a) a feedback control of the engine/air fuel ratio based on the oxygen content in the exhaust gases detected by the exhaust gas oxygen sensor, or
   b) the diagnosis of the catalytic converter based on the output signals of the upstream and the downstream sensor

Other methods can be found in **JP6265498 (1994)**, **JP8005602 (1996)**.

Plurality of catalytic converters arranged in series in the exhaust pipe

The method of **EP0727568 (1996)** refers to a catalytic apparatus including a first catalytic converter (upstream converter) and a second catalytic converter (downstream converter), both so arranged in series as to be served as a purification means for combustion exhaust gas (fig. 72).

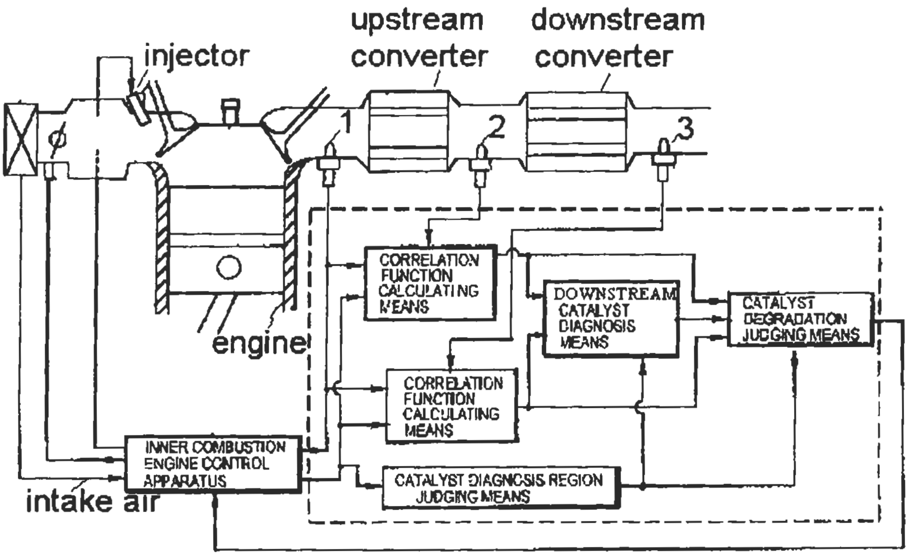


Fig. 72 (from EP0727568)

A first air/fuel ratio sensor 1 is made to be mounted in the midst of the exhaust manifold upstream of the first catalytic converter in order to detect the density of oxygen in the exhaust gas and the amount of fuel injection from the injector is corrected by the detected signal of the first air/fuel ratio sensor 1.

A second air/fuel ratio sensor 2 is installed in the downstream of the upstream catalytic converter, and a third air/fuel ratio sensor 3 is installed downstream of the downstream catalytic converter.

The amount of intake air passing through the air cleaner and the throttle valve, both not shown, and through the throttle sensor for detecting the throttle angle is measured by the air flow sensor. The control apparatus of the internal combustion engine calculates an optimal amount of fuel injection by judging the measured values from the air flow sensor and the engine rotation sensor not shown, and controls the internal combustion engine so that the fuel may be injected by the injector based on the calculated values.

An input signal describing the operation status of the internal combustion engine is supplied to the catalytic diagnosis region judging means. It is then judged whether the operation status of the engine is located in the region adequate for rational judgment of the catalytic converters.

A correlation method for the correlation between the output signals of the air/fuel ratio sensors installed upstream and downstream of the catalytic converters, similar to this of fig. 67, is used for the catalytic diagnosis of the catalytic apparatus.

The method comprises the following steps:

1) performing diagnosis of the upstream converter by using the output signals of the first and second air/fuel sensors
2) performing diagnosis of both catalytic converters (overall converter) by using the output signals from the first and third air/fuel sensors
3) diagnosing the efficiency of the downstream converter based on the diagnosis information of the upstream converter and the overall converter e.g. by referring to a data map which is formed as a two dimensional matrix defined by a couple of axis representing a diagnosis information of the upstream converter and a diagnosis information of the overall converter

The individual diagnosis operation of the upstream and the overall converter is performed at distinctive operation regions adequate for their corresponding diagnostic mode.

Correlation methods of treatment of the output signals of the upstream and downstream sensors, like the ones mentioned in previous methods of this chapter, are used in order to evaluate the efficiency of the upstream and overall catalytic converter.

The method of **DE19620417 (1996)** also diagnoses the degradation of two catalytic converters mounted in series in the exhaust pipe of an internal combustion engine (fig. 72). Only two oxygen sensors are used in this method. The first sensor is installed upstream of the first converter (upstream sensor 1) and the second sensor is installed downstream of the second converter (downstream sensor 3). The method comprises the following steps:

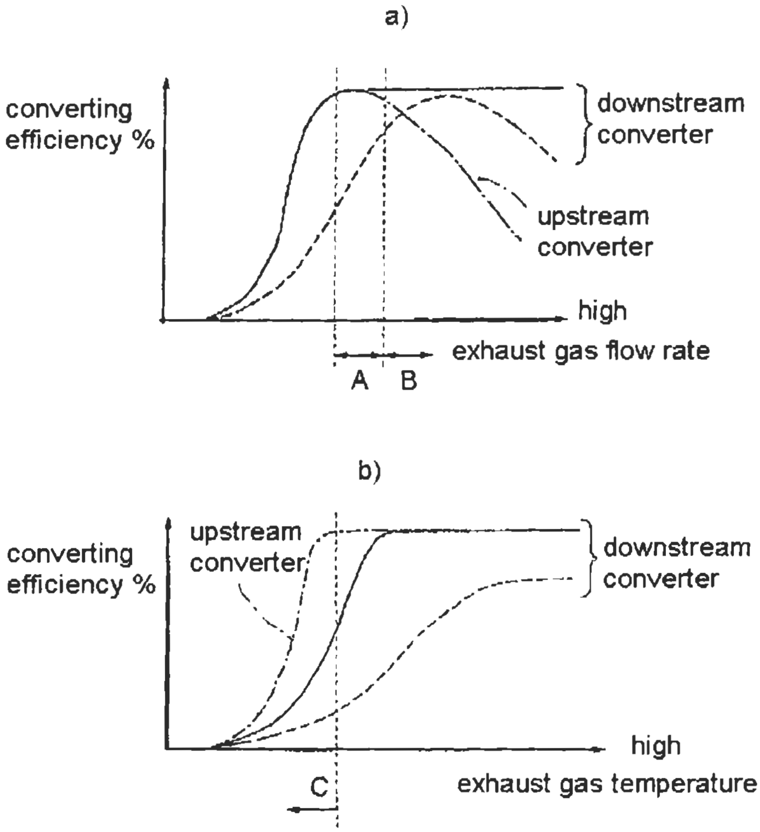


Fig. 73 (from DE19620417)

1) operating the engine in a state that allows the deterioration diagnosis of the catalytic converter
2) diagnosing the degradation of each catalytic body or the catalytic converter as a whole by means of the signals of the upstream and the downstream sensor, in a plurality of different diagnostic regions of a catalytic converter. A different diagnosis operating region of the engine corresponds to each catalytic body or to the converter as a whole. These regions are:
    a) a relatively low load region A of the engine for diagnosing both converters (fig. 73a). In this narrow region A the activation of the two

converters takes place with almost the same speed increase for both of them and the converging capability of the converters is saturated

b) a high load operating region B of an engine loading corresponding to an operating region for diagnosing the downstream converter, which is higher than that of the operating region for diagnosing the upstream converter (fig. 73a). The volume of exhaust gases passing through the upstream converter is so high that its converging capability is exceeded. The exhaust gases cannot be purified in the upstream converter and the influence of this converter in the purification of the gases is very small. Only the deterioration of the downstream converter can be diagnosed in this case

c) an operating region C to diagnose the upstream converter, which corresponds to a region before the activation of the downstream converter (fig. 73b). This region corresponds to a condition just after engine start up where the temperature of the exhaust gases is low and only the upstream converter is activated

3) calculating a correlation function between the output signals of the two oxygen sensors
4) comparing the averaged calculated correlation function with a threshold
5) deciding that the catalytic converters as a whole or each catalytic converter separately are deteriorated, when the correlation function is greater than the threshold

Chapter 1.8

Mazda Motor Corporation

The methods proposed by Mazda Motor Corp. have been applied, except where otherwise mentioned, for an engine layout similar to that of fig. 74, where an engine system provided with a failure detection device for an air/fuel ratio feedback control system in accordance with a preferred embodiment is schematically shown.

The engine intake system includes a plurality of individual intake pipes, independently connected to combustion chambers (not shown) of the engine, and a common intake pipe to which the individual intake pipes are connected all together through a surge tank. The common intake pipe is provided with an air cleaner, an air flow meter, immediately downstream of the air cleaner, and an "idle-switch installed" throttle valve, i.e., a throttle valve provided with an idle switch, disposed upstream of that close to the surge tank. In each of the individual intake pipes, a fuel injector is disposed.

The exhaust system includes a plurality of individual exhaust pipes, independently connected to the combustion chambers of the engine, and a common exhaust pipe to which the individual exhaust pipes are connected all together. The common exhaust pipe is provided with a catalytic converter.

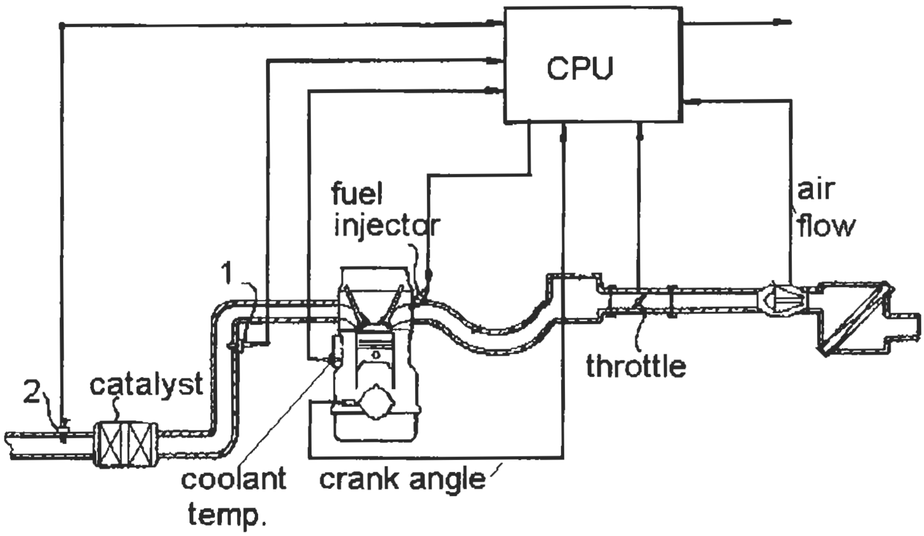


Fig. 74 (from US5414995)

Upstream and downstream of the catalytic converter, respectively, an upstream air/fuel sensor 1 and a downstream air/fuel sensor 2 in the common exhaust pipe are disposed. Each of the air/fuel ratio sensors 1 and 2 includes an oxygen sensor. The engine is provided with an angle sensor, cooperating with a crankshaft, to detect an angular velocity of the crankshaft as an engine speed, and a temperature sensor for detecting the temperature of engine coolant. The downstream air/fuel ratio sensor 2 has a heater. The heater is activated to turn "on" to heat the downstream air/fuel ratio sensor 2 only while failure of the upstream air/fuel ratio sensor 1 is detected.

The fuel injectors are controlled by a control unit including a microcomputer and deliver a correct quantity of fuel depending upon a pulse width. In order to adjust the pulse width, the control unit receives various electric signals, as fuel injection control parameters, from the air-flow meter, the idle-switch installed throttle valve, the crankshaft angle sensor, the coolant temperature sensor, and the upstream and downstream air/fuel ratio sensors 1 and 2.

In the method of **JP5272329 (1993)** the engine operates for a prescribed time in a rich air/fuel condition and then a feedback-control based on the output signal of the upstream sensor is applied to the engine air/fuel ratio to converge it to a stoichiometric one. The degradation of the catalytic converter is then judged according to the output signal of the downstream sensor.

In the method of **JP5312024 (1993)** both temperature and oxygen content of the exhaust gases are measured upstream and downstream of a lean NO_x catalytic converter. The measurement takes place within specified time intervals immediately after starting a lean stationary operation of the engine. Multiple values of exhaust gas temperature and oxygen content differences are calculated upstream and downstream of the converter. In case that the temperature difference of the exhaust gases is lower than a threshold or the oxygen content difference is higher than a specified value, it is judged that the lean NO_x converter is deteriorated.

The methods of **US5337555 (1994)** and **US5414995 (1995)** first judge the deterioration condition of the upstream sensor by forming the ratio of the reversal frequency of the output signal of the upstream sensor (from rich to lean state and the opposite) to the reversal frequency of the output signal of the downstream sensor. The feedback control is based on the output of the upstream sensor in order to maintain a desired engine air/fuel ratio. Further, the feedback control parameter is corrected according to the deterioration of the upstream sensor. It is then concluded that the catalytic converter is deteriorated when the ratio of reversal frequencies is not equal to one during off-idling and when the ratio is smaller than a predetermined threshold frequency ratio during on-idling, while the ratio is equal to one during off-idling. Failure judgment of the upstream sensor is made when the feedback control parameter is below a predetermined threshold value, which may be changed according to levels of degradation of the catalytic converter.

The method of **US5337558 (1994)** first checks whether or not the engine runs with a feedback control, whether or not the vehicle speed is within certain limits and whether or not a change of rate of the vehicle speed is less than a predetermined rate. If all conditions are satisfied, then the catalytic converter deterioration detection starts by counting the frequency of the signal outputs of the upstream and downstream oxygen sensors. The output ratio of the reversal frequency of the output signal of the upstream sensor (from lean air/fuel ratio to rich air/fuel ratio and vice-versa) to the reversal frequency of the output signal of the downstream sensor is calculated and it is compared to a predetermined value. If this ratio is lower than the predetermined value, then the catalytic converter is considered as deteriorated.

The method takes into account possible deterioration of the oxygen sensors. Practically as output ratio is used a frequency ratio of reversal of an output from the downstream oxygen sensor with respect to a threshold value to an output from the upstream oxygen sensor with respect to a threshold value. If at least one of the sensors has been deteriorated, the threshold value of the deteriorated oxygen sensor is varied so as to correctly change the frequency ratio of reversal, thereby avoiding an erroneous deterioration detection of the catalytic converter due to deterioration of the oxygen sensor.

In the method of the patent disclosure **JP7259540 (1995)** the engine air/fuel ratio is feedback-controlled based on the signal of the upstream sensor in order to achieve a target air/fuel ratio. The deterioration of the catalytic converter is assessed from the relation of the output signals of the upstream and downstream oxygen sensors. During the time of deterioration detection, an air/fuel ratio constant is altered in some extent, to prevent the occurrence of any mistakes of the detection of the catalytic converter degradation due to variations of the wave form of the upstream sensor.

Other methods presented by Mazda Motor Corp. should be found in **JP4303754 (1992)**, **JP6280547 (1994)**, **JP6280661 (1994)**, **JP6280662 (1994)** and **JP6346723 (1994)**.

Engines with multiple cylinder groups

In **US5228287 (1993)** a method to monitor a catalytic converter is presented for an engine with two cylinder banks as the one of **US5357753 (1994)** (see chapter 1.3). The arrangement of the sensors is similar to the one of fig. 38 except for the fact that the sensor placed between the junction of the two exhaust gas branches and the catalytic converter is removed.
The method consists of the following steps:

1) detecting an air/fuel ratio based on an emission level of exhaust gas by means of the oxygen sensors disposed in each individual exhaust passage upstream of the catalytic converter and upstream of the common junction point of the individual exhaust gas passages
2) detecting an oxygen level of exhaust gas passed through the catalytic converter by means of the downstream oxygen sensor
3) feedback-controlling air/fuel ratios for the cylinder groups independently based on emission levels detected by the upstream oxygen sensors
4) detecting vehicle driving conditions
5) monitoring a difference between phases in change of air/fuel ratios for both said groups of said cylinders based on an emission level of exhaust gas detected by said upstream oxygen sensors only when detecting a specific vehicle driving condition
6) feedback-controlling an air/fuel ratio for the cylinder groups all together based on either one of the upstream oxygen sensors during detection of the deterioration of the catalytic converter
7) detecting deterioration of the catalytic converter based on a reversal frequency of the signal provided from the downstream oxygen sensor and a reversal frequency of a signal representative of an emission level detected by one of the upstream oxygen sensors, only when detecting no difference between said phases
8) determining a critical deterioration of said catalytic converter based on a ratio between the reversal frequencies of the signals of the downstream and upstream sensor

The method of **US5233829 (1993)** refers to a V-type internal combustion engine (fig. 75).
The intake system of the V-engine is endowed with a common upstream intake pipe connected to the surge tank. The common upstream intake pipe is provided with an air flow sensor for detecting an air flow rate and a throttle valve for regulating the amount of intake air and hence the engine output.
Each branch intake pipe is provided with a fuel injection valve located at a downstream portion thereof. The exhaust system of engine is endowed with a pair of upstream exhaust manifold pipes, which extend from the exhaust ports, respectively, and a common downstream exhaust pipe, into which the upstream exhaust pipes converge.

The common downstream exhaust pipe is provided with a main catalytic converter for purifying exhaust gas. Each upstream exhaust pipe is provided with a secondary catalytic converter (or pre-catalyst or light-off catalytic converter). Each of the secondary catalytic converters is smaller in capacity than the main catalytic converter in order to be activated very fast after start up of the engine.

Upstream from the secondary catalytic converters, first exhaust sensors are disposed. Downstream from the secondary catalytic converters, second exhaust sensors are provided. Downstream from the main catalytic converter, a third exhaust sensor is provided. These exhaust sensors detect the emission level of residual oxygen in exhaust gases.

Air/fuel ratio feedback control is performed by a electric control unit (ECU) incorporated in the engine. The electric control unit also determines functional deterioration of the catalytic converters. It receives various signals, such as an air flow rate signal from the air flow sensor representative of an air flow rate, a throttle opening signal from the throttle opening sensor representative a throttle opening of the throttle valve, a vehicle speed signal from a speed sensor representative of a vehicle speed, an engine speed signal from an engine speed sensor representative of an engine speed in rpm, a temperature signal from a temperature sensor representative of the temperature of engine coolant, and emission level signals from all exhaust sensors representative, respectively, of emission levels of residual oxygen in exhaust gas. The air/fuel ratio control and the deterioration detection or determination are executed based on these signals.
In addition, the electronic control unit controls a warning lamp to signal critical deterioration of the secondary catalytic converters, as well as critical deterioration of the main catalytic converter.

Air/fuel ratio control is accomplished as the electronic control unit reads each signal. The electronic control unit calculates the amount of air to be supplied into the combustion chamber for each cycle based on an air flow rate signal and an engine speed signal. Subsequently, the electronic control unit calculates, based on the calculated amount of air, a basic fuel injection rate at which the fuel injection valve injects fuel into the combustion chamber. Thereafter, the electronic control unit decides whether or not the engine is put in engine operating conditions for the air/fuel ratio feedback control. That is, the air/fuel feedback condition is fulfilled when the engine operates in a specific engine operating range defined by throttle opening, which represents engine load, and engine speed, and in a specific range of cooling water temperatures higher than a predetermined temperature. If in fact the engine operates in both the specific ranges, the electronic control unit controls the fuel injection valves so that the optimal air/fuel ratio is achieved for each row of the cylinders of the left and right cylinder banks.

Air/fuel feedback control is executed e.g. for the left cylinder bank in such a manner that the electronic control unit sets a feedback correction value for an increase in fuel injection rate when an emission level signal from the first exhaust sensor indicates a leaner air/fuel ratio. The electronic control unit also sets the feedback correction value for a decrease in fuel injection rate when an emission level signal from the first exhaust sensor indicates a richer air/fuel ratio. An actual fuel injection rate is determined after a correction of the basic fuel injection rate by the feedback correction value and the temperature of cooling water. The electronic control unit provides an injection signal corresponding to the actual fuel injection rate to the fuel injection valves for the row of the cylinders in the left cylinder bank.

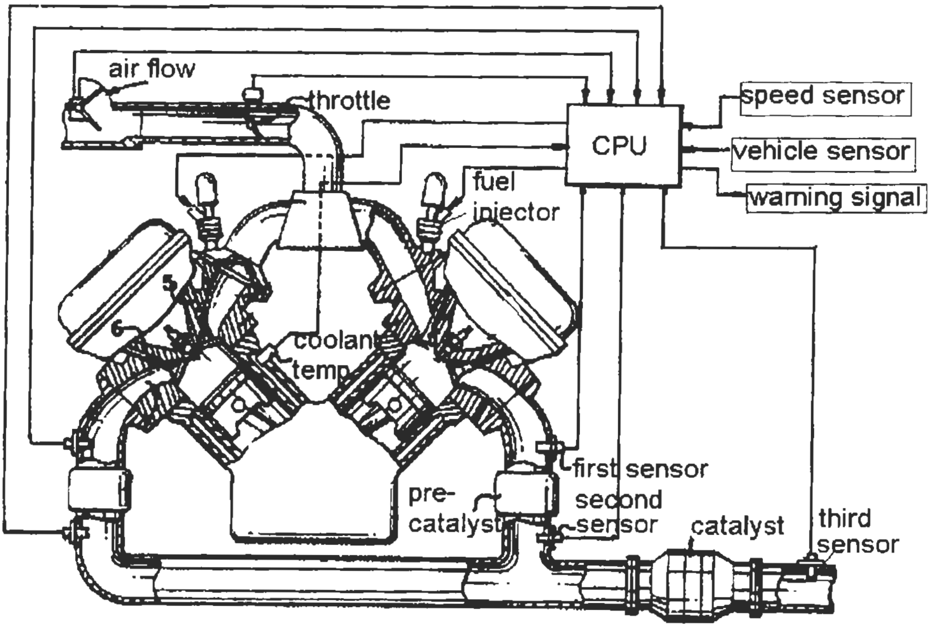


Fig. 75 (from US5233829)

The method comprises the following steps:

1) detecting an emission level of exhaust gas upstream of each secondary catalytic converter by means of the first exhaust sensors installed upstream of the secondary catalytic converters.
2) detecting an emission level of exhaust gas downstream of each secondary catalytic converter by means of the second sensors installed downstream of the secondary catalytic converters.
3) detecting an emission level of exhaust gas downstream of the main catalytic converter by means of the third sensor installed downstream of the main catalytic converter.
4) feedback controlling air/fuel ratios for said two groups of cylinders independently based on emission levels detected by each first air/fuel sensor
5) detecting vehicle operating conditions (specific throttle opening and specific engine speed)
6) feedback-controlling an air/fuel ratio for said two groups of cylinders based on an emission level detected by the second emission sensor only when detecting a specific vehicle operating condition

7) detecting deterioration of the main catalytic converter based on a first ratio of reversal frequencies of signals representative of emission levels provided from the second and third air/fuel sensors
8) determining a critical deterioration of the secondary catalytic converter when this first ratio is higher than a predetermined value
9) further detecting deterioration of the secondary catalytic converters based on a second ratio of reversal frequencies of signals representative of emission levels provided from the first and second air/fuel sensors
10) determining a critical deterioration of said secondary catalytic converter when this second ratio is higher than another predetermined value.

The patent disclosure **JP5321642 (1993)** presents a similar method to this of **US5233829 (1993)** presented above.

Chapter 1.9

Siemens Automotive SA - Siemens AG

The method of **WO9309335 (1993)** and **US5487269 (1996)** is applied for the layout of fig. 76 and is explained with the help of fig. 77.

Fig. 76 shows an internal combustion engine equipped with an air filter, an air inlet duct and a throttle valve for regulating the inlet air flow rate, downstream of which there is an inlet pressure sensor which supplies a signal to a computer (CPU). A sensor for the speed of the engine, fixed facing a flywheel of this engine, supplied a second signal to the computer. The latter receives a third signal supplied by an oxygen probe 1 placed in the pipe of the exhaust gases of the engine, upstream of a three-way catalytic converter.
The computer comprises electronic signal processing, calculation and memory means necessary for controlling the opening time t_i, or injection time, of one or more fuel injectors. The assembly constitutes a closed-loop regulation (feedback) device for this injection time, the loop being closed by the third signal supplied by the oxygen probe 1.

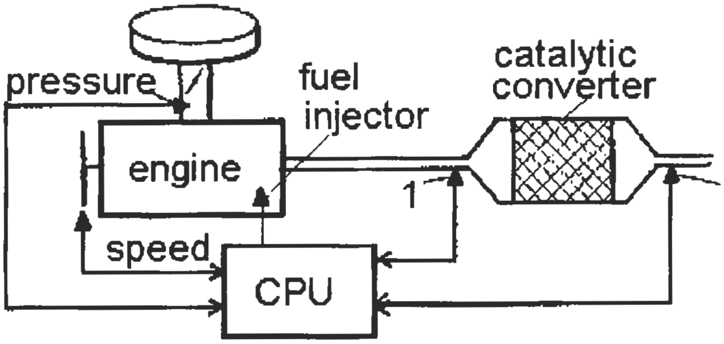


Fig. 76 (from WO9309335)

A second oxygen probe 2 is placed downstream of the catalytic converter. This probe is of the conventional type supplying a signal which switches between two levels when the oxygen content of the exhaust gases passes through a predetermined threshold. When such a probe is placed upstream of the catalytic converter, the threshold corresponds to a composition of exhaust gases resulting from the combustion of a strictly stoichiometric air/fuel mixture. The signal supplied by the probe 2 is used by the computer for the purposes of the present inventions. To this end, the computer is loaded with specific software suitable for executing the various stages of the methods according to the inventions.

According to the method, in a closed loop control and at a stabilized speed, the mean injection time t_{im} (time t_i of opening of fuel injector) is measured (fig. 77b). During a first interval Δt_1, an open loop control takes place with a forced variation of the fuel injection time t_i about t_{im} of deviation corresponding to the limits $\dot{Q}_{min}$ and $\dot{Q}_{max}$ of the oxygen storage capacity of the catalytic converter in a non-deteriorated state. If this deviation is off-centered so that only the lower limit $\dot{Q}_{min}$ (fig. 77e) of the quantity of oxygen that can be stored is attained, the output signal V_{O2} of the downstream oxygen sensor (fig. 77f) is blocked during the time interval Δt_1 at its high level (some oxygen remains in the exhaust gases at the outlet of the catalytic converter). During a following interval Δt_2, the injection time t_{ib2} is modified in a direction, which tends to unblock the signal. Two different conditions can be distinguished:

a) The output signal of the downstream sensor starts oscillating (fig. 77f). The two limits $\dot{Q}_{min}$ and $\dot{Q}_{max}$ are exceeded and the variation ($\dot{Q}_{max}$ - $\dot{Q}_{min}$), namely the current capacity of the catalytic converter is too low and the catalytic converter is deteriorated (fig. 77e)
b) The two limits $\dot{Q}_{min}$ and $\dot{Q}_{max}$ are not attained and the output signal V_{O2} of the downstream oxygen sensor remains blocked at the starting

level. The catalytic converter is capable of absorbing the minimum of the quantity of oxygen stored defining a non-deteriorated catalytic converter provided that in a subsequent validating time interval Δt_3, the output signal V_{O2} of the downstream sensor switches clearly from one level to the other following a new offset still in the same direction. The value t_{ib3} of the base injection time is taken now as center of the forced deviation of the opening time t_i (fig. 77b).

The amplitude of this deviation remains the same throughout all time intervals Δt.

Concluding, during progressive and monotonically modified evolution of the base injection time used during successive time intervals Δt_1, Δt_2,..,Δt_n, a catalytic converter is considered as non-deteriorated when the output signal of the downstream sensor switches clearly from one level to another, whereas a catalytic converter is considered as deteriorated when at an intermediate time interval e.g. Δt_2 the output signal of the downstream sensor oscillates.

A procedure is also presented for indirectly detecting the limits $\dot{Q}_{min}$ and $\dot{Q}_{max}$ and for calculating the base injection time to be used in this method.

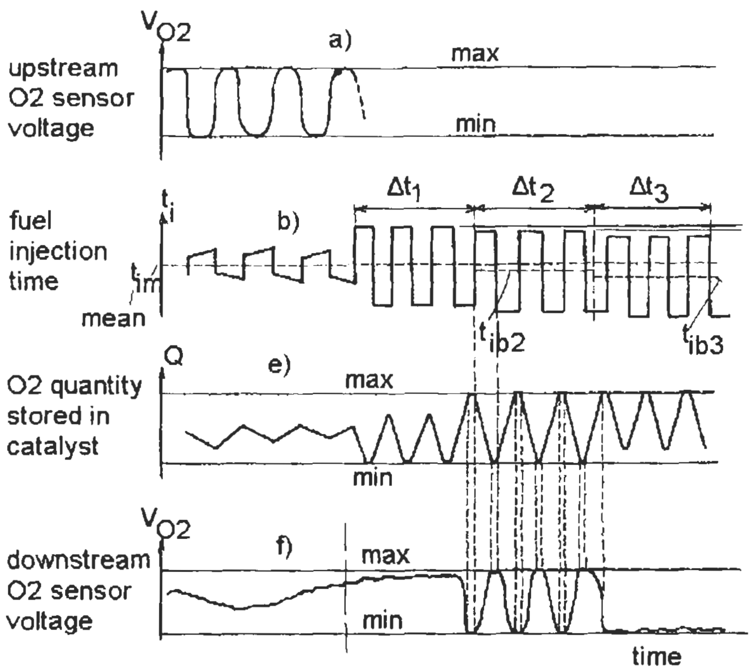


Fig. 77 (from WO9309335)

The method of **EP0626506 (1994)** is applied during a specific time interval and comprises the following steps:

1) determining the number of times n_R during which both the output signals of the upstream and downstream sensors indicate a rich air/fuel ratio
2) determining the number of times n_L during which both the output signals of the upstream and downstream sensors indicate a lean air/fuel ratio
3) determining from both n_R and n_L the minimum value $n_{min} = \min(n_L, n_R)$
4) comparing n_{min} to a predetermined limit value ε
5) judging that the catalytic converter is deteriorated when $n_{min} > \varepsilon$

The method of **WO9420737 (1994)** presents the case of monitoring during start-up the efficiency of an electrically heated catalytic converter (EHC) placed upstream of a normal three-way catalytic converter (fig. 78).

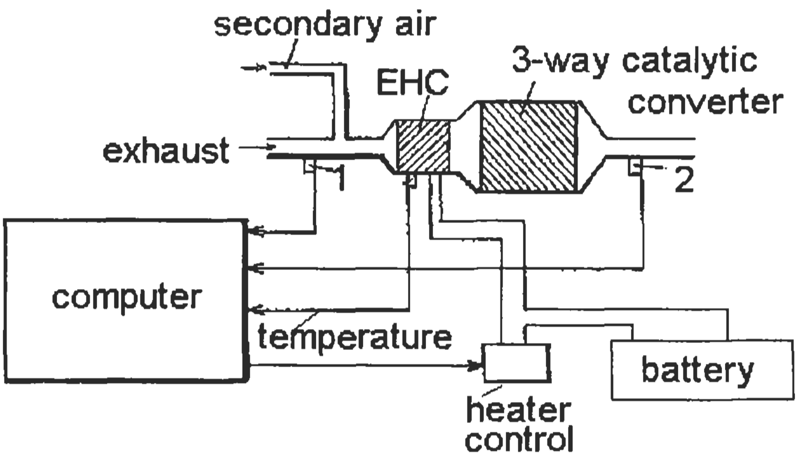


Fig. 78 (from WO9420737)

The upstream oxygen sensor is placed upstream of the EHC, whereas the downstream sensor is placed downstream of the three-way catalytic converter. The method works as follows:

1) controlling the air/fuel ratio of the engine by means of an open loop feedback control during a cold start-up of the engine (rich air/fuel ratio)
2) heating the EHC by means of a heater during the cold start-up of the engine
3) measuring the temperature of the EHC
4) controlling the engine with a closed-loop feedback control when the temperature of the EHC passes a certain limit e.g. 350-400 degrees C (fig. 79a)
5) checking the condition of the three-way catalytic converter by using the method of **WO9309335 (1993)** described above, and if the condition of the catalytic converter is good then
6) measuring the output signal of the upstream sensor (fig. 79b)
7) measuring the output signal of the downstream sensor (figs. 79c,d)
8) judging whether the EHC is deteriorated (fig. 79d) or not (fig. 79c) depending on the oscillations present on the signal of the downstream sensor. Significant oscillations of the signal means that the EHC is in a deteriorated state, taking into account that the three-way catalytic converter has been already checked to be in good condition.

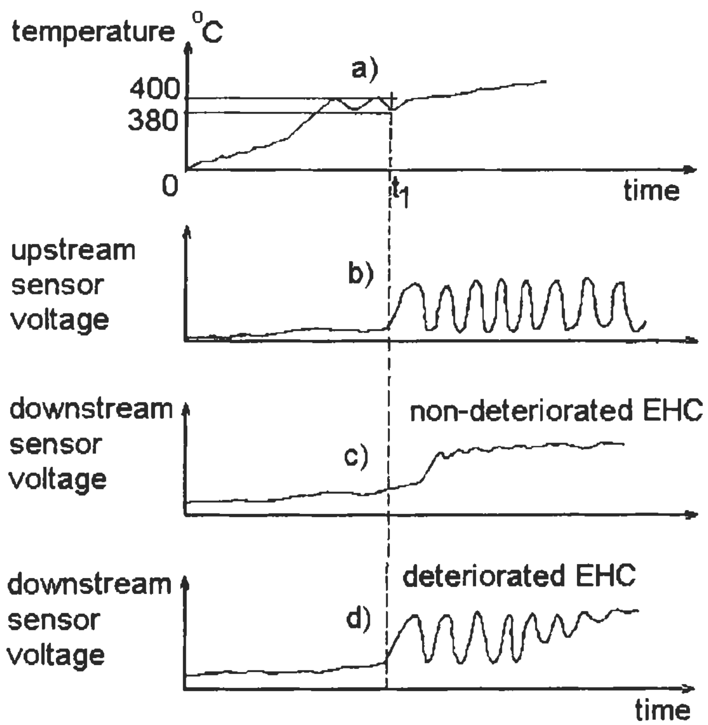


Fig. 79 (from WO9420737)

In **EP0634567 (1995)** two oxygen sensor probes with different response times are used for the determination of the deterioration state of the catalytic converter. The response times of the probes may be altered by varying the material of the probes, or by using a catalytic active mantle which surrounds the probe, or by using different protective sleeves or by changing the thickness of the sensor elements.
During feedback control the output signals of the two probes oscillate. By comparing the oscillations of the two signals useful conclusions about the deterioration state of the catalytic converter may be drawn when compared to predetermined values. The method allows the evaluation of the efficiency of the catalytic converter over a wider efficiency range than other methods.

In the method of **DE19506012 (1996)**, the second (downstream) λ probe is installed inside the catalytic converter at a position close to the inlet of the converter. The volume of the converter between the inlet of the converter and the second λ probe is greater than the volume of the converter which is necessary for the conversion of the pollutants when the internal combustion engine is in a stationary mode. In a second embodiment, the downstream λ probe is installed between two monoliths which form the catalytic converter. The method of **EP0634567 (1995)** is used for the evaluation of the condition of the converter.

In the method of **GB2307557 (1997)** an exhaust sensor with a substrate with two sensor elements for measuring the oxygen partial pressure is installed in or downstream of the catalytic converter. The exhaust gas in the region of the first sensor element is activated by a catalytic layer to produce a chemical reaction. The exhaust gas environment of the first sensor element is separated from the exhaust gas environment of the second sensor element in such a way that the exhaust gas environment of the second sensor element is not catalytically activated. The voltage obtained between the first and second sensor elements is used for monitoring the conversion capability of the catalytic converter.

The method of **DE19540673 (1997)** uses a downstream oxygen sensor which has a layer of metal-oxide with slightly catalytic or non-catalytic properties. The electric resistance of the sensor layer is measured for a value of the air/fuel ratio parameter λ that is lower than one and for a value of the air/fuel ratio parameter λ that is higher than one. When the difference of these resistance values is greater than a reference value, then the converter is considered to be deteriorated.
The oxygen sensor can be installed downstream of the converter or inside the converter.
The metal-oxide used as a sensor layer is Strontium Titanate ($SrTiO_3$) or Cerium-oxide (CeO_2) or Gallium-oxide (Ga_2O_3) or Titanium-oxide (TiO_2).

Chapter 1.10

NGK Spark Plug Co.

In the method of **US4884066 (1989)** the air/fuel ratio oscillates around the stoichiometric value from lean to rich and vice versa. If the amplitude of the oscillation of the output signal of the downstream sensor is bigger than a predetermined value the catalytic converter is considered as deteriorated. The sensor used downstream of the catalytic converter is constructed so that its output and the air/fuel ratio are in direct proportional relationship.

In the method of **US5157921 (1992)** the engine air/fuel ratio forcibly oscillates and a ratio of the amplitudes of the oscillating output signals of the upstream and downstream sensors is formed. The ratio can have one of the following forms:

$$R_1 = \frac{a_1 - b_1}{a_1} \times 100$$

where
a_1, b_1: output amplitudes of upstream and downstream sensors respectively (fig. 80), or

$$R_2 = \frac{a_2 - b_2}{a_2} \times 100$$

where
a_2, b_2: output amplitudes of lean mixtures of upstream and downstream sensors respectively (fig. 80), or

$$R_3 = \frac{a_3 - b_3}{a_3} \times 100$$

where
a_3, b_3: output amplitudes of rich mixtures of upstream and downstream sensors respectively (fig. 80).

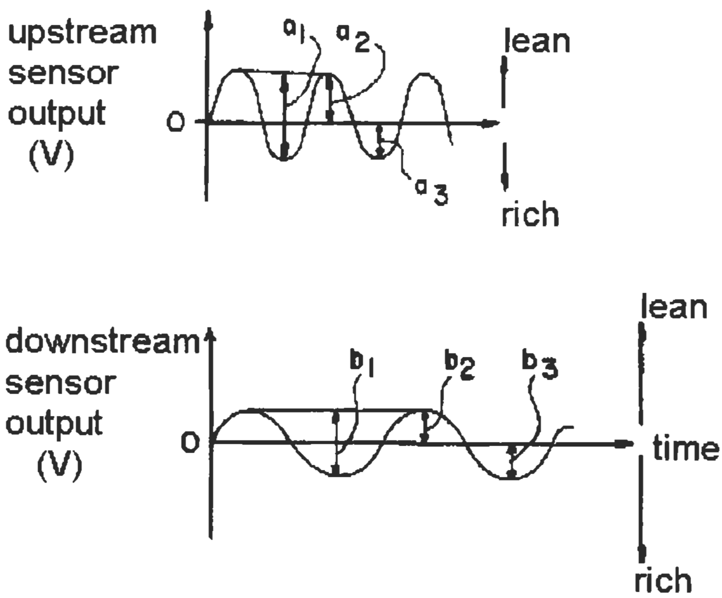


Fig. 80 (from US5157921)

R_1 is compared with a predetermined mean converted rate of HC, CO and NO_x to determine a mean converted rate of the catalytic converter for HC, CO and NO_x in the exhaust gases.
R_2 is compared with a predetermined mean converted rate of NO_x to determine a mean converted rate of the catalytic converter for NO_x in the exhaust gases.
R_3 is compared with a predetermined mean converted rate of HC and CO to determine a mean converted rate of the catalytic converter for HC and CO in the exhaust gases.

The method of **US5357750 (1994)** allows a determination to be made of the conversion rate of particular component gases, NO_x, CO and HC, of the exhaust gas converted by the catalytic converter and includes the steps of:

1) producing a nearly linear diagram graphically relating the output of an air/fuel ratio detector located downstream of the catalytic converter with a predetermined mean converted rate of HC, CO and NO_x
2) determining whether exhaust gas input to the catalytic converter is rich or lean in air/fuel ratio, based on the output of an oxygen sensor located upstream of the catalytic converter
3) measuring the output amplitude of an air/fuel ratio detector located downstream of the catalytic converter
4) using the diagram obtained in step 1, matching the amplitude obtained in step 3 with the diagram obtained in step 1 and finding a corresponding converted rate from the diagram based on the matching
5) determining that the converted rate obtained in step 4 is the converted rate of the NO_x component gas of the exhaust gas when the oxygen sensor located upstream of the catalytic converter determines that the exhaust gas is lean
6) determining that the converted rate obtained in step 4 is the converted rate of either the HC or CO component gases of the exhaust gas when the oxygen sensor located upstream of the catalytic converter determines that the exhaust gas is rich.

Other methods proposed by NGK Spark Plug: **JP5196588 (1993)**.

Chapter 1.11

Suzuki Motor Corporation

The methods of Suzuki Motor Corp. for determining deterioration of a catalytic converter have been applied for a layout similar to that of fig. 81.

The intake passage includes an air flow meter, an intake throttle valve and an intake manifold which are sequentially connected from the upstream side. The intake passage in the intake manifold is constructed by: a surge tank portion serving as an intake collecting section and first to fourth parallel branch intake passage portions (only a single branch passage being shown in fig. 81) which are branched from the surge tank portion. The first to fourth branch intake passages are respectively communicated with first to fourth cylinders (only a single cylinder being shown in fig. 81).

The exhaust passage is formed by an exhaust manifold, an upstream side exhaust pipe, a catalytic converter, and a downstream side exhaust pipe which are sequentially connected from the upstream side. The exhaust passage in the exhaust manifold is constructed by: first to fourth parallel branch exhaust passages which are respectively communicated with the first to fourth cylinders, and an exhaust collecting portion to which the first to fourth branch exhaust gas portions are collected.

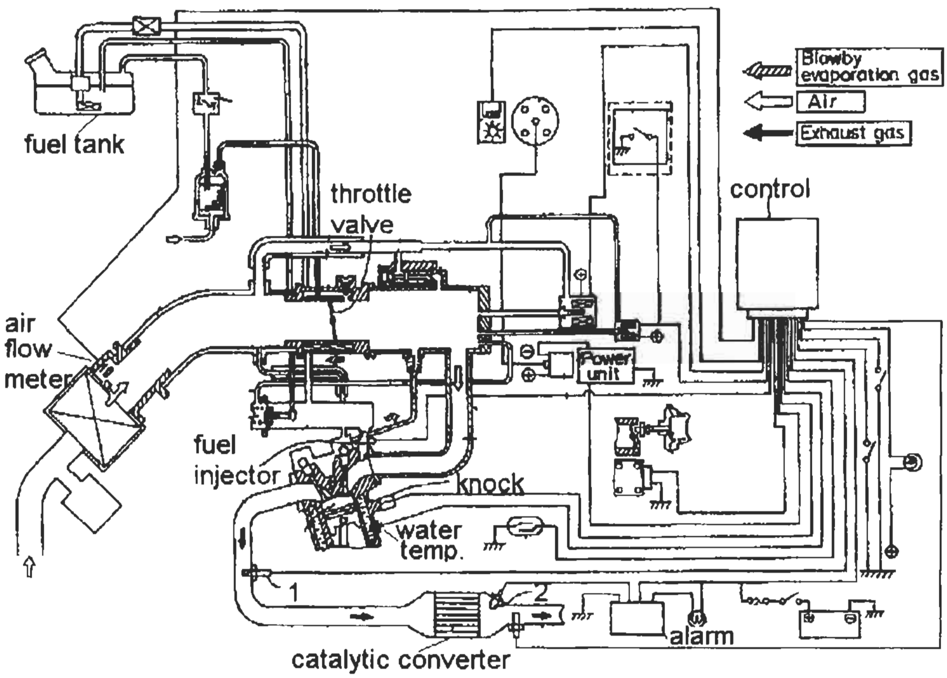


Fig. 81 (from US5379587)

A fuel injection valve connects to each cylinder, and communicates with a fuel tank by a fuel supply passage through a fuel distributing passage. The fuel is fed by a fuel pump through a fuel filter. The passage distributes and supplies the fuel to the first to fourth fuel injection valves.

A fuel pressure adjusting section adjusts the pressure of fuel that is provided by the fuel distributing passage. The fuel pressure adjusting section adjusts the fuel pressure to a predetermined value by an intake pressure which is led from a connecting passage which communicates with the intake passage. The remaining surplus fuel is returned to the fuel tank by a fuel return passage.

Further, the fuel tank is communicated with the intake passage of the throttle body by a passage for evaporated fuel. A bypass passage communicates with the intake passage and bypasses the intake throttle valve. An idle air amount control valve is provided in the bypass passage for controlling flow there through. When it is necessary to adjust idle rotational speed at start up of the engine, at high temperature, and due to an increase in electrical load and the like, the idle air amount control valve opens or closes the bypass passage, thereby increasing or decreasing the air amount and stabilizing the idle rotational speed.

The air flow meter, first to fourth fuel injection valves, idle air amount control valve, and air amount control valve for power steering are connected to a control section serving as a control means. A crank angle sensor, a distributor, an opening degree sensor of the intake throttle valve, a knock sensor, a water temperature sensor, and a vehicle velocity sensor are connected to the control section, respectively. The distributor is connected to the control section through an ignition coil and a power unit for ignition.

An upstream oxygen sensor 1 serving to detect oxygen concentration as an exhaust component value is provided on the upstream side of the catalytic converter and a downstream oxygen sensor 2 provided on the downstream side of the catalytic converter are connected to the control section. The control section executes what is called a dual oxygen feedback control in a manner such that fuel supply amounts to the first to fourth fuel injection valves of the internal combustion engine are controlled.

The air/fuel ratio is first feedback controlled to a value in a stationary operating range of the internal combustion engine by a first detection signal from the upstream oxygen sensor 1, the air/fuel ratio is open controlled in case of an accelerating/decelerating operation other than the stationary operating range of the internal combustion engine, and when the second feedback control performing conditions are satisfied, the air/fuel ratio is second feedback controlled by a second detection signal from the downstream oxygen sensor 2, and in cases other than the second feedback control performing conditions, the air/fuel ratio is open controlled.

Patent disclosure **JP6081635 (1994)** comprises two methods.

1) The first method judges deterioration of the catalytic converter by the calculated area ratio of the output signals of the upstream and downstream oxygen sensors. The signals are measured within a specific time interval starting at the fuel reset time after fuel cut during deceleration. The areas are calculated by integrating the signals in time.
2) The second method judges deterioration of the catalytic converter by measuring the duration of response time from the fuel cut ending time until the time when the judgment voltage outputted from the two oxygen sensors exceeds a specified judgment voltage.

The method of **JP6200811 (1994)** comprises the following steps:

1) checking whether deterioration judging conditions are accomplished and in case they do
2) calculating a standard comparison value from a) the measured delay times of the upstream and downstream sensors during a rich/lean variation of the engine air/fuel ratio during feedback-control and b) the feedback correcting amount

3) correcting a specific execution timing by means of the standard comparison value
4) calculating an average value of the standard comparison value measured in a specific number of cycles
5) judging the deterioration of the catalytic converter from the average value of the standard comparison value

The method of **US5379587 (1995)** comprises the following steps:
1) feedback-controlling the engine air/fuel ratio by detecting signals of the upstream and downstream exhaust sensors (dual feedback control)
2) judging if certain conditions of engine load and rotational speed are fulfilled and in case they do
3) setting a feedback correction amount to be larger than that in a non-deteriorated state
4) stopping the dual exhaust sensor feedback control
5) setting a rich judgment (or determination) delay time ΔT_{LR} and a lean judgment (or determination) delay time ΔT_{RL} (fig. 82a) in accordance with a ratio at the time of the dual exhaust sensor feedback control so as to set a rich/lean judgment delay time to a predetermined value, where
   a) the rich determination delay time ΔT_{LR} elapses from a rich inversion time (point "a") of the upstream detection signal (fig. 82a) to the beginning of the decrease (point "b") in the feedback control-corrected quantity (fig. 82b)
   b) the lean determination delay time ΔT_{RL} elapses from a lean inversion time (point "c") of the upstream detection signal (fig. 82a) to the beginning of the increase (point "f") in the feedback control-corrected quantity (fig. 82b)
6) setting the upstream sensor feedback correction amount to a deterioration judgment value by a skip correction amount K_S and an integration correction amount K_I (gradient) (fig. 82b)
7) measuring a downstream sensor response delay time. This delay time is the time from the moment the upstream sensor switches e.g. from rich to lean air/fuel ratio till the time the downstream sensor switches in the same direction
8) repeating the measurement of the downstream sensor delay time for a certain number of times and calculating an average value of the delay time
9) checking if the average value of the delay time is stable and in case it is stable
10) correcting the downstream exhaust sensor response delay time by an engine load and an exhaust temperature
11) comparing the downstream exhaust sensor response delay time after completion of the correction with the deterioration judgment value defined in step 6
12) determining whether the catalytic converter has deteriorated (fig. 83c) or not (fig. 83b), depending if the measured delay time of the downstream sensor is bigger or not than said deterioration judgment value

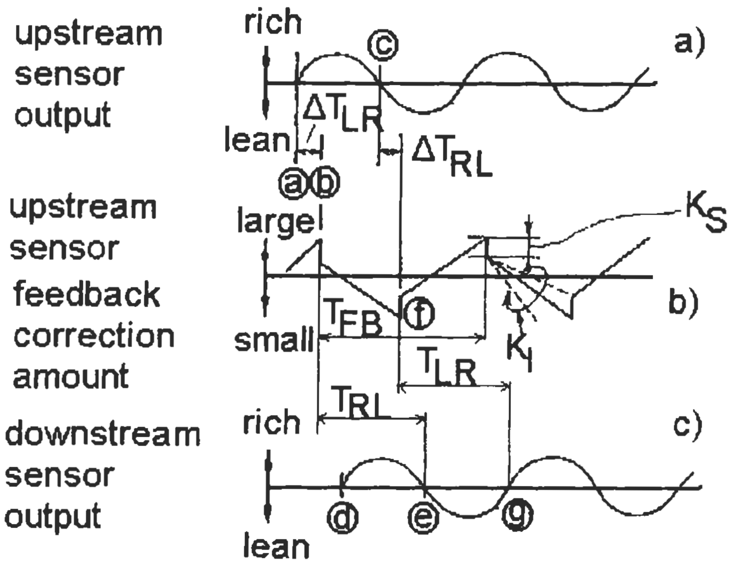


Fig. 82 (from US5448886)

In another embodiment of the invention, the following steps are considered:

1) performing a first feedback control to set the engine air/fuel ratio to a target value on the basis of a first signal generated from the upstream sensor
2) performing a second feedback control to correct the first feedback control by a second detection signal which is generated from the downstream sensor
3) judging if predetermined deterioration judgment performing conditions of the engine are satisfied and in case they do
4) calculating the ratio of the periods of inversion (T_1, T_2) of the output signals of the upstream and the downstream sensor in a predetermined operating time (fig. 83)
5) measuring the upstream and downstream voltage signal surrounding areas (A_1, A_2) within the predetermined operation time in accordance with respective areas which are surrounded by loci of periods of time during which the upstream and downstream voltage signals are inverted, thereby calculating an area ratio (fig. 83)
6) measuring an operation state value in said predetermined operating time from the operating state of the internal combustion engine, thereby calculating a correction value
7) correcting the ratio of periods of inversion and the ratio of areas as calculated in steps 4 and 5 respectively by means of the correction value calculated in step 6
8) judging the condition of the catalytic converter from deterioration judgment arithmetic operation values defined from the corrected ratios of step 7

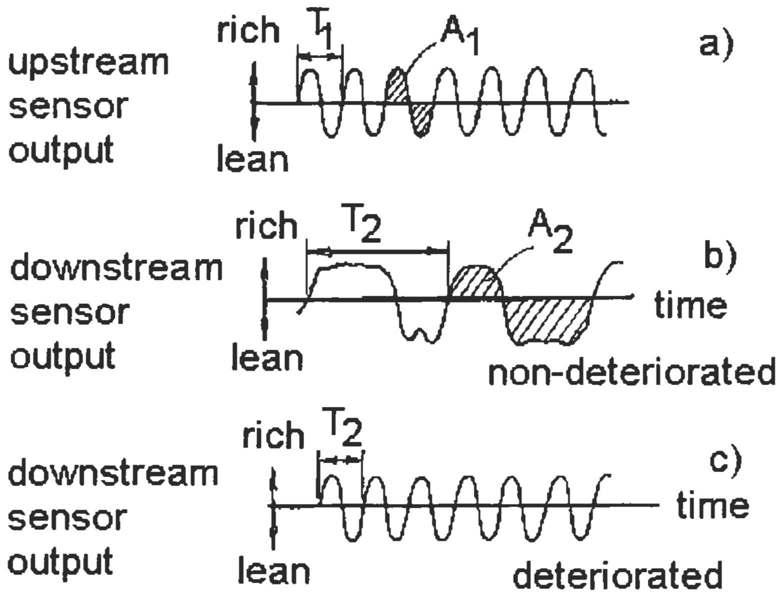


Fig. 83 (from US5379587)

The method of **US5448886 (1995)** comprises the following steps:

1) feedback-controlling the engine air/fuel ratio for matching the air/fuel ratio with a desired value in accordance with upstream and downstream detection signals respectively from the upstream and downstream exhaust sensors
2) judging if certain conditions of engine load and rotational speed are fulfilled and in case they do
3) determining a deterioration-determined time value TDLY from a calculation based on a rich determination delay time ΔT_{LR}, a lean determination delay time ΔT_{RL}, a lean response delay time T_{RL} and a rich response delay time T_{LR} (fig. 82)

$$TDLY = \frac{T_{LR} + \Delta T_{LR} + T_{RL} + \Delta T_{RL}}{2}$$

where:

a) the lean response delay time T_{RL} elapses from the beginning of a decrease (point "b") in an upstream feedback control-corrected quantity to a lean inversion time (point "e") of the downstream detection signal in response to rich and lean inversions of the upstream detection signal (fig. 82)

b) the rich response delay time T_{LR} elapses from the beginning of an increase (point "f") in an upstream feedback control-corrected quantity to a rich inversion time (point "g") of the downstream detection signal in response to rich and lean inversions of the upstream detection signal (figs. 82a-c)

c) the rich determination delay time ΔT_{LR} and the lean determination delay time ΔT_{RL} are defined in the above mentioned method of **US5379587 (1995)**.

4) repeating previous step for a certain number of times
5) calculating the standard deviation of TDLY and if the dispersion is smaller than a preset value then
6) calculating an average value of TDLY and correcting it in function of the engine air intake quantity and the period of feedback control T_{FB} (fig. 82b) and comparing the average value of TDLY to a predetermined value
7) considering the catalytic converter as deteriorated when the corrected average value of TDLY is equal or less than the predetermined value.

The method of **CA2153606 (1996)** comprises the following steps:
1) feedback-controlling the engine air/fuel ratio in accordance with the signal of the upstream sensor (first feedback control) to achieve a target value
2) feedback-controlling the engine air/fuel ratio so as to correct the first feedback control in accordance with the signal of the downstream sensor (second feedback control)
3) establishing predetermined catalytic converter deterioration-determining conditions
4) measuring the number of successive oscillations of the upstream and downstream sensor signals within a predetermined operation time and calculating the ratio N of the downstream signal oscillations n_2 to the upstream signal oscillations n_1

$$N = \frac{n_2}{n_1}$$

5) measuring the upstream and downstream voltage signal surrounding areas (A_1, A_2) within the predetermined operation time in accordance with respective areas which are surrounded by loci of periods of time during which the upstream and downstream voltage signals are inverted (fig. 83), thereby calculating an area ratio A

$$A = \frac{A_2}{A_1}$$

6) measuring the upstream and downstream signal voltage states (V_1, V_2) within the predetermined operation time in accordance with the upstream and downstream voltage signals, thereby calculating a voltage ratio V

$$V = \frac{\sum_{i=1}^{k} \left| V_{2(i)} - V_{2(i+1)} \right|}{\sum_{i=1}^{k} \left| V_{1(i)} - V_{1(i+1)} \right|}$$

where:

k: number of periods of upstream signal inversions within said predetermined operating time

7) calculating a deterioration measured value AZ of the catalytic converter based on the calculated ratios of steps 4 to 6

$$AZ = A \times N \times x_N \times V \times x_V$$

where

x_N : correction factor for N as weight addition,

x_V : correction factor for V as weight addition,

8) comparing the deterioration measured value AZ to a deterioration determining value, the latter being set for each engine load.

In **US5531069 (1996)**, it is first judged whether or not the catalytic converter is in a predetermined warm-up state in relation to any engine load of the internal combustion engine. The determination of the catalytic converter deterioration then takes place only when predetermined deterioration-determining conditions are fulfilled. The judgment of deterioration is determined by examining the output signals of the upstream and downstream oxygen sensors, as in any of the previous mentioned methods.

The method of **JP9096237 (1997)** inhibits the deterioration detection of the catalytic converter when the engine load is less than a lower limit value after correcting it with the atmospheric pressure. The feedback control of the engine air/fuel ratio is based on both output signal of the upstream or the downstream oxygen sensor

Other methods presented by Suzuki Motor Corp. are described in **JP6229309 (1994)**, **JP7019033 (1995)**, **JP7197807 (1995)** and **JP8326525 (1996)**.

Chapter 1.12

Mitsubishi Motors Corporation - Mitsubishi Electric Corporation

Fig. 84 shows a typical engine layout used by Mitsubishi for detecting the deterioration of a catalytic converter. An internal combustion engine is provided with an intake pipe for supplying an air/fuel mixture to the engine, an air cleaner disposed at an inlet port of the intake pipe, an intake manifold formed at a junction between the intake pipe and the engine and a fuel injector mounted in the intake pipe at a position upstream of a throttle valve. Further, mounted in the intake manifold is a semiconductor-type pressure sensor for detecting a pressure P within the manifold. This pressure P indicates an amount of the air/fuel mixture supplied to the engine from the intake pipe through the manifold. A throttle sensor is provided in association with the throttle valve for detecting the throttle opening degree φ. The engine is further equipped with an exhaust pipe for discharging an exhaust gas resulting from combustion of the air/fuel mixture within the engine. A ternary catalytic converter is installed in the exhaust pipe for eliminating HC, CO and NO_x from the exhaust gas. A first air/fuel ratio sensor 1 is mounted in the exhaust pipe at a position upstream of the catalytic converter with a second air/fuel ratio sensor 2 being disposed downstream of the catalytic converter.

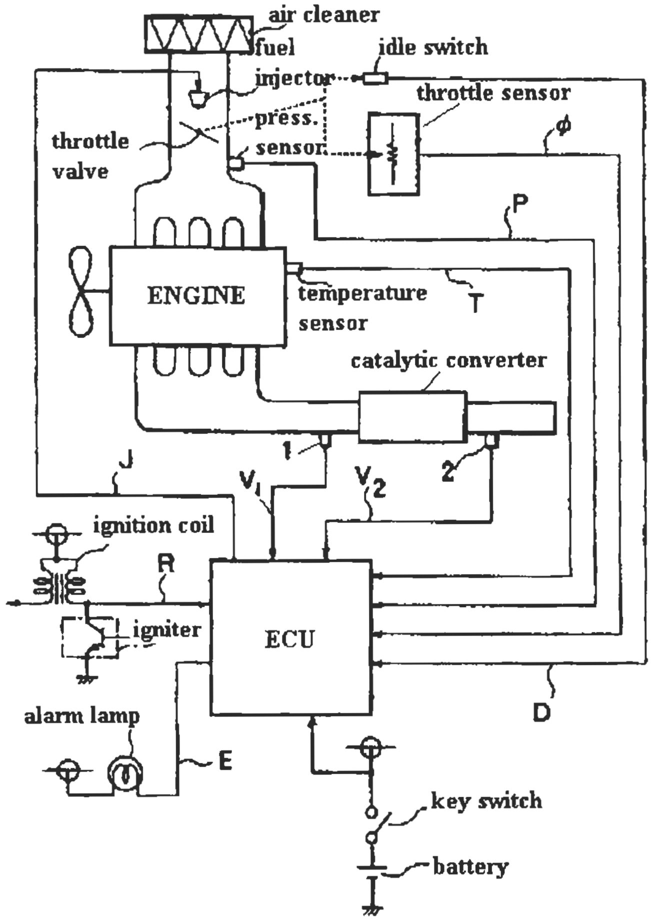


Fig. 84 (from US5425234)

For the control of the engine operation, there is provided an electronic control unit (ECU) having an input terminal to which an ignition coil composed of a boosting transformer and an igniter constituted by a power transistor for interrupting electric conduction through a primary winding of the ignition coil is connected. An idle switch which serves to detect the idling operation state of the engine in which the throttle valve is fully closed is provided integrally with the throttle sensor, wherein the output signals D and φ of both the idle switch and the throttle sensor are supplied to the electronic control unit. Supplied additionally to the electronic control unit are an output signal T of a thermistor-type water temperature sensor which is employed for detecting the temperature T of the engine cooling water and an output signal P of the pressure sensor mentioned above. An electric power for the electronic control unit and other components is supplied from an onboard battery via a key switch. An alarm lamp driven upon detection of abnormality such as deterioration of the catalytic converter and the like (indicated by a signal E) is connected to an output terminal of the electronic control unit. Further, a vehicle speed sensor for detecting a speed of a motor vehicle is installed in association with an axle. The operation of the fuel injector is controlled by the electronic control unit in dependence on the running or operation state of the engine while taking into account the air/fuel ratio detected by the sensors 1 and 2.

The electronic control unit receives as the engine operation state indicating parameters or quantities a variety of input signals including the throttle opening signal φ from the throttle sensor, the pressure signal P from the pressure sensor indicating the pressure within the intake manifold, the coolant water temperature signal T from the water temperature sensor, the idle signal D from the idle switch, a vehicle speed signal S from a vehicle speed sensor, a rotation or interrupt signal R generated upon every interruption of the electric conduction of the ignition coil and serving as an interrupt signal and air/fuel ratio signals V_1 and V_2 supplied from the first and second air/fuel ratio sensors 1 and 2, respectively. The electronic control unit generates a fuel injection control signal J under the control through an air/fuel ratio feedback control loop. The abnormality signal E for lighting the alarm lamp is generated upon detection of occurrence of abnormality (such as deterioration of the catalytic converter) in the engine operation.

The method of **JP63231252 (1988)** comprises the following steps:
1) feedback-controlling the engine air/fuel ratio according to the output signal of the upstream oxygen sensor
2) detecting the output signals of the upstream and downstream sensors
3) detecting the difference of the maximum values of the respective output signals of the upstream and downstream sensor
4) deciding that the catalytic converter must be replaced when this difference falls below a predetermined value

The method of **JP3031756 (1991)** comprises the following steps:
1) feedback-controlling the engine air/fuel ratio according to the output signal of the upstream oxygen sensor
2) calculating the width of the feedback correction factor
3) calculating the width of the change in the equivalent air/fuel ratio based on the air/fuel ratio measured by the downstream sensor
4) calculating the ratio of the width of the change in the equivalent air/fuel ratio to the width of the feedback correction factor
5) deciding that the catalytic converter has deteriorated when this ratio exceeds a predetermined value.

The method of **DE4233977 (1993)** and **US5417061 (1995)** comprises the following steps:

1) calculating individual integration values (S) corresponding to areas enclosed by output signals of the upstream and downstream oxygen sensors and designated signals (fig. 85), wherein a designated signal for the upstream sensor is variable in accordance with the output signal of the downstream sensor, and the integration values are calculated for areas both above and below an associated designated signal. The designated signals are corrected by a hysteresis factor
2) determining variable, individual time periods (T) between which the output signals reverse polarity with respect to the designated signals
3) calculating a parameter (C) for determining deterioration of the catalytic converter based on one of mean values and summation values of one of the integration values and the polarity reversal time periods in a predetermined time
4) determining deterioration of the catalytic converter by comparing said parameter with a predetermined value (C_{lim})
5) issuing an alarm when the catalytic converter is determined as deteriorated

More specifically the parameter (C) can be calculated by one of the following methods:

1) The sum of individual areas S_2 of fig. 85 is calculated within a time interval for the signal of the downstream sensor. The sum of individual periods T_2 within the above mentioned time interval is calculated as well. The average value of areas S_2 and periods T_2 is formed and the parameter (C) is defined as

$$C = \frac{\overline{S}_2}{\overline{T}_2}$$

2) The parameter (C) is calculated as the ratio of area S_1 of the upstream sensor to the area S_2 of the downstream sensor

$$C = \frac{S_1}{S_2}$$

3) In a third case the following equation defines the deterioration parameter

$$C = \frac{S_1}{T_1} \frac{T_2}{S_2}$$

4) The deterioration of the catalytic converter is also checked by the formula

$$C = \frac{T_1}{T_2}$$

where the catalytic converter is considered as deteriorated for $C>C_{lim}$, where C_{lim} is a threshold (limit) value of C

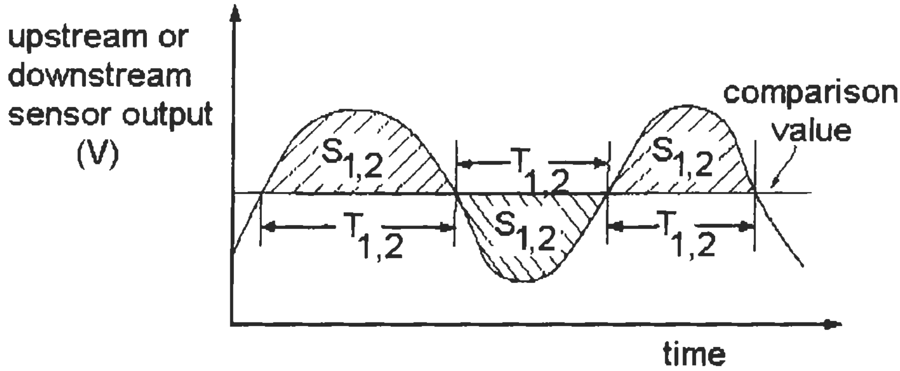


Fig. 85 (from US5417061)

The method of **US5363647 (1994)** comprises the following steps:

1) detecting concentration of a particular component of the exhaust gas upstream of the catalytic converter to output an air/fuel ratio signal indicating said concentration
2) detecting concentration of the particular component of the exhaust gas downstream of the catalytic converter to thereby output a downstream air/fuel ratio signal indicating the concentration
3) controlling an aimed air/fuel ratio of a mixture supplied to the engine by arithmetically determining an air/fuel ratio control quantity on the basis of the upstream and downstream air/fuel ratio signals
4) detecting the operation state of said internal combustion engine and when the operation state of the engine lies within a predetermined range:
5) filtering the downstream air/fuel ratio signal to thereby derive a filtered air/fuel ratio signal
6) comparing the downstream air/fuel ratio signal with the filtered air/fuel ratio signal
7) comparing a deterioration parameter value derived from the result of the comparison with a predetermined value (which varies in dependence on change in the operation state of the engine) corresponding to the detected operation state of the engine to thereby determine deterioration of the catalytic converter when the deterioration parameter value exceeds the predetermined value

The method of **JP6264725 (1995)** comprises the following steps:
1) detecting the load of the engine and calculating a load accumulated value within a specific time interval
2) checking whether or not the load accumulated value exceeds a fixed value and in case it does
3) detecting deterioration of the catalytic converter based on the output signals of the upstream and downstream oxygen sensors. The converter is considered as deteriorated when the detected deterioration value calculated from the output signals of the oxygen sensors is more than a fixed value.

The method of **US5425234 (1995)** comprises the following steps:
1) detecting concentration of a particular component of the exhaust gas upstream of the catalytic converter to output an air/fuel ratio signal indicating said concentration
2) detecting concentration of the particular component of the exhaust gas downstream of the catalytic converter to thereby output a downstream air/fuel ratio signal indicating the concentration
3) determining a deterioration parameter value at every predetermined time interval on the basis of the downstream air/fuel ratio signal
4) filtering the deterioration parameter value to output a filtered deterioration parameter value
5) determining deterioration of the catalytic converter when the filtered deterioration parameter value exceeds a predetermined value for a predetermined period. The comparison of the filtered deterioration parameter value with the predetermined value takes place when
    I) a difference between a currently sampled value of the filtered deterioration parameter value and a previously sampled value thereof exceeds a permissible upper limit value and/or
    II) a difference between a currently sampled value of the filtered deterioration parameter value and a precedent sampled value thereof exceeds a permissible upper limit value.

Fig. 86 refers to one embodiment of the invention. V_{O2} is the output signal of the downstream sensor and V_{fO2} is the linear filtered output signal of the downstream sensor given by the following expression

$$V_{fO2(n)} = (1 - k_s) \cdot V_{fO2(n-1)} + k_s \cdot V_{O2}$$

where:
(n) represents a current time point
(n-1) represents a precedent time point and
k_s is a filtering coefficient ($0<k_s<1$).

The downstream sensor signal V_{O2} is converted to the filtered signal V_{fO2} with a delay in the response time, which corresponds to a time constant of the filtering means (e.g. 100-300 milliseconds).

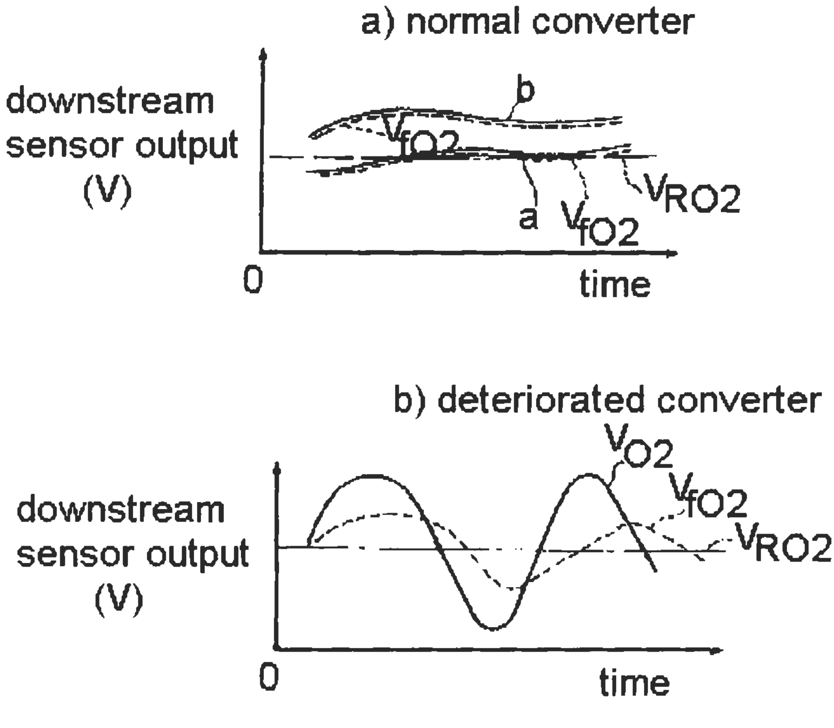


Fig. 86 (from US5425234)

When the catalytic converter is normal (fig. 86a), the filtered signal V_{fO2} follows the signal V_{O2} even when the level of the signal V_{O2} shifts from a solid line curve a to a curve b. The two signals V_{O2} and V_{fO2} essentially coincide because of the large time constant.
When the catalytic converter is deteriorated (fig. 86b), the level of the filtered signal V_{fO2} differs significantly from the non-filtered signal V_{O2} and intersects a downstream target value V_{RO2} due to a large delay in the response time to the signal V_{O2} of a large amplitude. The difference between the filtered and non-filtered signal increases beyond a predetermined value and indicates a deteriorated catalytic converter.

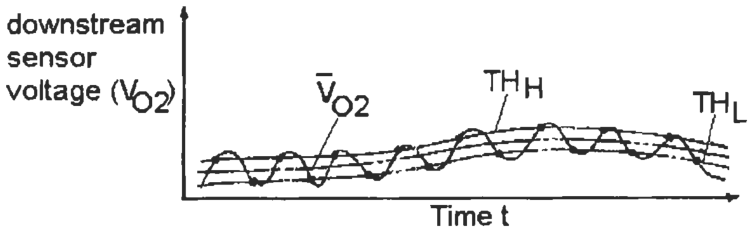


Fig. 87 (from DE19605103)

The method of **DE19605103 (1996)** comprises the following steps:

1) calculating an average value $\bar{V}_{O2}$ of the output signal of the downstream sensor by means of the formula:

   $$\bar{V}_{O2}(n) = a \cdot \bar{V}_{O2}(n-1) + (1-a) \cdot V_{O2real}$$

   where
   $(n-1)$ corresponds to calculated values in a previous cycle,
   V_{O2real} is the present value of the output signal of the downstream sensor and
   a is a filtering constant
2) variably setting reference fluctuation values (TH_H,TH_L) according to the average value $\bar{V}_{O2}$ of the output signal of the downstream oxygen sensor (fig. 87). The following formulas are used

   $$TH_H = \bar{V}_{O2} + \Delta V$$

   $$TH_L = \bar{V}_{O2} - \Delta V$$

3) measuring the number of times that the output signal of the downstream sensor crosses the reference fluctuation values (TH_H,TH_L) in a predetermined time interval Δt, and calculating a fluctuation frequency f_2 by dividing this number of crossing times with the predetermined time interval Δt
4) determining the ratio of the fluctuation frequency of the downstream sensor f_2 to the fluctuation frequency f_1 of the upstream oxygen sensor
5) determining deterioration of the catalytic converter when the ratio f_2/f_1 becomes greater than a predetermined threshold

In the method of **US5591905 (1997)**, first it is decided whether or not the catalytic converter is activated and only then the deterioration diagnosis procedure starts. In this way an erroneous decision of deterioration of the catalytic converter is avoided. The method comprises the following steps:

1) deciding whether a catalyst is activated in a catalytic converter
2) determining a steady state operation of the internal combustion engine
3) deciding deterioration of said catalyst only when it is decided that said catalyst is activated and when it is decided that the engine is in a steady state operation
4) detecting an operating state of the internal combustion engine by means of operating state detecting means
5) deciding that said catalyst is activated during a period starting after elapse of a first time count, in which an output value from said operating state detecting means is kept in a predetermined range
6) ending upon the elapse of a second time count commencing after said output value is out of the predetermined range
7) assessing the deterioration of the catalytic converter, after determining that the converter is activated, by comparing the signals of the upstream and downstream sensors by means of any of the methods described above.

The predetermined range is varied according to the operating state of the internal combustion engine. The operating state detecting means can be a hot-wire intake air flow sensor, an ignition coil, an igniter, a water temperature sensor, a vehicle speed sensor or an intake air flow rate sensor.

Fig. 88a shows the variation of the output voltage V_1 of the upstream sensor during feedback-control of the engine air/fuel ratio. Figs. 88b and c show the corresponding variation of the output voltage signal V_2 of the downstream sensor for the cases of a non-deteriorated and a deteriorated converter respectively. Fig. 88d shows the temperature of the catalytic converter, where T_c corresponds to the activation temperature of the converter at constant operation.
During a period t_0 in which the converter is activated, the air/fuel ratio signal V_2 can have a substantially constant value because of the purifying action of the converter in case the converter is normal (fig. 88b). In the case of a deteriorated converter (fig. 88c) the signal V_2 oscillates within the time period t_0 in a way similar to that of signal V_1 (fig. 88a). The deterioration of the catalytic converter is then easily recognized from the oscillation of V_2. However, when the temperature of the catalytic converter is lower than the activation temperature T_c, the air/fuel ratio signal V_2 shows the same wave form as that at a time of deterioration of the converter even if the catalytic converter is not deteriorated (figs. 88b-d). Consequently, when deterioration of the converter is decided depending upon the wave form of the air/fuel signal V_2, the deterioration of the catalytic converter is erroneously detected though the converter is not deteriorated.

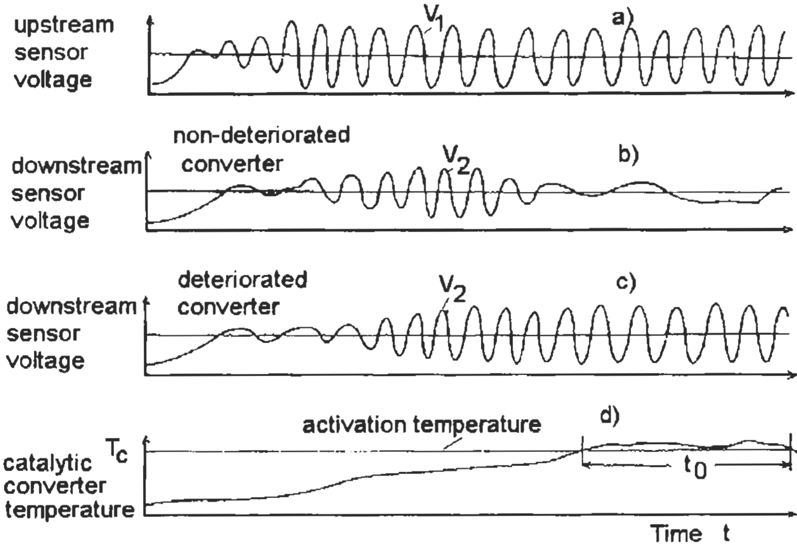


Fig. 88 (from US5591905)

The method of **US5640846 (1997)** presents an improved control of the engine air/fuel ratio to diagnose accurately the catalytic converter efficiency. The method comprises the following steps:

1) detecting the upstream concentration of a particular component of the exhaust gas to output a first air/fuel ratio signal indicating the upstream concentration
2) detecting the downstream concentration of the particular component of the exhaust gas to thereby output a second air/fuel ratio signal indicating the downstream concentration
3) controlling a target air/fuel ratio of a mixture supplied to the engine by arithmetically determining a target air/fuel ratio control quantity on the basis of the first and second air/fuel ratio signals. The control of the engine air/fuel ratio comprises the following steps:
    a) determining a first air/fuel ratio control quantity on the basis of the first air/fuel ratio signal
    b) determining a second air/fuel ratio control quantity on the basis of the second air/fuel ratio signal
    c) correcting the first air/fuel ratio control quantity with the second air/fuel ratio control quantity to thereby determine the target air/fuel ratio control quantity on the basis of the correction of the first air/fuel ratio control quantity
    d) filtering the first air/fuel ratio signal to compensate for variations in the output characteristics of the upstream sensor
4) assessing the efficiency of the catalytic converter by using e.g. the method of **US5363647 (1994)** described above.

Other methods: see **JP4181149 (1992)**, **JP6129240 (1994)**.

Chapter 1.13

Nissan Motor Co. Ltd.

Fig. 89 shows a typical engine layout used by Nissan Motor Co. for controlling an internal combustion engine and for detecting the deterioration of a catalytic converter.
The internal combustion engine has an air intake passage and an exhaust gas passage. The air intake passage has a plurality of fuel injectors which are arranged to feed fuel to respective combustion chambers through intake ports. A throttle valve is installed in the air intake passage at a position upstream of the fuel injectors. An air flow meter is further installed in the air intake passage at a position upstream of the intake valve. The air flow meter may be of a known hot-wire type. Although not shown in the figure, an air filter is mounted on top of the air intake passage to clean air fed to the engine proper.

The exhaust gas passage has a three-way type catalytic converter installed therein at a position upstream of a muffler. The exhaust gas passage has two oxygen sensors 1 and 2 installed therein at positions upstream and downstream of the converter. Each sensor 1 or 2 generates electromotive force in accordance with concentration of oxygen contained in the exhaust gas and shows a steep change of the electromotive force at the stoichiometric value of air-fuel ratio.

A water temperature sensor senses the temperature of cooling water of the engine proper, and a crank angle sensor which, for obtaining an engine speed, issues a pulse signal for each given crank angle. A temperature sensor also detects the temperature of exhaust gas discharged from the converter. The temperature in the converter is thus indirectly sensed by the temperature sensor.

Output signals produced by all sensors are fed to a control unit which contains a microcomputer. By analyzing information possessed by the output signals given by such sensors, the control unit controls the injectors to adjust the amount of fuel fed to each combustion chamber of the engine. That is, the so-called feedback control for the air-fuel ratio is carried out by usage of the information signals from the upstream and downstream oxygen sensors 1 and 2.

In addition, the control unit carries out a catalytic converter deterioration diagnosis. That is, when it is judged that the catalytic converter is deteriorated to a certain degree, an alarm lamp is lit.

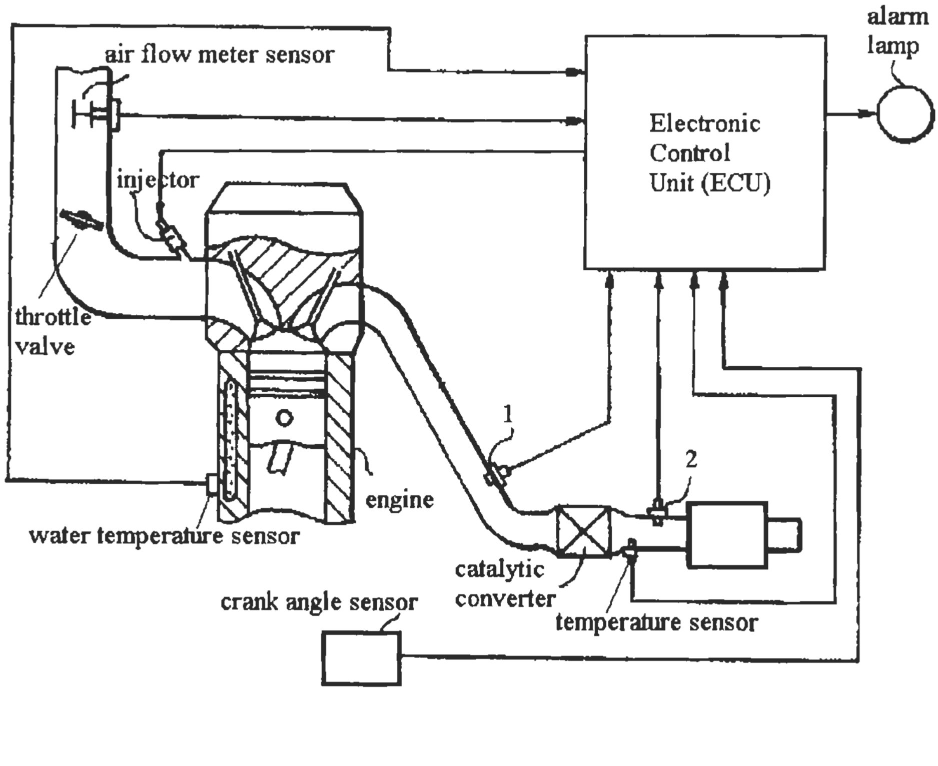


Fig. 89 (from US5644912)

In the method of **JP2310453 (1990)**, the response delay time of the downstream sensor output signal when compared to the upstream sensor output signal is a measure of the deterioration of the catalytic converter.

In the method of **JP4001449 (1992)** the criterion of degradation of the catalytic converter is the ratio of frequency of oscillation of the downstream sensor output signal to the frequency of oscillation of the upstream sensor output signal during a feedback control of the engine air/fuel ratio from rich to lean and vice versa.

In the method of **JP4116239 (1992)** the deterioration diagnosis of the catalytic converter is inhibited for accuracy reasons when the number of renewals of a learning value based on the output signal of the downstream sensor is lower than a specified value. The learning value is the value used to correct the feedback compensation coefficient used during the feedback-control of the engine air/fuel ratio. The feedback compensation coefficient is calculated based on the output signal of the upstream sensor.

In the method **of US5119628 (1992)** the following steps are considered:

1) detecting the air/fuel ratio of the exhaust gases upstream of the catalytic converter
2) detecting the air/fuel ratio of the exhaust gases downstream of the catalytic converter
3) checking whether the upstream sensor output signal is on the rich or on the lean side when compared to the stoichiometric value
4) determining a basic engine air/fuel ratio feedback control constant according to the output signal of the upstream sensor (lean or rich side)
5) checking whether the downstream output signal is inverted to rich or lean side across an air/fuel ratio feedback controlling rich (upper) or lean (lower) *slice level* respectively (fig. 90). Upper (lower) slice level is a predefined value being lower (higher) than the maximum (minimum) value of the sensor output signal for each operating condition and it always cuts the sensor output signal during deterioration detection
6) calculating a correction value of the basic air/fuel ratio feedback control constant according to the rich or lean side
7) determining an engine air/fuel ratio feedback correction coefficient on the basis of the basic feedback control constant corrected by the correction value
8) measuring a period of the engine air/fuel ratio feedback correction coefficient
9) measuring an amplitude of the air/fuel ratio feedback correction coefficient
10) setting a rich discriminating catalytic converter diagnosing slice level higher than a rich discriminating air/fuel ratio feedback controlling slice level and a lean discriminating catalytic converter diagnosing slice level lower than a lean discriminating air/fuel ratio
11) feedback controlling the slice level in such a way that the rich discriminating catalytic converter diagnosing slice level increases and the lean discriminating catalytic converter diagnosing slice level decreases, both increasing anyone of the measured period and amplitude of the air/fuel feedback correction coefficient (fig. 91), wherein the slice levels

comprise corresponding reference values to which the outputs of the air/fuel ratio sensors are compared

12) counting the number of inversions of the upstream sensor output signal across the stoichiometric air/fuel ratio
13) counting the number of inversions of the downstream sensor signal across the set catalytic converter diagnosing slice levels
14) checking whether the ratio of the downstream sensor counted value to the upstream sensor counted value exceeds a predetermined value
15) determining that the catalytic converter has been degraded when the ratio exceeds a predetermined value

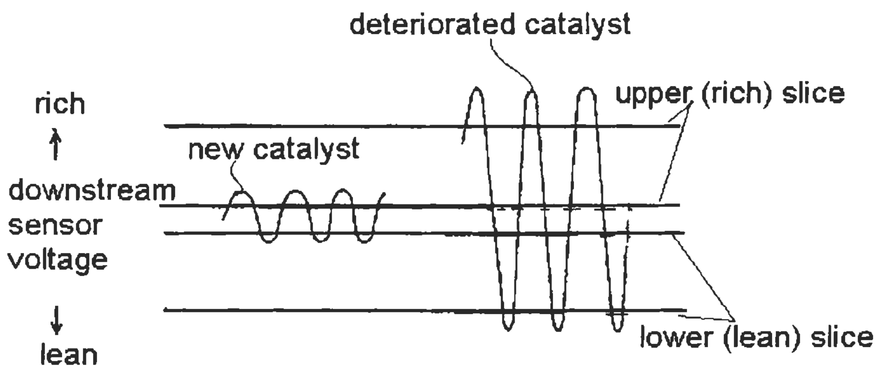


Fig. 90 (from US5119628)

In the method of **JP5312025 (1993)**, at the time of the diagnosis procedure, the mean engine air/fuel ratio is shifted to a rich value by means of a suitable feedback control. When the catalytic converter is deteriorated, then the output signal of the downstream sensor crosses a predefined slice level (as defined in **US5119628 (1992)**). The same procedure can be repeated by shifting the mean engine air/fuel ratio to a lean value.

The method of **JP5098945 (1993)** inhibits the deterioration diagnosis of the catalytic converter when during feedback-control of the engine, engine cooling water temperature, car speed, engine speed and basic fuel injection quantity are not in predetermined ranges. Namely, the diagnosis takes place only when the converter is activated under ordinary operating conditions.

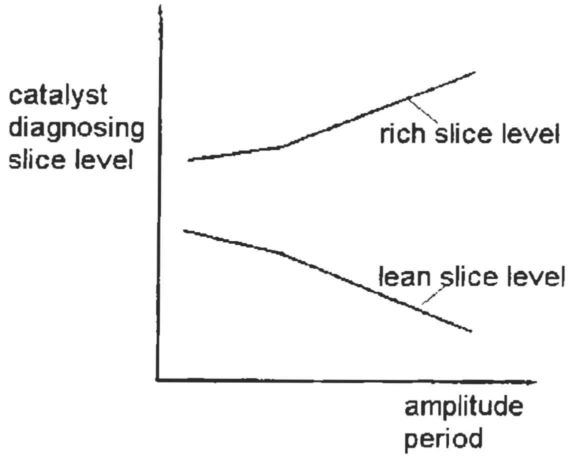


Fig. 91 (from US5119628)

In the method of **JP6074025 (1994)** the feedback-control of the engine air/fuel ratio during testing is based on the output signal of the downstream oxygen sensor, so as to largely swing the air/fuel ratio to rich and lean sides. When the catalytic converter is deteriorated, the inversion delay time between the output signals due to oxygen storage in the converter becomes shorter than a predetermined threshold.

In the method of **JP6254726 (1994)** the testing takes place when certain operating conditions are fulfilled. Then the exhaust gas temperature is raised by delaying the injection of fuel in the engine cylinders and by delaying the ignition at a time point later than the optimum ignition time. The temperature of the catalytic converter is thus kept high and the reliability of the diagnosis procedure by means of the oxygen sensors increases.

In the method of **JP7180534 (1995)** two HEGO sensors are installed upstream and downstream of the converter. When the frequency ratio of the output signals of the two sensors indicates a deteriorated converter, the heater of the downstream sensor is disconnected and the temperature of the downstream sensor becomes equal to the one of the catalytic converter. Then it is checked whether or not the measured output signal of the downstream sensor is within a certain range extracted from an output signal state available when the temperature of the downstream sensor is approximately equal to the activation temperature of the converter. If the measured output signal of the downstream sensor is out of this certain range, it is judged that the temperature of the converter is low and deterioration diagnosis should be repeated.

The method of **JP7189664 (1995)** comprises feedback-control of the engine air/fuel ratio based on the output signal of the upstream sensor. The feedback-control is corrected by means of a correction value based on the output of the downstream oxygen sensor. The deterioration of the converter is derived by comparing the number of inversions of the output of the downstream oxygen sensor with a threshold value. This threshold may be adjusted by increasing or decreasing its value and this adjustment depends on said correction value.

The method of **JP7189781 (1995)** comprises a first feedback-control mode of the engine air/fuel ratio based on the output signal of the upstream sensor. When it is judged that certain diagnosis conditions are satisfied the feedback-control switches to a second feedback-control mode based on the output signal of the downstream sensor. The inversion frequencies of the oxygen sensors are counted for both feedback-control modes and the deterioration of the converter is judged by comparing these inversion frequencies with predetermined values.

The method of **JP7243342 (1995)** comprises feedback-control of the engine air/fuel ratio based on the output signal of the upstream sensor. When certain operating conditions are achieved, the signal outputs of the two sensors are compared. Whenever the comparison result reaches a prescribed number, the comparison result is updated and it is weight averaged. The deterioration of the catalytic converter is detected based on the result of the weighted average.

The method of **JP7247830 (1995)** comprises feedback-control of the engine air/fuel ratio based on the output signal of the upstream sensor. It is judged whether or not the operating condition of the engine is in one or plural pre-stored catalytic converter diagnosis areas according to the operating conditions. When the judged result is in such a catalytic converter diagnosis region then the efficiency of the catalytic converter is assessed by comparing the output signals of the upstream and downstream sensors. The converter is considered as deteriorated when the comparison of the output signals shows deterioration in a plurality of such diagnosis areas.

The method of **JP7305623 (1995)** comprises the following steps:
1) checking if certain operating conditions are satisfied
2) feedback-controlling the engine air-fuel ratio
3) filtering the output signal of the downstream oxygen sensor based on the signal frequency of the upstream sensor output signal
4) calculating an amplitude ratio between the amplitude of the filtered signal of the downstream sensor and the amplitude of the signal of the upstream sensor

5) calculating an amplitude threshold in accordance with a judging result of the engine operating conditions
6) judging deterioration of the catalytic converter based on the comparison result of the amplitude ratio and the threshold value

The method **JP7310536 (1995)** comprises the following steps:
1) judging if the operating condition of the engine is within a domain of deterioration diagnosis of the catalytic converter
2) comparing the output signals of the upstream and downstream oxygen sensors
3) weight-averaging the comparison result of step 2 by a weight averaging means
4) reducing the weight of the weight averaging means to a prescribed time after the result of judgment attains the domain of deterioration diagnosis of the catalytic converter (step 1)
5) calculating the reduced weighted mean value
6) determining the efficiency of the catalytic converter based on the calculated result of step 5, even if the operating condition of step 1 is short.

In the method of **JP8128317 (1996)**, the total quantity of heat of the exhaust system is calculated from the starting of the engine. The engine air/fuel ratio is feedback-controlled based on the output of the upstream oxygen sensor. The feedback-control is further corrected based on the output signal of the downstream sensor. The ratio of periods of oscillation of the output signals of the upstream and downstream output signals is calculated. If the total quantity of heat reaches a prescribed value and the above mentioned ratio of periods does not decrease, it is judged that the catalytic converter is degraded.

In the method of **JP8177468 (1996)**, the judgment of the deteriorated of the catalytic converter is prohibited when the measured temperature of the exhaust gases upstream of the catalytic converter has a value lower than a specified threshold.

The method of **JP8177469 (1996)** performs the deterioration diagnosis of the catalytic converter by a first diagnostic means, that is, by comparing the output signals of the two sensors, during a forced variation of the engine air/fuel ratio from rich to lean and vice versa. When for any reason this first diagnostic means does not provide reliable results, a second means is activated to perform the diagnosis. That is, the engine air/fuel ratio is forcibly made lean, and this state is detected by the upstream and downstream oxygen sensors. Then the air/fuel ratio is inverted into a rich state. The time from the moment the rich inversion is detected by the upstream oxygen sensor to the moment the rich inversion is detected by the downstream sensor (delay time) is measured and compared with a specific threshold in order to determine the degradation of the converter.

The method of **DE19539024 (1996)** comprises the following steps:

1) detecting the air/fuel ratio of the exhaust gases upstream and downstream of the catalytic converter by means of an upstream and a downstream sensor
2) estimating a basic engine fuel injection quantity in function of an operating parameter of the engine
3) determining a feedback air/fuel ratio correction coefficient based on the output signal of the upstream air/fuel sensor
4) correcting the basic fuel injection quantity by means of the feedback correction coefficient
5) comparing the oscillation state of the output signals of the air/fuel sensors from rich to lean and vice versa with decision standards, and assessing the performance of the catalytic converter from this comparison. The ratio of oscillation frequencies or the phase shift between the upstream and downstream sensor output signals are the criteria for judging the performance of the catalytic converter.

The method of **US5557929 (1996)** comprises the steps of:
1) diagnosing the deterioration of the catalytic converter (any of the above mentioned methods can be used)
2) detecting a predetermined engine operation condition at which the temperature of the catalytic converter becomes high
3) calculating a first time period at which a control for stopping fuel to be supplied to the engine is made
4) calculating a second time period at which a control for increasing an amount of fuel to be supplied to the engine is made
5) avoiding an operation of diagnosing of step 1, when a deviation between the first and second time periods is not less than a predetermined value under the predetermined engine operating condition of step 2.

The method of **JP8246853 (1996)** comprises the following steps:
1) operating the engine with a rich air/fuel ratio
2) switching the air/fuel ratio from the rich value to a lean one
3) measuring a first delay time, that is the time needed for the downstream oxygen sensor output signal to be reversed from the rich to the lean state, after the upstream sensor output signal has been reversed from the rich to the lean state
4) switching the air/fuel ratio from the lean value to the previous rich one
5) measuring a second delay time, that is the time needed for the downstream oxygen sensor output signal to be reversed from the lean to the rich state, after the upstream sensor output signal has been reversed from the lean to the rich state
6) calculating the dispersion of a difference in response of first and second delay times
7) assessing the efficiency of the catalytic converter by comparing the dispersion with a predetermined threshold

The method of **US5644912 (1997)** comprises the following steps:

1) measuring the oxygen content of the exhaust gases upstream and downstream of a catalytic converter by means of two oxygen sensors installed in the exhaust system upstream and downstream of the converter
2) feedback-controlling the air-fuel ratio of mixture fed to the engine in accordance with an output signal issued from the upstream oxygen sensor
3) detecting the elapsed time (time lag) from the time on which the output signal from the upstream oxygen sensor carries out a rich-lean reverse to the time on which the output signal from the downstream oxygen sensor carries out a corresponding rich-lean reverse
4) calculating an average value of time lags which are measured each time the rich/lean reverse takes place in the output signals from the upstream and downstream oxygen sensors
5) causing a step change, upon a given diagnosing mode thereof, in a feedback correction factor in synchronization with the rich/lean reverse of the output signal from the downstream oxygen sensor, thereby correcting the air-fuel ratio of mixture to a generally stoichiometric value
6) deriving a judgment reference value in accordance with the detected number of times for which the measurement of the time lag is repeated
7) comparing the judgment reference value with the averaged time lag to judge the deterioration degree of the catalytic converter
8) suspending the judgment of the deterioration of the catalytic converter when the averaged time lag is within a predefined border zone

In a second embodiment of the invention, instead of calculating an average value of time lags (step 4), an integrated value of the amount of air fed to the engine within the time lag of step 3 is calculated. An average of integrated values, which are derived each time the rich/lean reverse takes place in the output signals of the two oxygen sensors, is then calculated.
A judgment reference value is then derived in accordance with the detected number of times for which the measurement of the time lag is repeated (step 6). The judgment reference value is compared with the average of the integrated values to judge the deterioration degree of the catalytic converter (step 7). The judgment of the deterioration of the catalytic converter is suspended when the average of integrated values is within a predefined border zone (step 8).

Other methods presented by Nissan are: **JP7301115 (1995)**, **JP7301116 (1995)**.

Engines with multiple cylinder groups

The method of **JP5098946 (1993)** proposed by Nissan refers to the case of an engine with multiple cylinder groups, where there is an auxiliary catalytic converter in each individual exhaust passage of each cylinder group. A main three-way catalytic converter is also installed in the common exhaust pipe section of all cylinder groups (fig. 56). The distribution of exhaust sensors is similar to the one of fig. 56.

The engine air/fuel ratio is feedback-controlled and the deterioration assessment of the auxiliary (secondary) catalytic converters and the main catalytic converter takes place by comparing the output signals of the oxygen sensors placed upstream of the auxiliary converters and the oxygen sensor placed downstream of the main converter.

Chapter 1.14

General Motors Corp.

Fig. 92 shows a typical engine layout used by General Motors Corp. for controlling an internal combustion engine and for detecting the deterioration of a catalytic converter.
An air metering means, such as a conventional butterfly valve (throttle) is provided in the inlet air path above which is located an airflow meter for measuring mass airflow into the engine and providing an output signal MAF indicative thereof. Air passing through the inlet air path enters an engine intake manifold (not shown) in which is disposed an air pressure sensor for measuring the absolute pressure of air in proximity thereto, and providing an output signal MAP indicative thereof.

A coolant temperature sensor is located in an engine coolant circulation path (not shown) to measure the temperature of the coolant passing by the sensor and to output a signal TEMP indicative thereof. The crankshaft rotates through operation of the engine at a rotational rate proportional to engine speed and a crank-angle sensor measures the engine speed.

The inlet air is combined with inlet fuel and the air/fuel mixture combusted in the engine through engine operation, and a substantial portion of the combustion products are drawn out of the engine via the exhaust pipe to a catalytic converter. An upstream oxygen sensor 1 is disposed in the exhaust gas pipe in position to sense the oxygen content of the engine exhaust gas before treatment thereof by the converter, and to output a signal PRECAT indicative thereof. A downstream oxygen sensor 2 is located in the exhaust pipe in position to sense the oxygen content of the engine exhaust gas after treatment thereof by the converter, and to output a signal POSTCAT indicative thereof.

An engine controller includes a central processing unit CPU, random access memory RAM , read only memory ROM , and non-volatile random access memory NVRAM. The controller processes engine control and diagnostic routines, such as through execution of step-by-step program instructions stored in ROM. The instructions provide for the processing of input signals indicative of the state of engine operating parameters, and for the generation of control commands applied to various generally known engine control actuators.

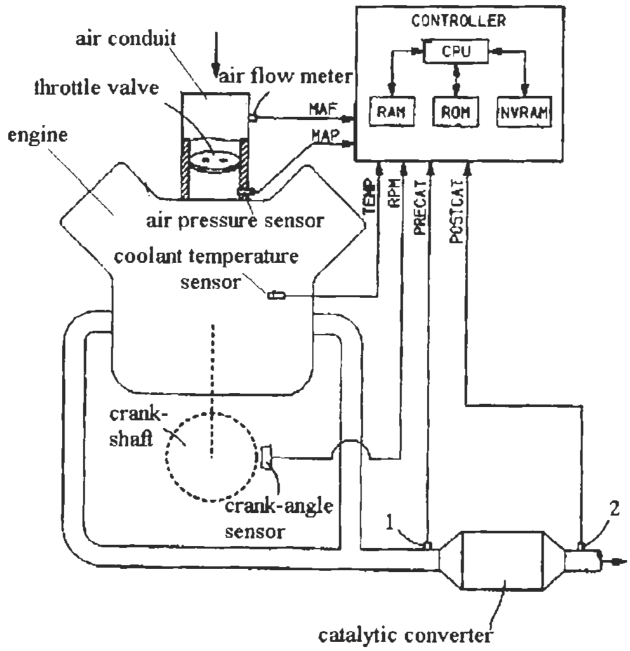


Fig. 92 (from US5431011)

In the method of **US5431011 (1995)** the following steps are considered:

1) periodically generating oxygen content signals by sampling an oxygen content of engine emissions that have passed through the catalytic converter
2) transforming the oxygen content signal into a signal indicating oxygen storage and release capacity of the catalytic converter by
    a) passing the signals through a differentiation process for estimating a rate of magnitude change between oxygen content signals

b) grouping each of the differentiated signals into one of a plurality of test periods
c) determining a maximum differentiation signal for each of the plurality of test periods
d) generating an average signal value as a predetermined function of the determined maximum differentiation signals

3) carrying out a first stage of diagnosis by comparing the average signal value to a predetermined first threshold
4) carrying out a second stage of diagnosis when the average value signal exceeds the predetermined first threshold
5) indicating a faulty catalytic converter upon failure of the second stage of diagnosis

In **DE19651559 (1997)** the deterioration of the catalytic converter is determined by one of the methods described in **US5509267 (1996)** and **US5431011 (1995)**. A difference between actual engine parameters and reference engine parameters provides a measure of the efficiency of the catalytic converter. Such parameters can be the ignition timing, the engine speed at set throttling settings and the heating system of the catalytic converter at cold start-up conditions. The engine is then controlled to take account of the deterioration of the catalytic converter. The temperature of the catalytic converter is estimated by means of detected operating parameters of the engine and it is adjusted to maintain the effectiveness of the catalytic converter.

The method of **EP0799984 (1997)** comprises the following steps:

1) measuring the oxygen content of the exhaust gas upstream and downstream of the catalytic converter by means of an upstream and a downstream oxygen sensor respectively
2) biasing during a monitoring period the air/fuel ratio of fluid passing into the engine from the stoichiometric ratio to a steady rich state while controlling in a closed-loop manner the performance of the engine on the basis of the upstream sensor signal
3) controlling the amount of rich bias in a manner as to avoid saturation of the sensors
4) generating lean transitions from the fuel rich condition
5) changing the duration of the lean excursions
6) determining the duration in which the signal of the downstream sensor is beyond a threshold
7) determining the oxygen ion storage capacity of the converter from the upstream and downstream sensor signals
8) determining the deterioration of the catalytic converter by evaluating the output signals of the upstream and downstream sensors

The method can be better explained by means of fig. 93. Fig. 93a shows the response of the upstream sensor to rich bias with long lean excursions. Low oxygen ion content exists in the exhaust gas and both sensors produce a low oxygen output signal. A lean excursion will increase the oxygen ion content in the exhaust gas, which will be immediately sensed by the upstream sensor. The same will not normally apply to the downstream oxygen sensor since the catalytic converter will absorb some or all of the excess oxygen ions, depending upon the oxygen capacity of the converter and the duration of the lean excursions.

Fig. 93b shows the response of the upstream sensor to a rich bias with short excursions. The troughs in the figure are much narrower than with long excursions since there will be less time during which there is an excess of oxygen ions in the exhaust gas. This will in turn lead to narrower troughs in the downstream sensor signal, so long as there is still breakthrough of oxygen ions. Short excursions are preferred in this embodiment to reduce or eliminate noticeable changes in engine performance.

Fig. 93c shows the response of the output signal of the downstream oxygen sensor for the case of an efficient catalytic converter. The signal is uneven compared to the upstream sensor signal, caused by oxygen ion absorption by the catalytic converter, and is also delayed relative to the upstream sensor signal.

Fig. 93d shows the response of the output signal of the downstream oxygen sensor for the case of a deteriorated catalytic converter. The signal is similar to the one of the upstream sensor (fig. 93b) and is little delayed relative thereto. This is a result of low oxygen ion absorption by the converter.

The time during which the downstream oxygen sensor passes through a threshold signal level is detected. This time, when compared to the equivalent time for the upstream sensor is directly related to the oxygen storage capacity of the converter.

The method is substantially unrelated to sensor response times, which can vary to give inaccurate results.

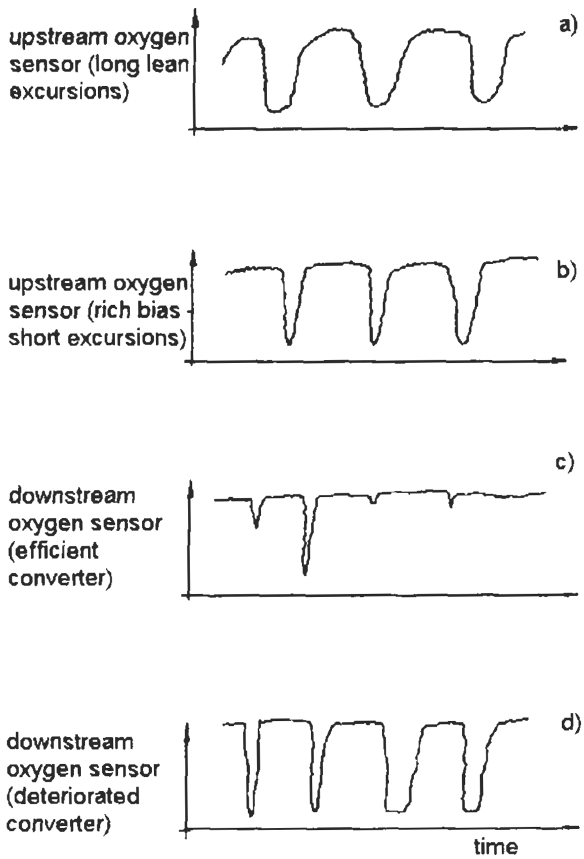


Fig. 93 (from EP0799984)

Plurality of catalytic converters arranged in series in the exhaust pipe

The method of **US5509267 (1996)** refers to the monitoring of two catalytic converters mounted in series in an exhaust pipe like the one of fig. 72. Three sensors are also used as in method of fig. 72. The method comprises the following steps:

1) sensing the oxygen content of the exhaust gas between the engine and the upstream converter by means of a first oxygen sensor
2) sensing the oxygen content of the exhaust gas between the upstream and the downstream converter by means of a second oxygen sensor
3) sensing the oxygen content of the exhaust downstream of the downstream converter by means of a third oxygen sensor
4) during non-diagnostic periods, sensing a first untreated oxygen content of the exhaust gas before this gas has been treated in one of the two converters by means of the first oxygen sensor
5) during a diagnostic period, sensing a second treated oxygen content of the exhaust gas after the gas has been treated by the upstream catalytic converter by means of the second oxygen sensor
6) during a diagnostic period, sensing a third treated oxygen content of the exhaust gas after the gas has been treated by the downstream catalytic converter by means of the third oxygen sensor
7) controlling engine air/fuel ratio in response to the second oxygen content during the diagnostic period
8) controlling engine air/fuel ratio in response to the first oxygen content during the non-diagnostic periods
9) determining the condition of the upstream catalytic converter by
    a) comparing an estimated oxygen storage capacity of the converter (as predetermined function of the sensed second treated oxygen content) with predetermined threshold or
    b) comparing the frequency variation of the sensed second oxygen content with a predetermined threshold
10) determining the condition of the downstream catalytic converter by
    a) comparing an estimated oxygen storage capacity of the converter (as predetermined function of the sensed third treated oxygen content) with predetermined threshold or
    b) comparing the amplitude of the sensed third oxygen content with a predetermined threshold

Chapter 1.15

Fuji Heavy Industries Ltd.

The method of **JP3281960 (1991)** diagnoses the deterioration of a catalytic converter in a state that an air/fuel ratio is stabilized. This is achieved by setting a delaying of the execution of the diagnosis when engine operating conditions are judged to be in a predetermined range for diagnosing the condition of the converter. The assessment of the condition of the converter is realized by comparing the signals of the upstream and the downstream sensor.

In the detection method of **US5337556 (1994)** the following steps are considered:

1) establishing certain engine operating conditions
2) detecting a first air/fuel ratio variation upstream of the catalytic converter by means of the upstream sensor
3) detecting a second air/fuel ratio variation downstream of the catalytic converter by means of the downstream sensor
4) setting a first upper and a lower slice level of the upstream air/fuel ratio sensor in accordance with each engine operating condition. Upper (lower) slice level is a predefined value being lower (higher) than the maximum (minimum) value of the sensor output signal for each operating condition and it always cuts the sensor output signal during deterioration detection
5) producing a first number signal from the number of intersections of the output of the upstream air/fuel ration sensor with the first slice levels
6) setting a second upper and a lower slice level of the downstream air/fuel ratio sensor in accordance with each engine operating condition
7) producing a second number signal from the number of intersections (cuts) of the output of the downstream air/fuel ratio sensor with the second slice levels

8) judging a deterioration of the catalytic converter by calculating a ratio between both number signals. The advantage is that a misjudgment of the deterioration is avoided by eliminating an amplitude output disturbance from the downstream air/fuel ratio sensor due to a fluctuation of the engine operating conditions

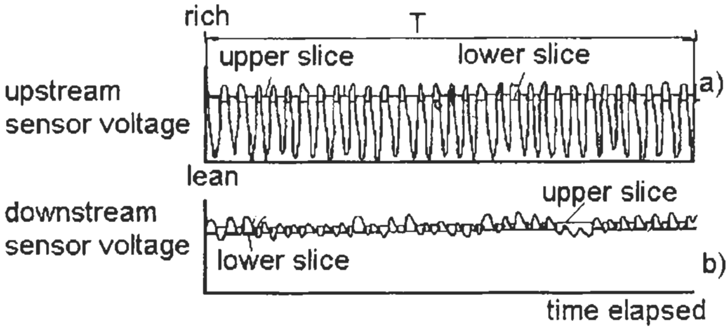


Fig. 94 (from US5337556)

Fig. 94 shows the case of a deteriorated catalytic converter. Figs. 94a and b show the variations of the upstream and downstream sensor output voltages during testing time T. The first and second upper and lower slice levels are also indicated on the same figures. As indicated above these slice levels depend on the operating conditions of the engine. The number of times that the downstream sensor output is cut by the second upper and lower slice levels is compared to the number of times that the upstream sensor output is cut by the first upper and lower slice levels. In this case the ratio is high indicating a deteriorated catalytic converter. low indicating an efficient catalytic converter.
In the case of fig. 95 this ratio is very low indicating an efficient converter.

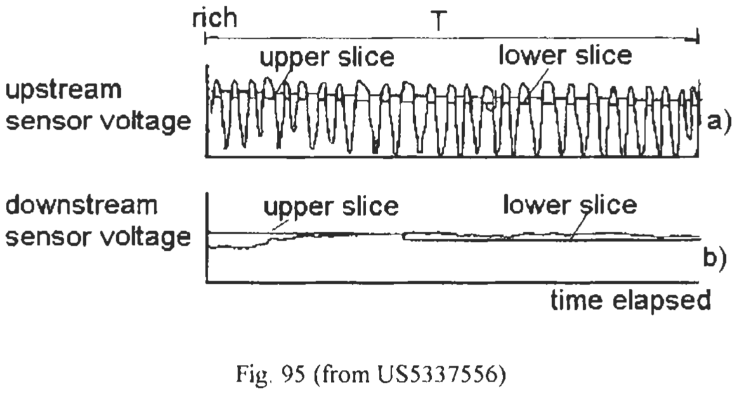


Fig. 95 (from US5337556)

Chapter 1.16

Other Methods

The testing layout used in all methods of this chapter is similar to the one of fig. 12.

- ***Lucas Industries Public Ltd Co.***

In the method of **EP0444783 (1991)** the following steps are considered:

1) feedback controlling the engine air/fuel ratio in response to the output signal of the upstream oxygen sensor
2) measuring the amplitude of the output signal variation of the downstream sensor
3) repeating step 2 for a plurality of times and measuring the corresponding plurality of amplitudes
4) averaging the plurality of amplitude values
5) comparing the averaged value to a threshold and signaling an unacceptable catalytic converter if the averaged value exceeds the threshold

Steps 2 to 4 can be repeated for each engine speed of a plurality of selected engine speeds and to compare each averaged value with a respective threshold in order to draw conclusions about the efficiency of the catalytic converter.

The method of **EP0636771 (1995)** comprises the following steps:

1) perturbing the oxygen concentration of the exhaust gas entering the catalytic converter such that the concentration repeatedly alternates between a rich and a lean value
2) counting the number of transitions of the gas leaving the catalytic converter in response to a predetermined number of transitions of the gas entering the catalytic converter and if a faulty catalytic converter is indicated then
3) integrating the oxygen concentration of gas leaving the catalytic converter while the oxygen concentration of gas entering the catalytic converter is less than a first predetermined oxygen concentration
4) repeating the previous step for a predetermined number of transitions of the oxygen concentration of the gas leaving the catalytic converter
5) summing the integrals $\Sigma(\Delta\lambda)_i$ calculated at steps 3 and 4 to form a first sum
6) correcting the first sum for engine load and for gas flow entering the catalytic converter so as to form a corrected value
7) subtracting the corrected value from a first predetermined threshold ε_1 to form a first difference
8) repeating steps 3 to 7 a predetermined number of times and forming a second sum of the first differences
9) comparing the second sum with a second predetermined threshold ε_2 and
10) indicating the catalytic converter to be faulty when the second sum exceeds the second predetermined threshold ε_2

- ***Magneti Marelli S.p.A.***

The method of **EP0715063 (1996)** comprises the following steps:
1) detecting the output signals of the λ sensors installed upstream and downstream of the catalytic converter
2) performing a high-pass filtering of the signals
3) calculating signal time averages ($\overline{V_1}$, $\overline{V_2}$) by means of an integration operation and a subsequent division for the duration of an integration window of the filtered output signals
4) multiplying the time averages by scaling factors (F_1, F_2) indicative of the excursions of the output signals
5) calculating a difference between the time averages multiplied by the scaling factors so as to generate a deviation signal AZ between the time averages

$$AZ = \frac{\overline{V_1} \cdot F_1 - \overline{V_2} \cdot F_2}{\overline{V_1} \cdot F_1}$$

6) calculating, starting from the deviation signal AZ, an output signal indicative of the efficiency of the catalytic converter

• *Pierburg GmbH & Co. KG*

In the method of **GB2177513 (1987)** the following procedure is considered:

1) detecting the oxygen content of the exhaust gases upstream and downstream of the catalytic converter by means of two oxygen sensors
2) increasing the amplitude of the engine air/fuel ratio oscillation around the stoichiometric value, by applying a periodic signal whose frequency is much lower than that of the output signal of the upstream sensor when this is functioning in normal operation. The periodic signal can be an externally generated one or an electronically filtered signal of the upstream sensor or the output signal of the downstream sensor
3) checking the amplitude of the output signal of the downstream sensor
4) judging that the catalytic converter is deteriorated when the detected amplitude of the signal of the downstream sensor becomes higher than a predetermined threshold.

• *Bayerische Motoren Werke AG*

In the method of **DE3830515 (1990)** the following steps are considered:

1) establishing stable operating conditions of the engine
2) detecting the oxygen content of the exhaust gases upstream and downstream of the catalytic converter by means of two oxygen sensors
3) calculating averaged values in time for each of the two output signals
4) calculating the difference of the averaged oxygen contents detected from the two sensors
5) calculating the ratio R of this difference to the averaged oxygen content $\bar{V}_{O2}$ detected upstream of the catalytic converter

$$R = \frac{(\bar{V}_{O2})_1 - (\bar{V}_{O2})_2}{(\bar{V}_{O2})_1}$$

6) comparing this ratio R to a predetermined value to draw conclusions about the condition of the catalytic converter

- ***The United States Environmental Protection Agency***

In [20] two general methods are presented for correlating the response differences of the oxygen sensors located upstream and downstream of the catalytic converter. They are the phase difference method and the integrated difference method.
sensors is Two variations of the phase difference method are identified:
1) The average time delay between threshold crossings of the upstream and downstream measured, indicating a general relationship between the average delay time and the efficiency level
2) The ratio of downstream threshold crossings to the upstream crossings is measured

Two variations of the integrated difference method are also identified:
1) the average area difference under the rich swing of the curve between the response of the upstream sensor and the response of the downstream sensor is identified, based on integration over a specified time interval regardless of the number of rich excursions of the sensor output signals
2) the average difference method is determined in a mathematical manner, based on each rich excursion of the sensor output signals

The integrated difference method appears to be better suited for on-board diagnostics and provides better correlation to efficiency with less data scatter than the phase difference method.

In the method of **US5228335 (1993)** the following steps are considered:
1) detecting the oxygen content of the exhaust gases upstream and downstream of the catalytic converter by means of two oxygen sensors
2) determining the upper and lower limit of the upstream oxygen output signal during a specified time interval, calculating the difference between the upper and lower limits, normalizing the difference between the upper and lower limits and calculating a specified percentage of the normalized difference to thereby establish a floating lower integration bound
3) determining the upper and lower limit of the downstream oxygen output signal during a specified time interval, calculating the difference between the upper and lower limits, normalizing the difference between the upper and lower limits and calculating a specified percentage of the normalized difference to thereby establish a floating lower integration bound
4) integrating the area between the oxygen content output signal and an established lower integration bound for a specific time interval and for both output signals
5) calculating the integrated area difference between the upstream and downstream output signals
6) comparing the integrated area difference with an established area value and in response thereto determining and indicating a level of catalytic converter deterioration

In figs. 96a,b the calculated areas are presented for both the upstream and downstream sensor output signals respectively. The areas are calculated by using any integration method between the output signals and some floating lower bounds, which are calculated as half the difference between the maximum and minimum sensor output voltages over the measuring interval. The advantage to the floating lower bounds is in the accommodation of changes in sensor output due to:

a) variations in real world vehicle operation
b) aging of sensors and
c) due to extended rich air/fuel ratio oscillations.

The method also eliminates areas which are outside a predetermined range of area values.

The method described above is investigated in great detail in [21].

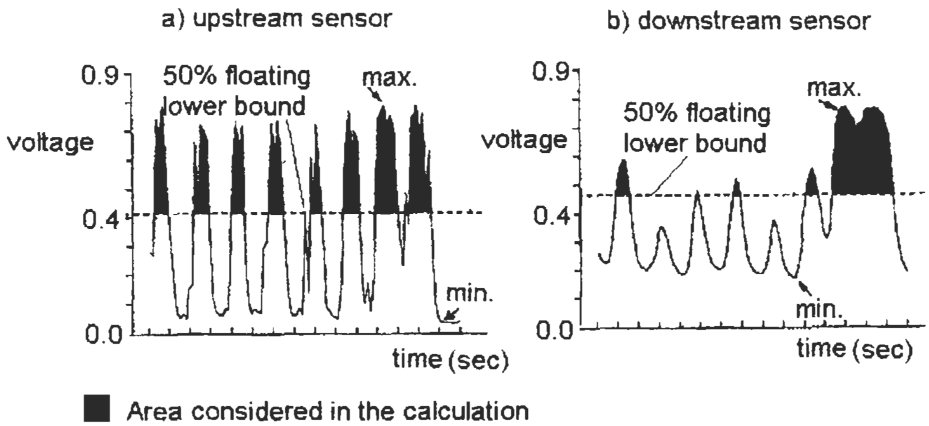


Fig. 96 (from US5228335)

- ***Weegen, Rainer***

In the method of **DE4219219 (1993)** a storage device is provided, which stores the output signals of the downstream sensor. The device excludes data received during the starting phase of the engine. Depending on the values stored, an indication signal is produced warning the driver about the malfunctioning of the catalytic converter. The data can also be handled in a garage by a specialized person in order to decide whether or not the catalytic converter must be replaced.

- ***FIAT Auto S.p.A.***

In the method of **EP0588123 (1994)** and **US5627757 (1997)** the following steps are comprised:

1) detecting the air/fuel ratio content of the exhaust gases upstream and downstream of the catalytic converter by means of two lambda sensors
2) calculating the moving average of each of the two signals V_1, V_2. The variable moving average $\overline{V}$ of a signal V is obtained from three successive values of the variable measured at the points, or at the moments k-2, k-1 and k:

$$\overline{V} = \frac{V_{k-2} + V_{k-1} + V_k}{3}$$

where $k = [2 - \infty]$

3) calculating the differences D_1, D_2 between the instantaneous values of the sensor output signals and the values of the moving averages

$$D_1 = V_1 - \overline{V}_1 \qquad\qquad D_2 = V_2 - \overline{V}_2$$

4) generating signals $f(D)$ relating to the difference between the instantaneous values and the moving averages. These signals $f(D)$ are generated by squaring and integrating the differences D and by calculating their mean quadratic deviations for the period in question
5) calculating an output signal AV indicative of the efficiency of the catalytic converter on the basis of the difference signals or signals derived therefrom. This signal can be one of the ratio and the difference between the difference signals or signals derived therefrom

$$AV = \frac{f(D_1)}{f(D_2)} \qquad \text{or} \qquad AV = f(D_1) - f(D_2)$$

- ***Volkswagen AG***

In the method of **DE4331153 (1994)** the significant variations of the amplitudes and/or the air/fuel ratio oscillation frequencies and/or the oscillation positions (phase shift) of the upstream and downstream lambda sensors consist the criteria of evaluation of a degraded catalytic converter. The evaluation takes place at partial load of the engine.

- ***Roth-Technik GmbH & Co. Forschung für Automobil- und Umwelttechniek***

In the method of **WO9516109 (1995)** the partial oxygen pressure is measured upstream and downstream of the catalytic converter by means of two lambda probes. The difference of the measured oxygen partial pressures gives an indication of the condition of the catalytic converter.

- ***Unisia Jecs Corp.***

In **JP7109918 (1995)** the diagnosis of the efficiency of the catalytic converter is based on the deviation of the output value of the downstream oxygen sensor from a reference value for a desired air/fuel ratio in the feedback control.

In **JP7189780 (1995)** the diagnosis of the efficiency of the catalytic converter is based on the comparison of the oscillation frequencies of the output signals of the upstream and the downstream sensor. The method also detects a possible defect of the downstream oxygen sensor.

In the method of **US5533332 (1996)**, the engine air/fuel ratio is feedback controlled by means of the output of the downstream oxygen sensor only, so that the air/fuel ratio approaches a target value. During the feedback control, the phase difference between the output signals of the upstream and downstream oxygen sensors is detected, and the performance of the catalytic converter is judged by means of this phase difference.

In **JP8284649 (1996)** a predetermined diagnostic region is detected, in which the degradation assessment is performed. During feedback control of the engine air/fuel ratio, the ratio of reversals of the output signals of the upstream and downstream sensor is formed for a number of times in this diagnostic region. The mean value of this ratio is then calculated and the deterioration of the catalytic converter is based on the comparison of this mean value to a predetermined threshold.

In **JP8303233 (1996)** a predetermined diagnostic region for assessing the functionality of the catalytic converter is defined, which is based on operation parameters of the engine. During operation of the engine, this region is changed according to the outside air temperature.

In **JP8303234 (1996)** the diagnosis takes place within a predetermined diagnostic region. The engine air/fuel ratio is feedback-controlled by performing weighed averaging of the output signal of the downstream sensor in accordance with an assumed temperature of the catalytic converter. The catalytic converter performance is based on the inversion ratio of the output signals of the upstream and downstream oxygen sensors. The wrong diagnosis of degradation of the catalytic converter is prevented in the case of chattering.

Other methods of Unisia Jecs Corp.: **JP8303235 (1996)**, **JP9033478 (1997)**.

Engines with multiple cylinder groups

In **JP7063045 (1995)** a method to monitor a catalytic converter is presented for an engine with two cylinder banks as the one of fig. 38. The arrangement of the oxygen sensors is similar to the one of fig. 38 except for the fact that the oxygen sensor placed between the junction of the two exhaust branches and the catalytic converter is removed. The air/fuel ratio for each bank of cylinders is feedback-controlled based on the corresponding output of the sensor installed downstream of the corresponding bank. The deterioration of the catalytic converter is based on a comparison of the output signals of the downstream sensor and the upstream sensors. When the output signal of one of the oxygen sensors fluctuates with an amplitude greater than a specified threshold, then the degradation diagnosis is prohibited in order to avoid an erroneous diagnosis.

The method of **JP7238824 (1995)** is applied to the case of a multiple cylinder bank engine with an air/fuel sensor installed in each cylinder bank exhaust pipe upstream of the catalytic converter and an air/fuel sensor installed in the common exhaust pipe section downstream of the catalytic converter. The general layout is this of fig. 56. The degradation of the secondary catalytic converters and the main catalytic converter is evaluated. During the evaluation, one group of cylinders (e.g. the left bank) is feedback-controlled by the left bank upstream oxygen sensor, whereas the air/fuel ratio of the right bank of cylinders is controlled to be fixed at a control value equivalent to a specified target value. The variation of air/fuel ratio detected by the downstream sensor corresponds then to the variations provoked by the feedback control of the left bank of cylinders. The detected output signals of the downstream sensor and the left bank upstream oxygen sensor are then used for the assessment of the secondary catalytic converter installed in the left exhaust branch as well as of the main catalytic converter. The same procedure is repeated for the right bank of cylinders.

The method of **JP8135432 (1996)** is applied in an engine layout with two cylinder banks similar to the one described in the **JP7063045 (1995)** (fig. 38). First it is evaluated which of the two upstream sensors has the fastest response (e.g. the left bank upstream oxygen sensor). The ratio of the number of reversals of the output signal of the upstream sensor with the fastest response and of the number of reversals of the output signal of the downstream sensor is then formed. The deterioration diagnosis of the catalytic converter is carried out by judging whether this ratio is lower than a specific threshold.

- ***FEV Motorentechnik GmbH & Co.***

The method of **DE4019572 (1992)** monitors the functionality of a catalytic converter, engine misfiring and/or variable injection. It uses two sensors placed in the exhaust path. One of the sensors has a catalytic activity. The difference in the outputs of the signals of the two sensors, provoked by the change in temperature when the HC/air mixtures react with the catalyst of one of the sensors, gives an indication of the condition of the converter and the misfiring of the engine. Oxygen sensors can be installed upstream and downstream of the converter.

- ***Hyundai Motor Co.***

The method of **WO9628646 (1996)** comprises the following steps:

1) determining if a certain time of operation of the engine has elapsed, in order to prevent an erroneous judgment
2) setting rich and lean adjusting parameters k_i for an engine air/fuel ratio after the certain time has elapsed
3) calculating virtual oxygen content sensing signals relevant to a predetermined period of time by using the formula:

$$\textit{virtual oxygen content sensing signals} = AM \cdot \sin(f \cdot n) + k_i$$

where,
AM: amplitude of the signals set in accordance with an automobile state,
f: frequency of the signals set in accordance with the automobile state
n: a time variable and

k_t : engine air/fuel ratio rich/lean adjustment parameter

4) judging engine air/fuel ratio rich/lean adjusting parameters, to determine whether the air/fuel ratio is stoihiometric, rich or lean
5) determining that the converter is deteriorated when the actual oxygen content of the exhaust gases downstream of the catalytic converter does not exist within a range of the virtual oxygen content set in accordance with a state of the engine air/fuel ratio (step 3)

The method of **DE19654693 (1997)** comprises the following steps:

1) checking if the engine cooling temperature is higher than a predetermined threshold
2) checking if the temperature of the exhaust gas is higher than a predetermined threshold, and if both conditions of step 1 and 2 are fulfilled then
3) feedback-controlling the engine air/fuel ratio based on the output signal of the upstream oxygen sensor
4) measuring the oxygen content of the exhaust gas upstream and downstream of the catalytic converter by means of the two oxygen sensors
5) calculating a first ratio of the measured output signals of the two sensors during a rich engine air/fuel condition
6) calculating a second ratio of the measured output signals of the two sensors during a lean engine air/fuel condition
7) calculating a first sum of first ratios during a predetermined time period
8) calculating a second sum of second ratios during the predetermined time period
9) comparing the first sum of ratios with a first predetermined reference value
10) comparing the second sum of ratios with a second predetermined reference value
11) determining the condition of the catalytic converter by means of the results of steps 9 to 10

- ***Osaka Gas Co. Ltd.***

In the method of **JP5010181 (1993)**, a catalytic converter is installed in the exhaust system of a methane engine. A first oxygen sensor for methane activation is installed upstream of the converter and a second oxygen sensor for methane activation or methane low activation is installed downstream of the converter. During a degraded state of the converter, for each pair of output signals of the two sensors, an output value of the output signal of the upstream sensor is stored as a deterioration reference value. This reference value is compared to the output signal of the upstream sensor during testing, and the converter is considered as deteriorated when the output signal value is higher than the reference one.

In the method of **JP5018231 (1993)**, a rhodium catalytic converter is installed in the exhaust system of a methane engine. A first oxygen sensor is installed upstream of the converter and a second oxygen sensor is installed downstream of the converter. The deterioration of the rhodium converter is based on the measured delay time of the output signals of the two sensors.

- ***Automobiles Peugeot - Automobiles Citroën***

Engines with multiple cylinder groups

The method of **FR2739139 (1997)** is applied for the layout of fig. 56, where one secondary catalytic converter is installed in each of the left and right cylinder bank exhaust branches. A main catalytic converter is installed in the common pipe section.

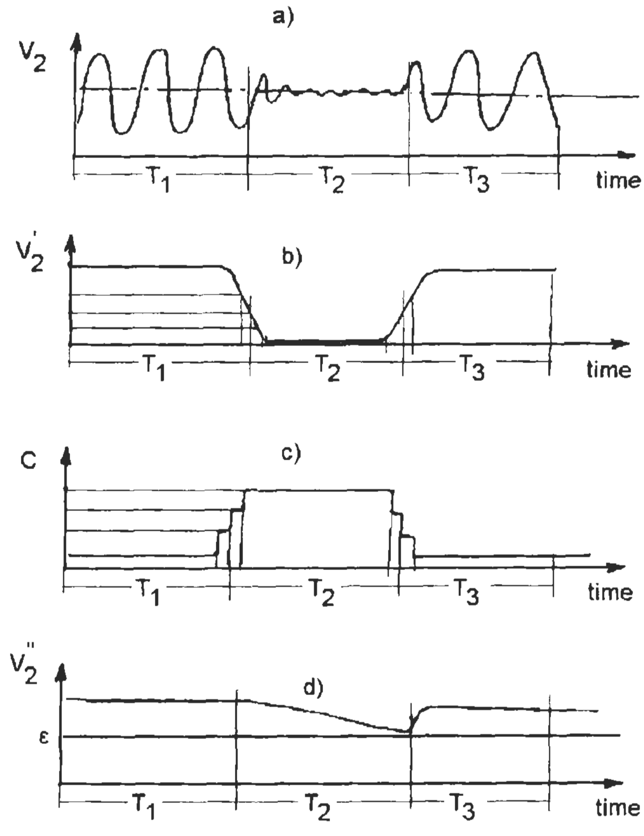


Fig. 97 (from FR2739139)

The method attempts to prevent a false determination of the efficiency of the main catalytic converter due to a phase opposition of the signals from the two banks of cylinders and it can be better explained by means of fig. 97.

Fig. 97a shows the measured variation of oxygen content V_2 in the exhaust gases downstream of the main catalytic converter. In time periods T_1 and T_3 there is a strong amplitude variation of V_2, whereas in time period T_2 the amplitude variation becomes very low due to the opposition in phase of the oxygen content in the exhaust gases of the left and right branch. Signal V_2 is then electrically treated in order to bring its average value to zero. Then the signal is reestablished and filtered to obtain an indicator V_2', which represents a sliding average amplitude of the original signal V_2 (fig. 97b). Signal V_2' is filtered by a low-pass filter with a time constant C which varies in function of the instant value of output signal V_2 or of the signal V_2' (fig. 97c). The time constant C is longer than the output signal V_2 and of a lower amplitude, in order to obtain a final indicator V_2" which decreases more slowly in time than V_2' (fig. 97d). The indicator V_2" is then compared to a predetermined threshold ε. If the indicator V_2" is superior of ε, this means that the amplitude of the output signal V_2 is excessive and the converter does not damp sufficiently the variations of oxygen in the exhaust gases and consequently indicates that the catalytic converter is deteriorated.

- ***Volvo AB***

In the method of **WO9641071 (1996)** each output signal of the upstream and downstream oxygen sensors is used as feedback-control parameter of the engine air/fuel ratio. The resultant signal fluctuations of the two sensors are analyzed to determine the time displacement between fluctuations in each of the two signals. The oxygen buffer capacity is then determined based on said time displacement.

- ***Denso Corp.***

The method of **DE19646008 (1997)** comprises the following steps:

1) calculating an amount of an exhaust gas component upstream of the catalytic converter when the actual air/fuel ratio upstream of the converter differs from the stoichiometric one. When the difference between the actual air/fuel ratio and a predefined upper limit of the air/fuel ratio is positive ($\Delta A/F_L$, fig. 98a) then this difference is integrated in time and the integrated area is called a lean component (fig. 98b). When the difference between the actual air/fuel ratio and a predefined lower limit of the air/fuel ratio is negative ($\Delta A/F_R$, fig.

98a) then this difference is integrated in time and the integrated area is called a rich component (fig. 98b)

2) calculating an amount of an exhaust gas component downstream of the catalytic converter when the corresponding actual air/fuel ratio downstream of the converter differs from the stoichiometric one. A lean and a rich component are defined similarly to these of step 1 and fig. 98
3) determining a time period during which the judgment of the condition of the converter should take place
4) determining a frequency that provokes saturation of the catalytic converter when operating with a lean or rich component during the judgment time period
5) calculating an average value of a maximum amount of the lean or rich component of the exhaust gas absorbed in the catalytic converter by dividing a maximum value, obtained by subtracting a total amount of the lean or rich component downstream of the catalytic converter from a total amount of the lean or rich component upstream of the catalytic converter during the judgment time period, with the saturation frequency of step 4
6) assessing the deterioration of the catalytic converter based on the average value of maximum amount of the lean or rich component that is absorbed by the converter

The patent disclosure also describes methods to assess the deterioration of the upstream and downstream oxygen sensors.

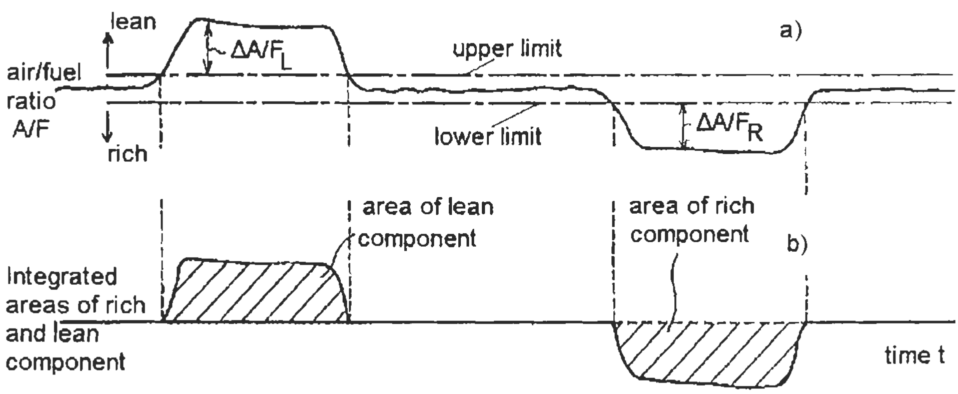


Fig. 98 (from DE19646008)

• *VDO Adolf Schindling AG*

The method of **DE19545693 (1997)** compensates for the uncertainties due to manufacturing tolerances and aging of the λ-probes used and comprises the following steps:

1) determining the oscillation amplitudes of the output signals of the upstream and downstream λ-probes respectively when the engine air/fuel ratio oscillates from lean to rich and back to lean during a testing period
2) calculating the ratio of the oscillation amplitude of the downstream probe to the oscillation amplitude of the upstream sensor
3) determining for each probe, after the probe has been changed, an extreme value of its corresponding output signal. The extreme values for each probe are calculated by continuously forming differences of subsequent discrete samples of the output signal. The extreme value becomes a maximum when the sign of a difference changes from positive to negative and the extreme value becomes a minimum when the sign of a difference changes from negative to positive
4) correcting the calculated ratio of amplitudes of step 2 by means of the extreme values of step 3
5) comparing the corrected calculated ratio value to a predetermined threshold
6) determining that the converter is deteriorated when the corrected calculated ratio is greater than the predetermined threshold

• *Regie Nationale des Usines Renault SA*

The method of **FR2746142 (1997)** comprises the following steps:

1) measuring the rotation speed (N) of the engine and the admission pressure (P) of the engine air/fuel mixture
2) calculating the flow velocity (V) of the exhaust gas in the catalytic converter in function of a model describing the gas flow in the exhaust pipe, the rotational speed (N) of the engine and admission pressure (P)
3) measuring the oxygen content of the exhaust gas upstream (u) and downstream (v) of a catalytic converter by means of an upstream and a downstream oxygen sensor. The values (u, v) are normalized in a way to be negative or positive depending on whether the engine air/fuel ratio is lean or rich
4) determining at every time point (t) the maximum quantity of oxygen (y) that can be stored in the catalytic converter and the quantity of oxygen (x) that is effectively stored in the catalytic converter. (x) and (y) are determined by making use of mathematical models of the chemical reactions taking place inside the catalytic converter. The models take into consideration the kinetics (c_1, c_2) of the reactions, which depend on the concentrations of oxidants (Ox) and reducers (Red) of the chemical species that participate in the reactions

and on the flux of gas that flows through the converter. More specifically the values (Ox, Red) are calculated by making use of the following formulas:

$$if\ v > 0: \quad Ox = v / K \qquad and \quad Red = 0$$

$$if\ v < 0: \quad Ox = 0 \qquad and \quad Red = -v / K'$$

where:
K and K' are characteristic parameters of the downstream oxygen sensor.

The chemical kinetics (c_1, c_2) of the reactions are calculated by making use of the following formulas:

$$c_1 = k_1\ (Ox)^{a1}\ (0.5y - x)^{b1} = C_1\ (x, y, v)$$

$$c_2 = k_2\ (Red)^{a2}\ (0.5y + x)^{b2} = C_2\ (x, y, v)$$

where:
k_1, a_1, b_1 and k_2, a_2, b_2 are the characteristic parameters of the two reactions

5) estimating the concentration (z) of the oxygen downstream of the catalytic converter by writing the low of variation of (z) in time:

$$dz/dt = - V/L\ [z(t) - u(t)] + (K/2e)\ [C_1(x, y, v) - C_2(x, y, v)]$$

where:
L is the length of the catalytic monolith
e is the void fraction of the monolith

6) estimating the quantity of oxygen (x) stored in the converter by means of the formula:

$$dx/dt = C1(x, y, v) - C2\ (x, y, v)$$

7) calculating the value of (y) by taking into account the difference of the measured (v) and calculated value (z) of oxygen content in the exhaust gas. The following formula is used:

$$dy/dt = - G\ f(t)\ [v(t) - z(t)]$$

where:
G is a parameter that allows to determine the convergence speed of the method,
f(t) is a function of the sign of (v). This function can be expressed as:

$f(t) = v(t)$, or

$f(t) = sign\ v(t)$, or

$f(t) = v2(t)\ [sign\ v(t)]$

8) solving the system of the above mentioned equations in an iterative way in order to obtain such values of (x), (y) and (z) that suppress the difference between the calculated (z) and measured concentration of oxygen (v) of the exhaust gas downstream of the catalytic converter
9) determining the condition of the catalytic converter by comparing the maximum quantity of oxygen (y) that can be stored in the catalytic converter calculated at step 8 with a predetermined threshold

The method can be also used with catalytic converters that store nitrogen oxides instead of oxygen.

- ***Deutsche Fernsprecher GmbH Marburg***

The method of **DE3811732 (1989)** presents an electric circuit used for functionally testing catalytic converters of motor vehicles. The circuit comprises a controllable switch for applying normal λ probe voltage or test voltage to a λ probe installed upstream of the catalytic converter.

- ***Other Methods***

Other methods of monitoring catalytic converters by means of oxygen sensors may be found in the following disclosures:

RU2059080 (1996) by **Elkar Stock Co.** and in [32].

PART TWO

CATALYTIC CONVERTER FUNCTIONALITY DIAGNOSIS BY MEANS OF TEMPERATURE MEASUREMENTS

Chapter 2

Catalytic Converter Functionality Diagnosis by Means of Temperature Measurements

This chapter comprises methods of diagnosing degradation of the functionality of catalytic converters by measuring the temperature of the exhaust gases. The measurement can be direct by making use of one or more temperature sensors placed upstream, downstream or inside the catalytic converter or the measurement can be indirect by estimating the temperature from other engine parameters. The methods are based on the useful information received from the heat release caused by exothermal reactions in the catalytic converter, which is an indication of catalyst light-off.

In the case of an efficient catalytic converter, the chemical reactions taking place within the catalytic converter generate heat so that the temperature of exhaust gases leaving the converter should be greater than the temperature of exhaust gases entering the converter. The temperature difference between inlet and outlet of the catalytic converter becomes then an important criterion for diagnosing the functionality of the catalytic converter.

The deterioration of a catalytic converter usually occurs at the front face of the converter (reaction zone). This aging reduces the temperature gradient from the front face of the converter and undesirably increases the inlet temperature needed for maximum conversion efficiency. Heating systems raise the temperature of an aged catalytic converter to reduce this deterioration in emission conversion (see [22]).

The diagnosis of catalytic converters by measuring the temperature of the exhaust gases becomes very important nowadays. In [22], temperature sensors are used to verify catalytic converter efficiency diagnosis evaluated by means of the dual-oxygen sensor technique. The results have shown that dual oxygen-sensor measurements for catalytic converter efficiency become questionable with introduction of ULEV standards.

In **WO9420738 (1994)** it is claimed that it is difficult to produce a signal qualitatively representative of the efficiency of a catalytic converter based on the output signals of an upstream and a downstream air/fuel sensor and this presents the vehicle manufacturer with a serious dilemma. If a high efficiency threshold is set, then the driver will be frequently given false warnings of failure of the catalytic converter and apart from the nuisance to the driver this could result in the warning signals being totally disregarded when the alarm is genuine. On the other hand, if a low threshold is set and the vehicle should fail to comply with the legislative requirements then the manufacturer could face serious financial penalties. For these reasons, it is proposed to use temperature measurement techniques to assess the functionality of a catalytic converter.

Temperature sensors used in monitoring of catalytic converters

Before examining in detail the diagnosing methods that use temperature sensors, it is worthwhile to describe some temperature sensors and to explain their operation principle.

The use of a simple thermocouple a few centimeters upstream of the converter inlet presents durability and signal processing problems, as the thermocouple voltage is too low for a typical vehicle data acquisition system. As mentioned already, the aging reduces the temperature gradient from the front face of the converter and causes a shift of the main reaction zone in the direction of the flow, so that different temperature profiles are expected during the course of aging. Thus, a single temperature measurement in a fixed position would probably not be sufficient to monitor exothermal heat release over a long operating period. So more sophisticated temperature sensors are necessary for monitoring the efficiency of catalytic converters.

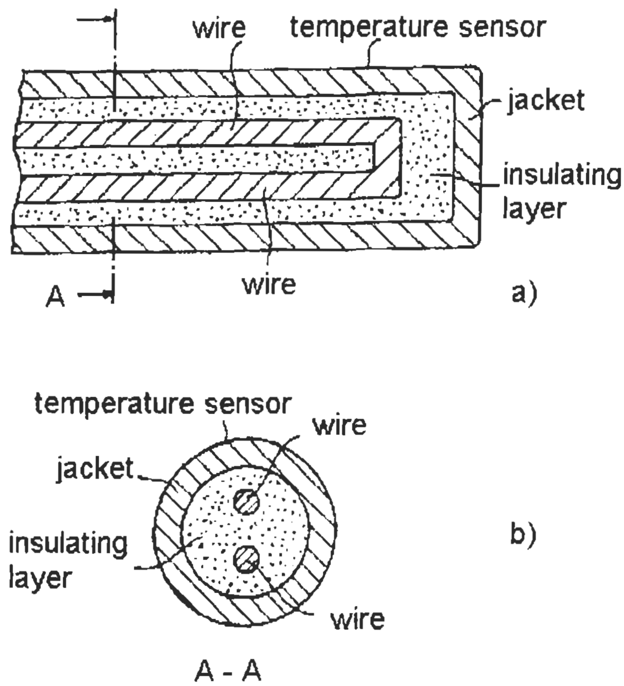


Fig. 99 (from WO9114855)

Fig. 99 shows such a temperature sensor presented by Emitec Gesellschaft in **WO9114855 (1991)**. The sensor is introduced between the metallic sheets of the converter. For purposes of illustration, fig. 99a shows a longitudinal section through the end of the temperature sensor, and fig. 99b shows a cross section taken along the line A-A of fig. 99a. The temperature sensor has a jacket, which may, for instance, be formed of "INCONEL" or some other high-temperature-proof steel with chromium and/or aluminum components. Depending on existing requirements, the jacket may also be formed of the same material as the metal sheets of the catalytic converter, which makes for a problem-free soldering together of the temperature sensor and the metal sheets or the jacket. A wire is installed in the shape of a U in the interior of the temperature sensor. The wire may, for instance, be formed of nickel or another material that has a resistance which is strongly dependent on temperature. An insulating layer, for instance of magnesium oxide powder, prevents contact of the two lines of the resistor wire, both with one another and with the jacket .

In reference [24] it has been proposed to install a linear temperature sensor diagonally in the catalyst bed (fig. 100). A linear sensor made by high temperature thermistor material can detect over-temperature conditions anywhere along its length, by indicating a temperature that is much more dependent on the maximum temperatures encountered over its length than on the lower ones. This ability is attributed to the dependency of its specific conductance k on temperature, according to the following relation (see [1]):

$$k = C_1 \cdot \exp(-\frac{C_2}{T}) \qquad \text{(in Siemens/meter or else S/m)}$$

where:
C_1, C_2 are sensor specific constants and
T is the absolute temperature.

The use of a sensor that is up to five times longer than the reaction zone of the converter results in a measured temperature that approximates the real maximum temperature with sufficient accuracy. The processed sensor signals of the above mentioned sensors indicate whether exothermal reactions, mainly CO and HC oxidation, take place in the catalytic converter or not.

In [22] different temperature sensors are described and compared to each other to evaluate their capability of diagnosing the deterioration of catalytic converters for on-board diagnosis of LEV/ULEV systems. Thermocouples, thermistors and resistive temperature detectors (RTDs) are used in the comparison. Different materials are discussed and verified.

However, problems can arise in the diagnosis of a converter by means of temperature measurements, because the measured temperature difference can fall, and even become negative, for an efficient converter during certain operating conditions of an internal combustion engine (see **EP0442648 (1991)**).

For instance, when a throttle controlling the admission of a combustible mixture to the engine is opened, the temperature of exhaust gas entering the converter can rise dramatically but, because of thermal lags, the temperature of exhaust gas leaving the converter rises more slowly. This can result in an indication of incorrect operation of a converter which is actually operating efficiently.

Similar problems can occur during other modes of operation of the engine giving rise to spurious or transient temperature differences which are detected as indicating inefficient operation of the converter.

An additional problem for detecting correctly the efficiency of an exhaust gas catalytic converter is a possible deterioration of a temperature sensor. The output of such a deteriorated sensor must be corrected during the diagnosis procedure in order to avoid erroneous results.

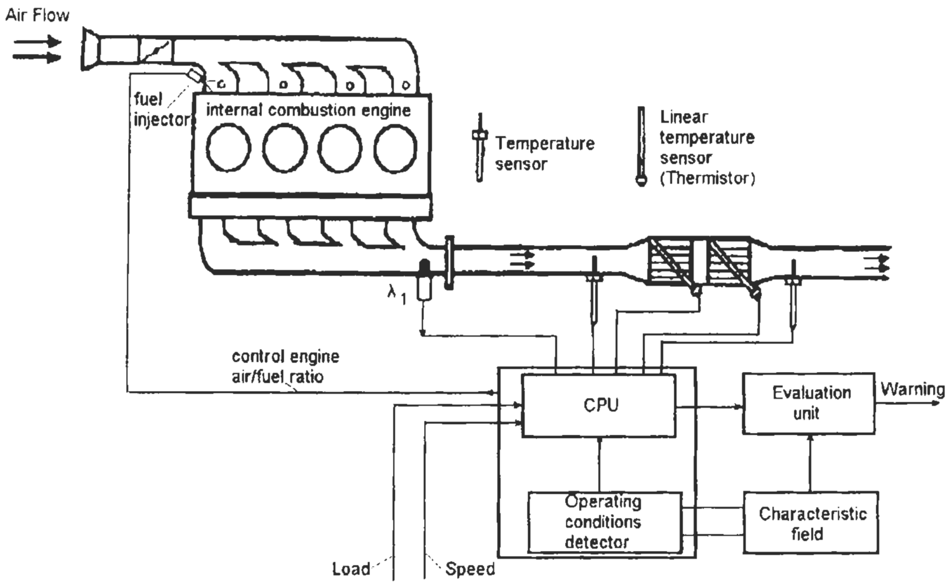


Fig. 100 (from [1] p. 174)

As already discussed in the Introduction of this monograph, it is common nowadays to use catalytic converters in exhaust systems that are heated during start-up of the engine in order to activate them as fast as possible. A failure of the heating system of such converters might take place (e.g. due to corrosion of the lead wires of an electric heater) and contributes to the complexity of detecting deterioration of a heated converter. So, more sophisticated methods than just measuring the temperature difference between the two sensors are necessary to assess the functionality of a catalytic converter.

In the methods of the 70's, simple temperature sensors are used to monitor deterioration of the catalytic converter. The signals are fed to simple instrumentation that can calculate the difference in temperature between inlet and outlet and produce a warning signal when this difference exceeds certain ranges.

In most modern OBD methods a control unit (computer) is used to assess the functionality of the catalytic converter. The control unit receives the output signal(s) of the temperature sensor(s) plus information concerning the operation conditions of the engine e.g. engine load, cooling water temperature, intake air flow etc. The control unit processes all the input and produces a warning signal in case a degraded catalytic converter is detected (fig. 100). The control unit may comprise calculation means, integrators, comparators, storage means etc. Signal filtering means, A/D converters and other necessary equipment may be included in the monitoring system.

For simplicity reasons, the two temperatures sensors mounted upstream and downstream of the catalytic converter will be called from here onwards just upstream and downstream temperature sensor.

In the case of indirect measurement of the temperature of the exhaust gases, the control unit receives different engine parameters and calculates the temperature of the catalytic converter based on this piece of information.

Chapter 2.1

Emitec Gesellschaft für Emissionstechnologie - Dr. Ing. H.c.F. Porsche AG

Most of the methods presented in this chapter are applied to the engine layout of fig. 101.
In fig. 101, there is seen an internal combustion engine (I.C.E.) with an electronic engine control, wherein in the present description the term "engine" always means the engine and all of its peripheral equipment such as ignition, fuel injection and air delivery devices, with the exception of measuring instruments and the engine control. The engine control unit (ECU) receives information from outside through measurement value feed lines, and from the information it ascertains control data, which are supplied to the engine through engine feed lines. Exhaust gases pass in the direction of the arrow, from the engine into an exhaust gas line, in which a lambda sensor λ is disposed. The lambda sensor in turn is connected to the engine control through a measured value line.

A catalytic converter is disposed in the exhaust gas line and is followed by an exhaust outlet line or pipe. The catalytic converter may include one or more individual disks and naturally the exhaust system can also be constructed as a dual or otherwise multiple system. The catalytic converter may also be electrically heated, at least in sub-regions, and may have corresponding electrical leads.

The catalytic converter has temperature sensors, which are connected to an electronic monitoring apparatus by measurement lines . In this way, the temperature of the exhaust gases upstream of the converter as well as the temperature of the walls or structures of the catalytic converter is directly measured downstream of the engine. In principle, the measured temperature values could also be carried from the temperature sensors directly to the engine control, but in the present exemplary embodiment prior processing in the electronic monitoring apparatus is preferred. This electronic monitoring apparatus can ascertain a temperature distribution in the catalytic converter and/or a mean value and/or a maximum value from the measured temperature values and can carry it ovcr a data line to the engine control.

In addition, the electronic monitoring apparatus can also monitor the functional capability of the catalytic converter from the measured data in the catalytic converter and optionally from data from the engine control delivered over data feed or supply lines, and carry the outcome of this monitoring to a display or a memory over a diagnosis line.

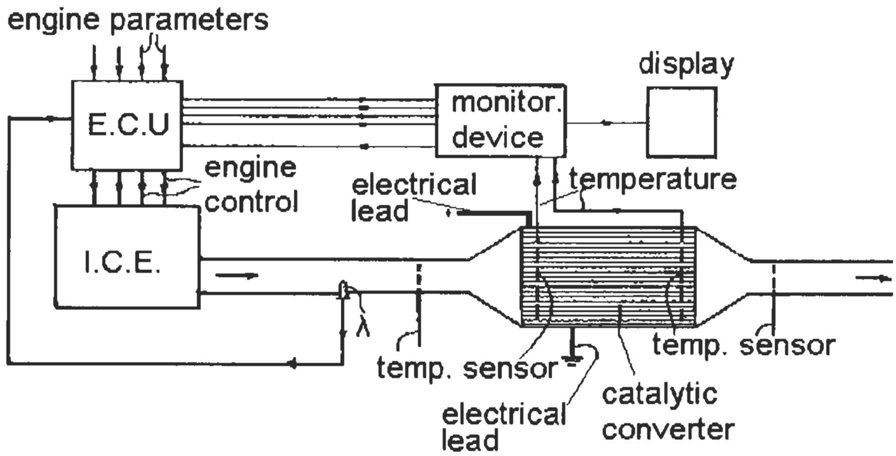


Fig. 101 (from WO9114855)

The method of **WO9114855 (1991)** refers to monitoring of the functionality of an electrically heated metallic catalytic converter of the honeycomb type and comprises the steps of:

1) selecting at least two measurement locations at respective three-dimensionally spaced-apart cross-sectional regions of the exhaust pipe, where at least one of the temperature measurement locations (or even both) is inside the catalytic converter
2) defining at least a partial volume of the catalytic converter of the exhaust system between the measurement locations being definitive for catalytic conversion of pollutants in the exhaust gas, with at least 50% of the active catalytic converter volume being between the at least two measurement locations

3) measuring and monitoring the temperature of the exhaust gases at the at least two regions by means of planar (fig. 102) and/or approximately linear temperature sensors
4) measuring the temperature at least at one of the measurement locations integrally over an approximately representative portion of at least one cross-sectional region and not in certain spots (fig. 102)
5) performing the monitoring step by forming at least one temperature difference between measured values at the at least two measurement locations
6) detecting a function of the catalytic converter, a control of the engine and a catalytic converter regulating system from at least one of an algebraic sign, an absolute magnitude and a behavior over time of the temperature difference.

The temperature sensors are re-calibrated after the engine has been stopped for a relatively long period of time.

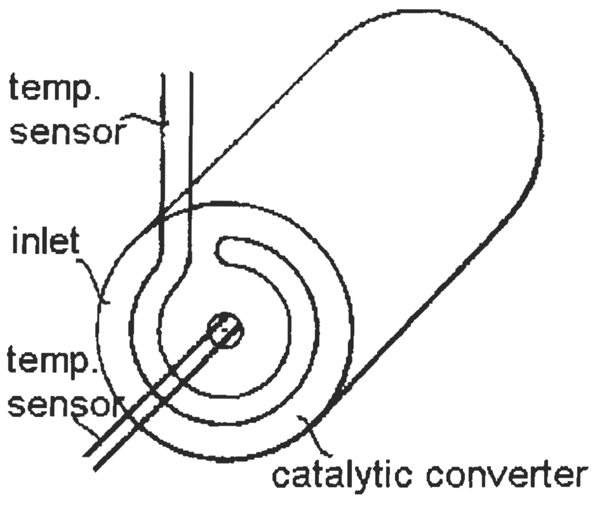


Fig. 102 (from DE4027207)

The method of **WO9114856 (1991)** for monitoring the efficiency of a catalytic converter is similar to that of **WO9114855 (1991)** described above. The method uses additionally the temperature difference indication of the sensors measured in the catalytic converter to control the function of the engine and to protect the catalytic converter from overheating.

In patent application **DE4027207 (1992)** two methods are presented. The first one, also described in **US5339628 (1995)**, comprises the following steps:

1) measuring the temperature at least at two locations by temperature measuring sensors of which at least one is disposed in the catalytic converter and which sensors are spaced apart in flow direction
2) periodically repeatedly determining a temperature measuring variable from signals issued by the sensors during operation of the engine with an engine monitoring system
3) averaging the temperature measuring variable over a sufficiently long period of engine operation to form a mean temperature value which is substantially unaffected by short-term load conditions e.g. forming mean temperature by integrating the temperature measuring variable over an observation period or by executing the following process:
    a) observing the temperature measuring variable over a given period of time
    b) periodically determining the temperature measuring variable at time intervals being substantially shorter than the given observation period and recording the temperature measuring variable in a memory of a multiple channel analyzer belonging to the engine monitoring system
    c) forming the mean temperature value from the contents of the memory, after the observation period has elapsed
    d) erasing the memory
4) comparing the mean temperature value with a predetermined limit value
5) indicating if a mean temperature value does not correspond to the limit value and ascertaining a catalytic activity of the catalytic converter.

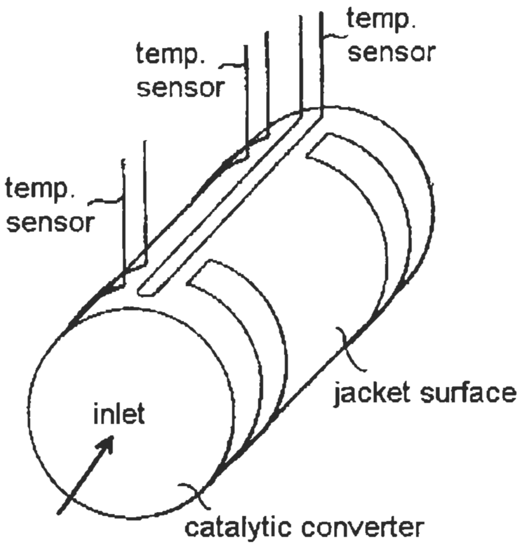


Fig. 103 (from DE4027207)

The temperature sensors can have the form of fig. 102 or can be mounted on a jacket surface of the catalytic converter (fig. 103). This version is advantageous because it does not require any alterations in the interior of the catalytic converter.

Fig. 104a shows the temperature variation of the exhaust gases in the interior of the catalytic converter from the inlet end to the outlet end of the catalytic converter when the configuration of fig. 102 is used. The solid line corresponds to a new catalytic converter, where the broken line corresponds to a degraded one. The temperature of the exhaust gases flowing in the catalytic converter is higher than a predetermined value in order to activate the catalytic converter. For a new catalytic converter the maximum temperature of the exhaust gases is attained immediately downstream of the inlet of the catalytic converter and it remains constant as far as the outlet end.

For the case of a degraded catalytic converter, the temperature rises slowly from the inlet end onwards and it is only at the outlet end of the catalytic converter that a pronounced temperature occurs. This is because there is still catalytic activity there. For the case of a new catalytic converter, the two sensors should measure almost the same temperature. The temperature difference is a measure of aging of the catalytic converter.

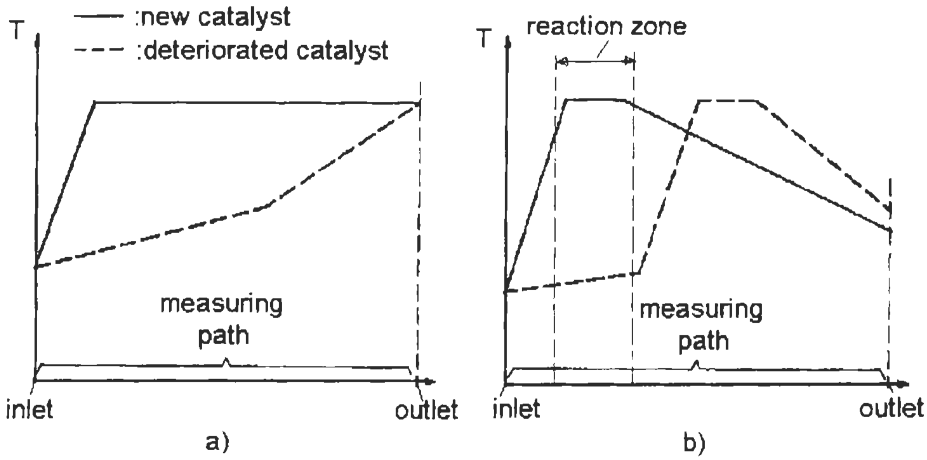


Fig. 104 (from DE4027207)

Fig. 104b shows the temperature variation of the exhaust gases on the external surface of the catalytic converter from the inlet end to the outlet end of the catalytic converter when the configuration of fig. 103 is used. An essential feature is that after reaching its maximum, the temperature does not remain substantially constant. Instead, it decreases again downstream of the zone of the catalytic converter in which the catalytic reaction primarily occurs (reaction zone). Downstream of this zone there is no catalytic activity on the jacket anymore and the temperature drops. As the catalytic converter deteriorates the region of high temperature moves towards the outlet end of the catalytic converter (broken line).

The second method of **DE4027207(1992),** also described in **US5428956 (1995)** comprises the following steps:

1) measuring a temperature at least at two temperature measuring locations associated to the catalytic converter by means of two sensors. A deviation over time of at least one of the temperature sensor signals is formed and the measurement is inhibited if the deviation over time differs substantially from zero
2) periodically repeatedly determining a temperature measuring variable from signals issued by the sensors during operation of the engine with an engine monitoring system. The temperature measuring variable is defined
    I) as a difference between the temperatures measured by the two temperature measuring sensors or
    II) by monitoring the signal of a first one of the temperature measuring sensors for discontinuous changes i.e. changes from a first steady operating state of the engine to a second steady operating time within a brief time. If such a discontinuous change occurs, then observing the signal of a second one of the temperature measuring sensors over a short period of time (1-3 seconds), and finally forming the temperature measuring variable from the changes over time of the signal of the second temperature measuring sensor
3) determining further measuring variables characterizing an applicable operating state of the engine. Variables of this kind include engine speed, exhaust gas temperature, exhaust gas pressure etc.
4) determining a temperature limit value from the further measuring variables and from at least one temperature measuring variable ascertained in an earlier measurement. The activity of the catalytic converter is recorded and it is taken into account for the applicable determination of the temperature limit value, over a period of time sufficiently long for averaging out special strains in each case
5) determining catalytic activity by comparing the temperature measuring variable with the temperature limit value
6) issuing a report if the temperature measuring variable is lower than the temperature limit value

The judgment of the catalytic activity of the catalytic converter in the method of **WO9203643 (1992)** is executed as follows:

1) measuring the temperature of the catalytic converter honeycomb body at a plurality of measurement points along the flow direction
2) performing each temperature measurement continuously during a time interval

3) forming a mean temperature value over the time interval from the temperature measured at the plurality of measurement points
4) measuring the temperature of the catalytic converter honeycomb body over the time interval at least at one measurement point forming an associated local temperature value. The measurement can take place in a thin segment of said catalytic converter extending perpendicular to the flow direction
5) monitoring the variations of the mean temperature value and the local temperature value over time
6) deriving the indication as to the function of the catalytic converter only if the variations over time of the mean temperature value and the local temperature value are below a predetermined limit value
7) comparing the mean temperature value with the local temperature value for deriving an indication as to the status of the catalytic converter

The temperature sensors are installed in a way similar to the one shown in fig. 103.

The method of **DE4038829 (1992)** is applied for a catalytic converter comprising: a) an inner region, a jacket surface surrounding the inner region and being disposed approximately parallel to the exhaust gas flow direction; b) the inner region conducting the exhaust gas flow through the inner region in the given flow direction; and c) a reaction zone being defined as a part of the inner region in which the catalyzed exothermic reaction predominantly takes place.

The method comprises the following steps:

1) measuring a distribution of temperature over the jacket surface along a measurement path being aligned approximately parallel to the given flow direction. The measurement of temperature can take place with one of the following ways (fig. 105):
   a) by evaluating heat radiation originating at the jacket surface by imaging the heat radiation originating at the jacket surface by means of an electronic image processing device and a photographic device such that the temperature distribution along the measurement path is displayed on an image obtained in the imaging step, or
   b) by means of a temperature sensor being located on and movable along the measurement path, or
   c) by means of a plurality of temperature sensors being disposed along the measurement path
2) defining a limit value of a temperature deviation
3) determining the reaction zone by locating a segment of the measurement path at which the temperature deviates by less than the limit value from a maximum value of the temperature along the measurement path. This can be achieved by
   a) covering the measurement path with a substrate having a color changing under the influence of heat and detecting the reaction zone by evaluating the color of the substrate (fig. 105), or
   b) comparing the measured distribution of the temperature with a multiplicity of predetermined standard distributions, for each of which the reaction zone is known and determining the reaction zone by

interpolation for the measured distribution of the temperature (see fig. 104b), or

c) locating a maximum temperature along the measurement path and defining a maximum temperature location; determining an interval along the measurement path around the maximum temperature location within which the temperature deviates by less than a predetermined limit value from the maximum value at the maximum temperature location, and defining a boundary of the reaction zone

4) determining the degree of degradation of a catalytic converter by using the location of the reaction zone with respect to the measurement path as a measure of the degree of degradation.

As shown in fig. 104 and fig. 105, the more downstream of the inlet end of the catalytic converter the reaction zone appears the more degraded the catalytic converter is.

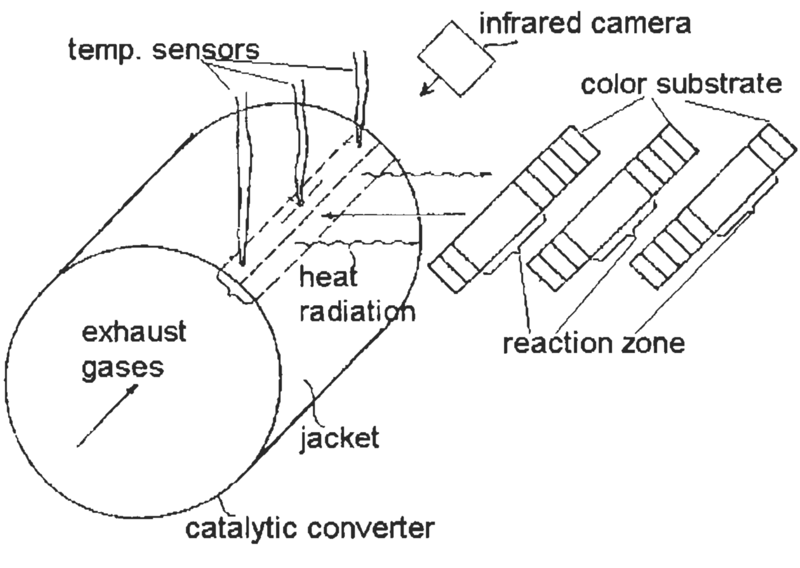


Fig. 105 (from DE4038829)

The method of **WO9314305 (1993)** refers to the monitoring the condition of an auxiliary (light-off) catalytic converter installed upstream of a main catalytic converter (fig. 106) and comprises the steps of:

1) measuring the temperature of the exhaust gases in a number of positions along the auxiliary catalytic converter
2) evaluating the measured temperature values and/or their variation with time and/or their correlation
3) using the method of **WO9114855 (1991)** mentioned above to draw conclusions for the degradation of the auxiliary catalytic converter
4) measuring the temperature of the exhaust gases inside the main catalytic converter
5) drawing conclusion for the condition of the main catalytic converter by using the same evaluation means as the one of step 2.

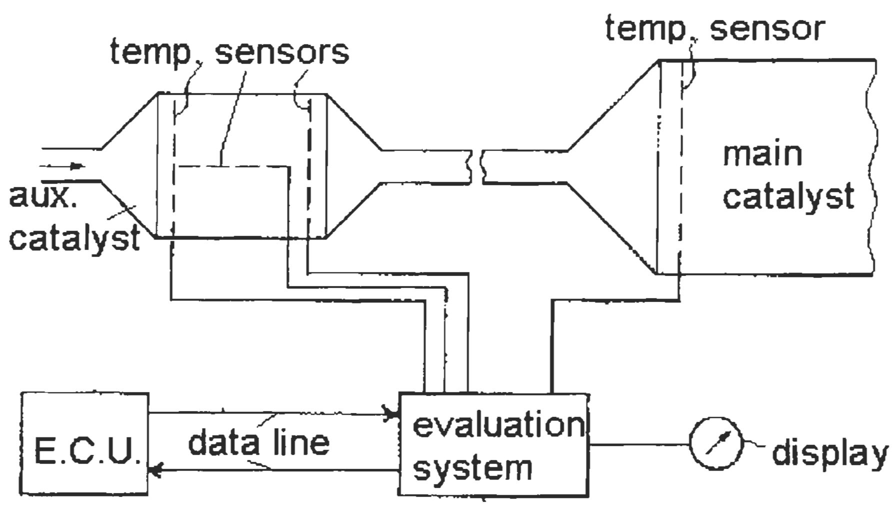


Fig. 106 (from WO9314305)

The method of **DE4227207 (1994)** comprises the following steps:

1) measuring the temperature of the exhaust gases inside the catalytic converter during normal operation of the catalytic converter (fig. 101)
2) modifying the operation conditions of the engine by varying an operation parameter of the engine. Such parameters can be considered:
    a) the concentration of hydrocarbons in the exhaust gases entering the catalytic converter, or
    b) the concentration of oxygen in the exhaust gases entering the catalytic converter, or

c) the concentration of nitrogen oxides in the exhaust gases entering the catalytic converter, or
d) a combination of the operation parameters described in a)-c)

3) measuring the variation of the exhaust gas temperature inside the catalytic converter in space or in time from the normal condition to the new conditions imposed
4) determining the degree of deterioration of the catalytic converter based on the behavior of the measured temperature variation.

In fig. 107 the variation of temperature with time dT/dt is shown for the case of a catalytic converter working under normal conditions and a catalytic converter working with excess of hydrocarbons (HC).

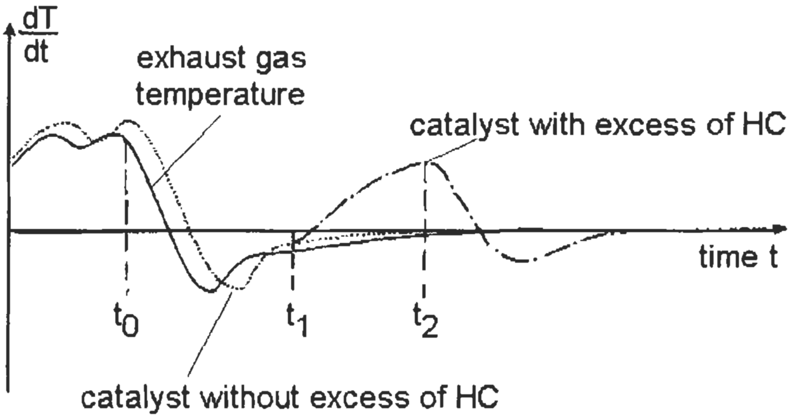


Fig. 107 (from DE4227207)

The temperature variation of the exhaust gases is also shown. The test starts at certain operating conditions of the engine where the temperature measured in the catalytic converter is more or less constant (point t_0). At t_0 a constant load operating condition is imposed to the engine and at t_1 the quantity of HC entering the catalytic converter increases till time point t_2. For the case of a catalytic converter working under normal conditions (no increase of HC) the increase of the temperature derivative variation in time is insignificant. For the case of a catalytic converter working under test conditions (increased HC entering the catalytic converter) a jump in the increase of the temperature derivative is observed. The greater the difference in the max. values of temperature derivatives between a catalytic converter working under test conditions and a catalytic converter working under normal conditions the better the efficiency of the catalytic converter is.

In the method of **WO9404800 (1994)** the catalytic converter is divided in a number of volume elements K_1 to K_4 (fig. 108). One temperature sensor is installed in each of the volume elements indicating representative reaction temperatures in each of the elements. A modification of chemical and/or physical properties of the exhaust gas mixture takes place in a way similar to the one of the method of **DE4227207 (1994)** described above (step 2). The method of **DE4227207 (1994)** as presented in fig. 107 is then applied separately for each volume K_1 to K_4. The difference of the max. values of the temperature derivatives between a catalytic converter operating under test conditions (increased quantity of HC) and a catalytic converter operating under normal conditions is compared to predetermined values for each of the volumes K_1 to K_4. The results are stored in a storage device and are processed in a later stage to draw conclusions for the efficiency of the catalytic converter in different operating conditions.

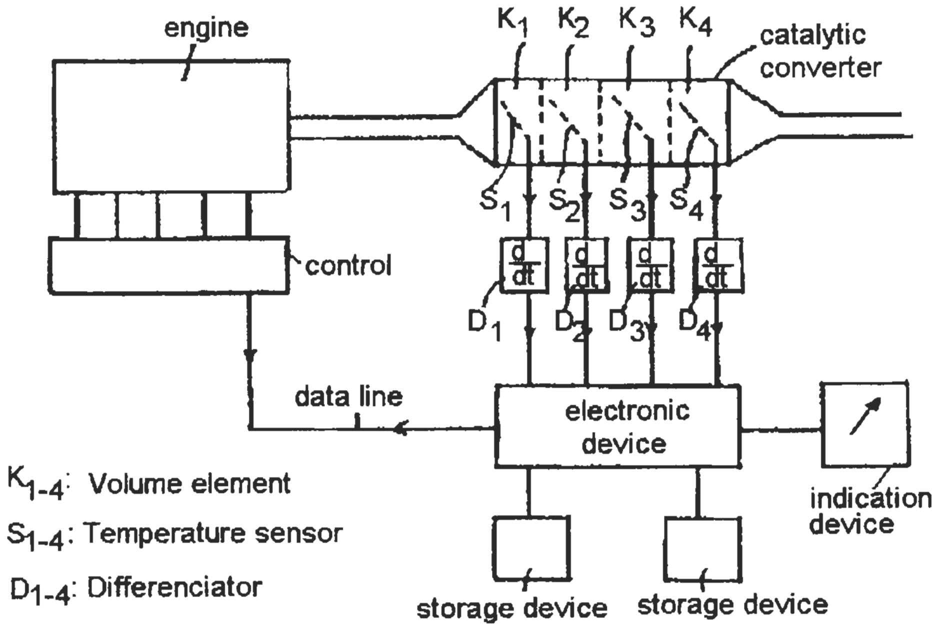


Fig. 108 (from WO9404800)

The method of **DE4308661 (1994)** and **US5560200 (1996)** proceeds as follows:

1) measuring the temperature T_2 of the catalytic coating at a certain point of the catalytic converter by means of a temperature sensor integrated in the structure of the catalytic converter
2) measuring the temperature T_1 of the exhaust gases upstream of the catalytic converter
3) forming the time derivatives

$$\frac{dT_2}{dt}, \frac{dT_1}{dt}$$

4) forming the difference

$$AV = \frac{dT_2}{dt} - \frac{dT_1}{dt}$$

5) specifying the elapsed time t_i after the engine start up, at which the difference AV changes sign
6) measuring the temperature T_2 of the catalytic coating at time point t_i after the engine start up, at which the difference AV changes sign
7) determining deterioration of the catalytic converter by comparing the temperature T_2 of the catalytic coating measured at time point t_i with predetermined values.

Instead of measuring the temperature directly, one can estimate the exhaust gas temperature upstream of the catalytic converter from engine operating parameters like: air flow, fuel flow, speed, engine temperature etc. The data can be stored in a memory device and be processed later at a workshop.

The method of **DE4302779 (1994)** comprises the following steps:

1) operating the internal-combustion engine during a first time period and determining a first operating condition of the internal-combustion engine via one or more parameters of the internal-combustion engine and the exhaust gas train.
2) operating the internal-combustion engine during a second time period in the first operating condition, if at least one of the sensed parameters corresponds to a specified desired value, or if said at least one of the sensed parameters does not correspond to the specified desired value. Then the internal-combustion engine is adjusted into a second operating condition by changing a value of at least one of the sensed parameters of the internal-combustion engine and, recognizing the second operating condition by comparing the up-to-date parameter

values with specified desired values for the second operating condition. The second operating condition can be

a) a coasting operation or

b) an idling operation of the internal-combustion engine.

The ignition of at least one cylinder is switched off temporarily when the engine operates under coasting or idling condition

3) acting upon the exhaust gas catalytic converter with an exhaust gas pulse which does not correspond to the second operating condition existing during the second time period and which produces one of an under or over-stoichiometric engine operation. The pulse is generated with a brief additional injection of fuel in the cylinders
4) sensing values of at least one first parameter of the exhaust gas train which changes as a result of the exhaust gas pulse. The parameter can be

   a) a temperature measured in the exhaust train or

   b) a concentration of the exhaust gases measured by a λ sensor
5) forming at least one first parameter difference between a parameter value (e.g. rotational speed or load) sensed before or while the exhaust gas catalytic converter is acted upon by the exhaust gas pulse and its value after the exhaust gas catalytic converter is acted upon by the exhaust gas pulse, and comparing the first parameter difference with a specified first desired difference range, and continuing the process if the first parameter difference is within the first parameter desired difference range
6) comparing the value of the first parameter with a specified desired value and by a subsequent comparison of the thus determined change with a desired change range

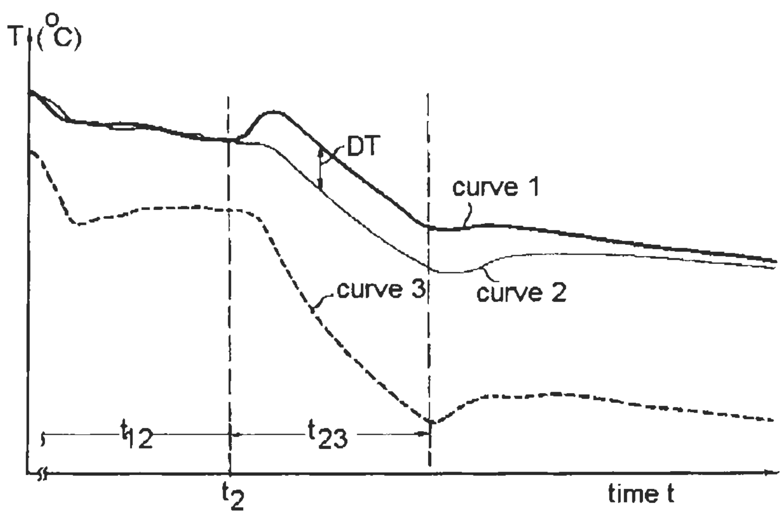


Fig. 109 (from DE4302779)

Fig. 109 shows the variation of temperature T of the exhaust gases downstream of the catalytic converter in function of time for the case of an efficient converter with a brief additional injection of fuel (curve 1), for the case of an efficient converter without a brief additional injection of fuel (curve 2) and for the case of a deteriorated converter with a brief additional injection of fuel (curve 3). During time period t_{12}, curves 1 and 2 are identical. At time point t_2, a temperature rise DT is observed for curve 1 when compared to curve 1 due to the additional injection of fuel. For curve 3, despite the additional injection, the curve is similar to curve 1 and it is also clearly shifted toward lower temperatures.

Chapter 2.2

Nissan Motor Co.

The method of **GB1373826 (1974)** comprises a thermocouple comprising two wires having terminals connected to each other so as to form detecting junctions which are positioned upstream and downstream of the catalytic converter respectively, and an ampere-meter measuring the difference in temperature between the two measuring points. When the difference in temperature between downstream and upstream catalytic converter temperature indication is lower than a predetermined value then the catalytic converter is considered as deteriorated.

The method of **DE2346425 (1974)** comprises the following steps:

1) measuring the temperature of exhaust gas at the inlet port of the converter by means of a first temperature sensor which produces a signal analogous to the temperature
2) measuring the temperature of exhaust gas at the outlet port of the converter by means of a second temperature sensor which produces a signal analogous to the temperature
3) producing an operating temperature signal when the voltage of the inlet temperature signal exceeds a first predetermined value
4) producing a difference signal analogous to the difference between the inlet and outlet temperatures of the converter as represented by the inlet and outlet temperature signals
5) producing a failure signal when the voltage of the difference signal is below a second predetermined value
6) producing an alarm signal when the operating temperature signal and the failure signal are applied simultaneously thereto

In the method of **JP1232106 (1989)** and **US5060473 (1991)** a first temperature sensor is arranged inside the catalytic converter (fig. 110). The following steps are considered:

1) monitoring the temperature of the catalytic converter to produce a temperature indicative signal. The temperature monitoring takes place by means of the first temperature sensor of fig. 110 by measuring:
   a) a temperature in the vicinity of the upstream side of said catalytic converter, or
   b) a temperature at a position in the vicinity of where the temperature of the catalytic converter becomes maximum when the catalytic converter is in a normal state
2) monitoring engine driving condition for producing an engine driving condition indicative signal
3) generating a reference value signal representative of a temperature criterion for determination of a deteriorated catalytic converter, and said reference signal value being generated on the basis of the engine driving condition indicative signal value
4) comparing the catalytic converter temperature indicative signal value with said reference value to produce an alarm when the catalytic converter temperature indicative signal value is smaller than the reference value.

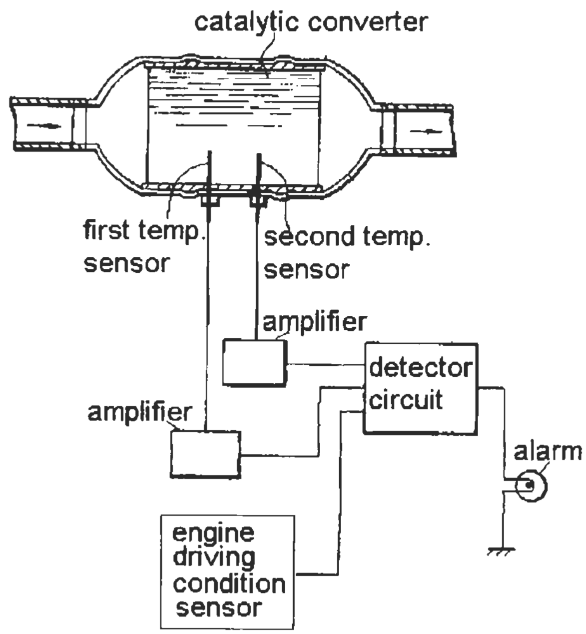


Fig. 110 (from US5060473)

Alternatively a second temperature sensor can be installed downstream of the first sensor, with respect to flow of the exhaust gas, to produce a second catalytic converter temperature indicative signal (fig. 110). A difference of the first and second catalytic converter temperature indicative signals is derived and compared with the reference value generated at step 3. This comparison gives useful information about the condition of the catalytic converter.

Fig. 111 shows the relation between the condition of a catalytic converter and the temperature distribution inside the catalytic converter from the entrance to the exit.

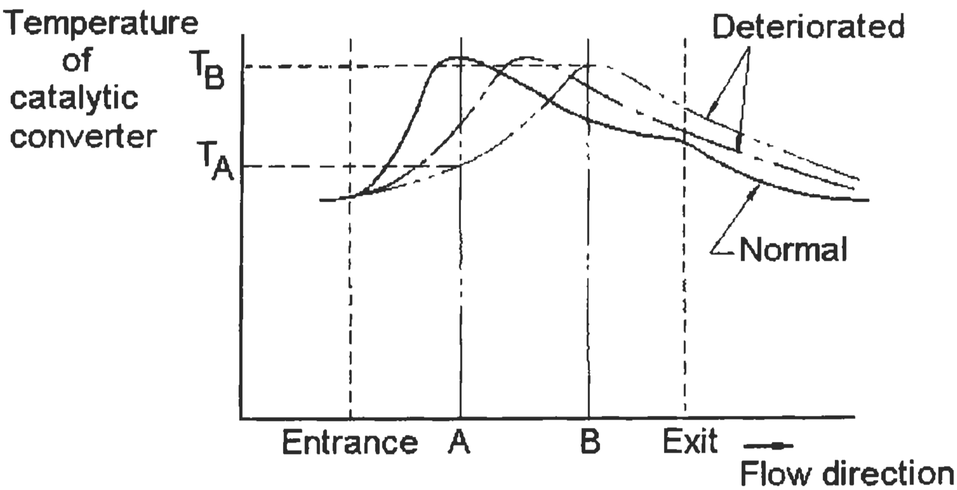


Fig. 111 (from US5060473)

For a new catalytic converter the peak reaction temperature appears at a point A adjacent to the entrance of the catalytic converter. As the catalytic converter deteriorates with time, the peak reaction temperature moves towards a point B located at a point adjacent to the exit of the catalytic converter. This happens because the pollutant absorbing reaction at the entrance of the catalytic converter becomes incomplete. For deteriorated catalytic converters the measured temperature at point A is lower than the one when the catalytic converter is fresh. So

as presented in the first embodiment of the invention, a first temperature sensor located at this point can monitor the condition of the catalytic converter.
Since the temperature of the catalytic converter depends on the exhaust gas temperature it can fluctuate. A more precise monitoring of the catalytic converter takes place then by locating a second temperature sensor at point B, as presented in the second embodiment of the present invention. The difference of the temperatures indicated by the two sensors gives then a more reliable indication of the condition of the catalytic converter.

In the method of **JP3050315 (1991)** a first temperature sensor is installed upstream of the catalytic converter and a second temperature sensor is installed inside the catalytic converter at a point adjacent to the entrance of the catalytic converter. The difference of the two sensor signals is formed and when this difference becomes lower than a reference value, a warning signal is produced indicating a degraded catalytic converter.

The method of **US5060474 (1991)** comprises a system to detect failure of a catalytic converter and a secondary air supply system installed upstream of the catalytic converter. The part concerning the failure detection of the catalytic converter only is presented below. The following steps are comprised:
1) controlling the secondary air supply to feed air in the exhaust system upstream of the catalytic converter
2) deriving a first temperature of the exhaust system at a first position located between the secondary air supply position and the catalytic converter, when secondary air is fed to the exhaust system
3) deriving a second temperature of the exhaust gases at a second position located inside or downstream of the catalytic converter, when secondary air is fed to the exhaust system
4) deriving a first difference between the first and second temperature
5) controlling the secondary air supply to stop feeding secondary air into the exhaust system upstream of the catalytic converter
6) deriving a third temperature of the exhaust gases at said first position, when secondary air supply is stopped
7) deriving a fourth temperature of the exhaust gases at said second position, when secondary air supply is stopped
8) deriving a second difference between the third and fourth temperature
9) comparing the first difference with the second difference and when they are found equal deciding that the catalytic converter is deteriorated when the first temperature is less than the third temperature

In the method of **JP6264724 (1994)** an air/fuel regulation sensor is mounted in the exhaust pipe upstream of the catalytic converter. A temperature sensor is mounted downstream of the converter. The method comprises the following steps:
1) judging whether the engine operating condition of the engine is in a state to perform the assessment of the efficiency of the catalytic converter

2) fixing the engine air/fuel ratio to a rich or a lean side for a fixed period
3) detecting a first exhaust gas temperature downstream of the catalytic converter
4) changing the engine air/fuel ratio to a value opposite to this of step 2
5) detecting a second exhaust gas temperature downstream of the catalytic converter
6) calculating the difference between the measured first and second temperature values of steps 3 and 5
7) comparing the calculated temperature difference with a predetermined value and drawing conclusions about efficiency of the converter from this comparison

In **JP7180536 (1995)** one temperature sensor is mounted upstream of the catalytic converter and one temperature sensor is installed inside or downstream of the catalytic converter. The assessment of deterioration of the catalytic converter is based on the measured temperature difference between the two sensors. A correction of the temperature difference takes place in order to compensate a deterioration of the temperature sensors.

In **JP7180537 (1995)** a temperature sensor is mounted inside the catalytic converter in its central part. The sensor has two sensing elements. One sensing element is positioned in the center of a cross section of the converter and the other sensing element is positioned in a radial position away from the center of the same cross section of the converter. The temperature values measured by the two sensors are compared with each other. When a temperature difference at a certain time point exceeds a predetermined threshold, it is decided that the converter is deteriorated.

In the method of **DE19643674 (1997)** the temperature of the catalytic converter that is used for the evaluation of the converter performance is determined indirectly from the operating parameters of the engine. The method comprises the following steps:
1) determining if the engine starts-up from cold or warm conditions
2) determining a reference heat quantity in dependence on the condensation that takes place in the converter during a cold start-up, or determining a reference heat quantity for the case of a warm start-up, where no condensation takes place in the converter
3) evaluating the operating conditions of the engine
4) calculating the temperature of the catalytic converter in relation to the operating parameters of the engine
5) evaluating the volume of the engine intake air
6) integrating in time (starting from engine start-up) the heat quantity that the exhaust gases transfer to the converter during normal operating conditions of the engine. The heat quantity is calculated from the temperature of the catalytic converter and the volume of intake air
7) fixing a temperature value of the catalytic converter, when the total heat quantity transferred to the catalytic converter from the exhaust gases of the engine is equal to or smaller than the corresponding reference heat quantity

8) calculating the temperature value of the catalytic converter from a formula that uses the temperature of the catalytic converter during normal operating conditions of the engine as a parameter, when the total heat quantity is greater than the reference heat quantity

Other methods presented by Nissan Motor Co can be found in **JP8082213 (1996)** and **JP8093456 (1996)**.

Chapter 2.3

Robert Bosch GmbH

The method of **DE2643739 (1978)** detects the efficiency of a catalytic converter consisting of two parts K_I and K_{II} (fig. 112 and fig. 113). Two embodiments are presented.
In the first embodiment a temperature sensor is installed upstream of K_I and an additional sensor is installed in the reaction zone of K_I (fig. 112). The temperature distribution in the catalytic converter is presented by the graph of fig. 112. For the case of a functional catalytic converter, the temperature inside K_I and K_{II} is higher than the temperature outside the catalytic converter due to the exothermic oxidation reaction taking place in the catalytic converter. In the case of a degraded catalytic converter, the temperature inside the catalytic converter is lower than the temperature upstream of the catalytic converter (dashed line). When the difference in temperature between the value measured inside the catalytic converter minus the temperature measured upstream of the catalytic converter is lower than a predetermined value then the catalytic converter is considered as deteriorated. The method requires that the catalytic converter is fully warmed-up before the detection starts.

In the second embodiment two sensors can be installed close to one another inside K_{II} or downstream of the catalytic converter (fig. 113). One sensor is similar to those ones of the previous embodiment, whereas the other sensor has a catalytic coating similar to the coating of the catalytic bodies K_I and K_{II}. When the catalytic converter is functional the two sensors show a similar temperature indication (fig. 113a). When the catalytic converter is degraded then the non-catalytic sensor indicates a low temperature value whereas the catalytic sensor still indicates a high temperature value because of the exothermic oxidation reaction taking place on the sensor itself (fig. 113b).

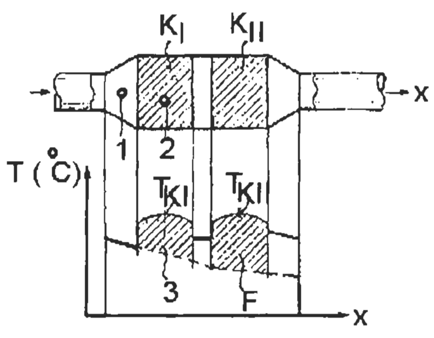


Fig. 112 (from DE2643739)

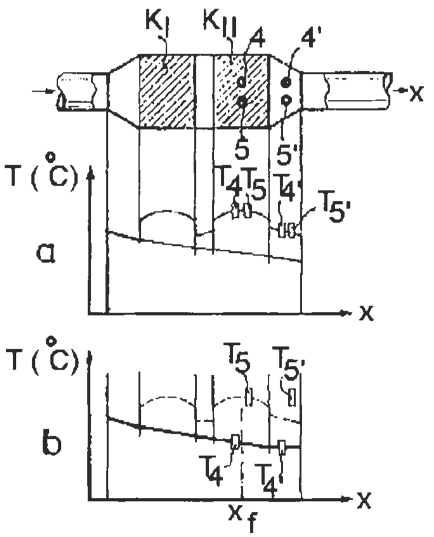


Fig. 113 (from DE2643739)

The method of **DE4211092 (1993)** comprises three embodiments, which can be explained by means of fig. 114, where a variation of temperature in the catalytic converter versus time is shown. According to the invention, at a time interval of 5 min after start up of the engine a new catalytic converter reaches its activation temperature.
The first embodiment comprises the following steps:

1) operating the engine under such conditions that the temperature of the catalytic converter is lower than the activation temperature of a new converter
2) measuring the temperature over which the catalytic converter, heated by the exhaust gases, begins to convert
3) comparing the temperature at which the catalytic converter begins to convert with a predetermined value T_0, which lies above the activation temperature of a new catalytic converter
4) determining that the catalytic converter is functional when the temperature at which the catalytic converter begins to convert is smaller than the predetermined value T_0

The second embodiment comprises the following steps:

1) operating the engine under such conditions that the temperature of the catalytic converter is lower than the activation temperature of a new converter
2) measuring the time interval Δt to reach a predetermined temperature, which is higher than the activation temperature of a new catalytic converter
3) comparing the measured time interval Δt with a predetermined value Δt_0
4) determining that the catalytic converter is functional when the measured time interval Δt is smaller than the predetermined value Δt_0

The third embodiment comprises the following steps:
1) operating the engine under such conditions that the temperature of the catalytic converter is lower than the activation temperature of a new converter
2) calculating the temperature T_{tm} of the catalytic converter by means of a theoretical model. Actual values of operating parameters of the engine and the converter are given to the theoretical model in order to calculate the temperature T_{tm}
3) checking the actual temperature T of the catalytic converter when the calculated temperature T_{tm} reaches a predetermined value T_0, which lies above the activation temperature of a new catalytic converter
4) determining that the catalytic converter is functional when the actual temperature T of the catalytic converter is greater than the predetermined value T_0

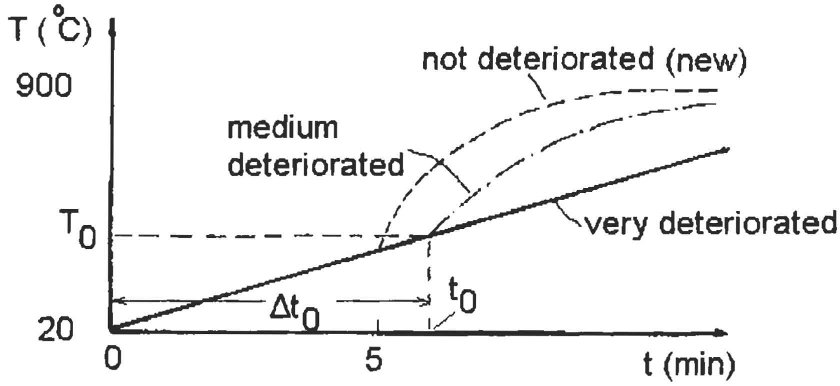


Fig. 114 (from DE4211092)

The method of **DE4330997 (1995)** monitors the behavior of a catalytic converter during startup of the engine and comprises the following steps:
1) determining a temperature T_{cat} of the activation region of the catalytic converter. This activation region represents the region of the catalytic converter which in principle treats the

exhaust gases pollutants during heating up of the catalytic converter. The activation region can be an auxiliary light-off catalytic converter located upstream of a main catalytic converter, or it can be the front upstream part of the catalytic converter when no auxiliary light-off catalytic converter exists

2) feeding the catalytic converter with an air/fuel mixture

3) determining the startup behavior of the catalytic converter depending on the influence that the feeding of the air/fuel mixture has on the temperature T_{cat} of the startup activation region. This is achieved by comparing

   a) the difference of temperature T_{cat} of the activation region from a reference value T_{ref} with a predetermined value and/or
   b) the first and/or the second derivative in time of T_{cat} with predetermined values.

As T_{ref} one of the following can be chosen:

   a) the temperature T_{cat} when no conversion of air/fuel mixture takes place in the startup activation region, or
   b) the temperature T_{cat} just before feeding the air/fuel mixture to the catalytic converter, or
   c) the temperature of the exhaust gases before they enter in the catalytic converter

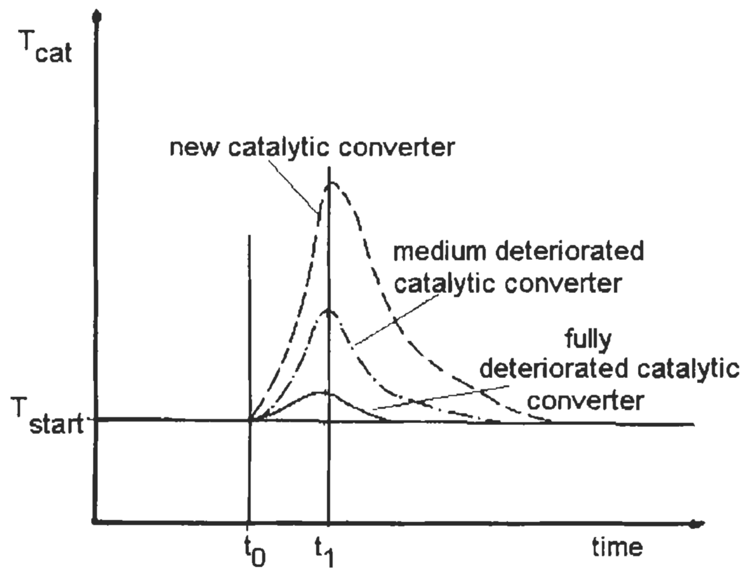


Fig. 115 (from DE4330997)

Fig. 115 shows the variation of temperature T_{cat} of the activation region with time for a new, a medium deteriorated and a fully deteriorated catalytic converter. During testing, the engine idles and the catalytic converter is fully warmed-up. For $t<t_0$, T_{cat} is constant ($=T_{start}$) and it is the same for all three converters. From time point t_0 till time point t_1 an air/fuel mixture is added to the catalytic converter. The measured temperature variation from point t_0 onwards depends then on the condition of the catalytic converter. At time point t_0 the increase of T_{cat} is steeper for new catalytic converters than for aged ones. Additionally the maximum temperature observed in the activation region is higher for new catalytic converters than aged ones. That means that the new catalytic converter converts higher quantities of air/fuel mixture in the activation region, it releases higher heat energy and warms up the catalytic converter faster than when the catalytic converter is aged. The slope of the curve i.e. the first or second derivative of T_{cat} and the difference of T_{cat} from a reference temperature T_{ref} can be a measure of the efficiency of the activation region of the catalytic converter. At t_1 the addition of the air/fuel mixture stops and the temperature of the three converters returns to value T_{start}, which they had before heating them up.

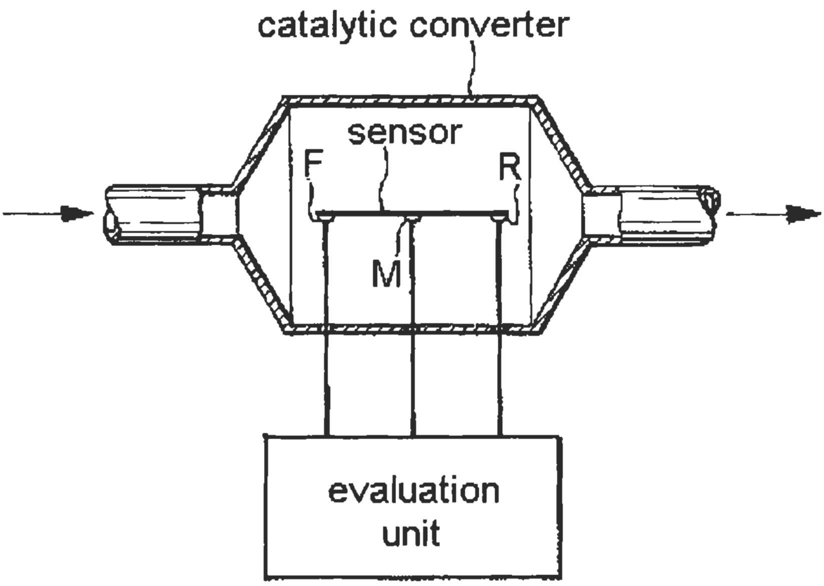


Fig. 116 (from DE4338547)

In the method of **DE4338547 (1995)** a temperature sensor element is installed in the longitudinal direction of the catalytic converter (fig. 116). The sensor has an electrical resistance with defined temperature dependence. The electrical resistance of the sensor is measured at two, at least, regions of the sensor (fig. 116). The functionality of the catalytic converter is evaluated by comparing the ratio of the resistance of the front part of the catalytic converter over the resistance of the rear part of the catalytic converter with a predetermined value. When the ratio is bigger than the predetermined value then the catalytic converter is considered as deteriorated. The method is based on the fact that in a new converter the major conversion of pollutants takes place in the front part (F) of the converter, whereas for a deteriorated converter the conversion region moves towards the rear part (R).

The method of **DE4426020 (1996)** comprises the following steps:
1) measuring the temperature downstream of the catalytic converter
2) estimating the temperature downstream of the catalytic converter by means of a theoretical model
3) calculating the difference between the measured and the estimated temperature at certain operating conditions
4) judging that the catalytic converter is deteriorated when this difference is bigger than a predetermined value.

Chapter 2.4

Volkswagen AG

In the method of **DE2351828 (1975)**, two temperature sensors are installed close to one another downstream of the catalytic converter. The first temperature sensor has a catalytic layer on its surface whereas the second sensor is inactive. In case of failure of the catalytic converter, hydrocarbons and CO will pass through the catalytic converter without being treated. These pollutants react then with the catalytic layer of the first sensor, increase the temperature on the surface and the heat produced changes the electric resistance of the sensor. The difference in the electric resistance of the catalytic and the non-catalytic temperature sensors gives then an indication of the condition of the catalytic converter.

In the method of **DE4100241 (1991)** the catalytic converter has the form of a honeycomb. Inside the honeycomb and in its longitudinal direction, there is a hole which allows a small portion of untreated exhaust gases to pass through (fig. 117). Two non-catalytic temperature sensors are installed downstream of the catalytic converter. One of the sensors is aligned with the hole and measures the temperature of the untreated gases, whereas the other sensor measures the temperature of the treated gases. When the difference of the two temperatures becomes lower than a certain value then the catalytic converter is considered as deteriorated.

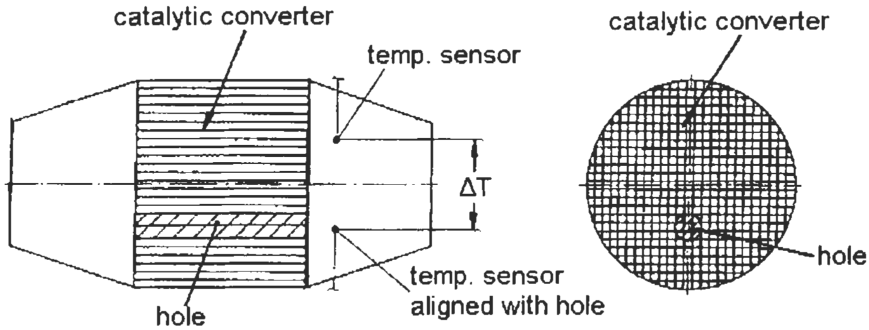


Fig. 117 (from DE4100241)

In the method of **DE4100397 (1992)** the following steps are considered:

1) heating up the catalytic converter to its activation temperature
2) suppressing at least one ignition during a deceleration phase of operation of the engine, causing a defined amount of unburned air/fuel mixture to be supplied to the catalytic converter
3) measuring the temperature of the exhaust gases upstream (first sensor) and downstream of the catalytic converter (second sensor)
4) forming the difference of the two temperatures and judging that the catalytic converter is deteriorated when the difference is lower than a certain value.

In an alternative embodiment the second sensor is installed inside the catalyst matrix and the unburned fuel is injected directly in the exhaust pipe by means of a fuel injector.

The method of **DE4122787 (1992)** comprises the following steps:

1) measuring the temperature of the exhaust gases upstream of the catalytic converter by means of a first temperature sensor
2) measuring the quantity of the exhaust gases flowing through the catalytic converter
3) calculating a temperature value of the exhaust gases downstream of the catalytic converter by making use of the measured upstream temperature of the exhaust gases, the exhaust gases flow rate through the catalytic converter, the geometry and the thermal capacity of the catalytic converter
4) measuring the temperature of the exhaust gases downstream of the catalytic converter by means of a temperature sensor

5) comparing the calculated and the measured temperature values downstream of the catalytic converter
6) judging that the catalytic converter is deteriorated when the difference of the two temperatures is higher than a certain value

The method of **GB2295033 (1996)** comprises the following steps:
1) measuring the temperature of the exhaust gases upstream and downstream of the catalytic converter by means of two temperature sensors
2) filtering the output signal of one of these temperature sensors
3) forming an actual temperature difference value ΔT_{12f} between the filtered signal of one of the sensors and the unfiltered signal of the other sensor
4) reading out a desired temperature difference ΔT_{12} from a predetermined map. The map uses the engine speed, the exhaust gas temperature and the current fuel injection quantity of the engine as input variables
5) filtering value ΔT_{12} read out in a desired value filter and receiving value $(\Delta T_{12f})'$
6) reading out a current time window from a time characteristic map as a function of the exhaust gas temperature
7) triggering a monitoring signal when the value $(\Delta T_{12f})'$ becomes higher than ΔT_{12f} for the duration of the current time window.

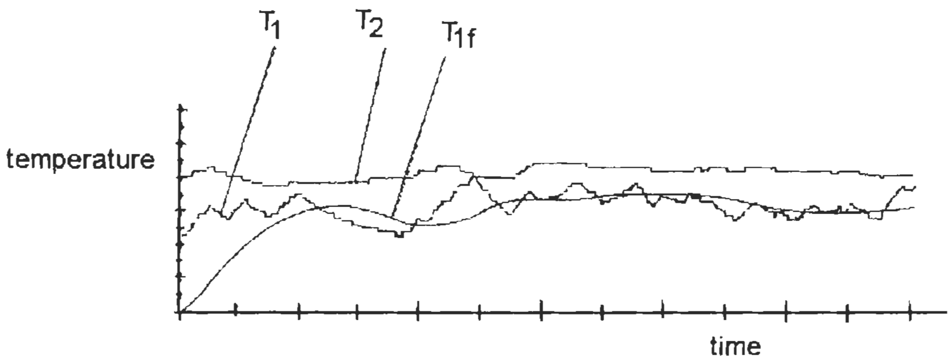


Fig. 118 (from GB2295033)

Fig. 118 shows the variation of temperature T_1 measured upstream of the catalytic converter, the variation of temperature T_2 measured downstream of the catalytic converter and the variation T_{1f} of the filtered variation of temperature T_1.

The higher values downstream of the converter caused by the exothermic reaction emerge clearly. Also clear, however, is the overall uneven shape, particularly of curve T_1. There is not always a usable difference between the curves T_1 and T_2. The temperature difference ΔT_{12f} which is always present between the curves T_{1f} and T_2 is clear.

Chapter 2.5

Ford Motor Co. - Ford France SA - Ford Werke AG - Ford Motor Co. Canada - Ford Motor Co. Ltd.

The method of **WO9420738 (1994)** is applied when the engine operates in a cruising or steady state mode and comprises the following steps:

1) operating the engine in a cruising or steady state mode
2) perturbing the air/fuel ratio of the engine to increase hydrocarbons and carbon monoxide of the exhaust gases without causing engine misfire i.e. by enriching the air/fuel mixture by 5 to 10 percent above stoichiometry for a duration between 10 and 30 seconds. This is sufficient to cause a readily sensed temperature increase without affecting the output power and torque of the engine
3) adding air to the exhaust gases prior to their reaching the catalytic converter
4) monitoring changes in the temperature of the exhaust gases in response to this perturbation by
   a) measuring the rise in average temperature of the catalytic converter after the lapse of at least one time interval following the step change of the constituents of the exhaust gases, or
   b) measuring the rate of rise of the average temperature of the catalytic converter after the lapse of at least one time interval following the step change of the constituents of the exhaust gases, or
   c) comparing the temperature at different volume elements of the catalytic converter spaced from one another in the direction of flow of the exhaust gases after the lapse of at least one time interval following the step change of the constituents of the exhaust gases

The temperature is measured by means of thermistors that are designed to sense the temperature along the entire length of the converter.

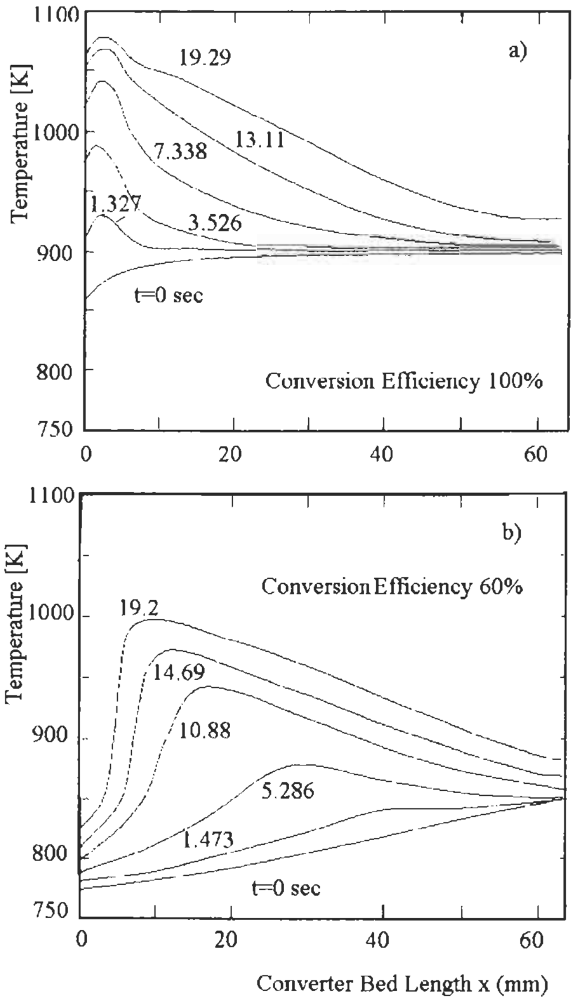


Fig. 119 (from WO9420738)

The method can be better explained by means of fig. 119. Fig. 119a illustrates the variation of temperature along the length of a catalytic converter at different times following the step perturbation of step 2 for a converter operating at 100% efficiency, whereas fig. 119b shows the corresponding curves for a converter operating at 60% efficiency. For an efficient converter, after 5 seconds most of the temperature increase is concentrated at the front end of the catalytic converter and this front slice is considerably hotter than the remainder of the converter. On the other hand, in the case of an inefficient converter, the temperature rise at the front end of the converter after 5 seconds is significantly lower than the temperature rise deeper within the converter. For efficient converters, the exothermic catalytic reaction is completed while the exhaust gases are still at the front end of the converter whereas in a less efficient converter the exothermic reaction takes longer to complete. The exhaust gases also tend to cool the catalytic converter and the cooling effect is strongest at the front end of the catalytic converter. As a result after 5 seconds the front end of a converter operating with 60% efficiency is cooler than the center of the converter.

It is therefore possible measuring the temperature in different slices of the catalytic converter to determine the conversion efficiency by a comparison of the relative temperatures after a given time following a step increase in the combustible constituents of the exhaust gases reaching the catalytic converter.

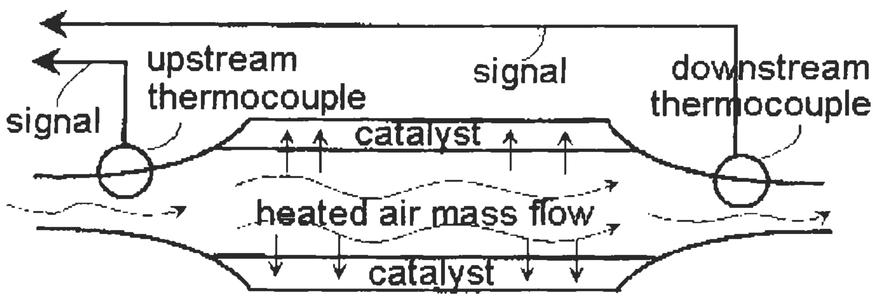


Fig. 120 (from GB2282467)

The method of **GB2282467 (1995)** judges the operability of a catalytic converter during light-off by determining the time required for the catalytic converter to light off during a cold start-up by,

1) propelling a heated air mass $\dot{m}_{air}$ through the converter (fig. 120)
2) determining an initial heat transfer rate $\dot{Q}_{air}$ from the heated air mass to the catalyst material of the catalytic converter as follows:

$$\dot{Q}_{air} = \dot{m}_{air} \cdot C_{Pair} \cdot (T_1 - T_2)$$

where
$(T_1 - T_2)$ is the temperature difference between the temperature of the heated air mass before entering the converter and the temperature of the heated air mass after exiting the converter and
C_{Pair} is a constant representative of the specific heat of the air

3) determining an initial temperature $\frac{DT_{cat}}{Dt}$ of the catalyst material by using the equation:

$$\dot{Q}_{air} = A \cdot C_1 \cdot \dot{m}_{air} \cdot a \cdot (\frac{(T_1 + T_2)}{2} - T_{cat})$$

where
A is the total surface area of the exhaust pipe and catalyst material between the upstream and the downstream sensor,
C_1 is a constant representative of the heat transfer from the heated air mass to the catalyst material and
a equals to 0.5 or 0.9 for laminar or turbulent flow respectively.
Step 3 is repeated twice in a time step Δt to calculate two values of the catalyst temperature T_{cat} and to form the initial rate of temperature of the catalyst

4) forming a first ratio from the initial heat transfer rate and the initial rate of change of temperature
5) determining a subsequent heat transfer rate from the heated air mass to the catalyst material
6) determining a subsequent rate of change of temperature of the catalytic converter
7) forming a second ratio from the subsequent heat transfer rate and the subsequent rate of change of temperature
8) comparing the second ratio to the first ratio to track a trend of these ratios
9) repeating steps 1 through 8 until the trend of these ratios exhibits a predetermined downturn
10) determining the time required for the catalytic converter to light-off during a cold start-up to be the time from the air propelling step 1 to the time required for the downturn of step 9
11) comparing this time to a threshold value and
12) determining that the catalytic converter is defected if this time exceeds the threshold value

Fig. 121 shows the ratio of the rate of heat transfer from the heated air mass to the catalyst material over the rate of change of the temperature of the catalyst material in function of light-off time. The time point t_0 at which a downturn of the ratio occurs is checked against a threshold value ε. If $t<\varepsilon$ the catalytic converter is deemed to be operational.

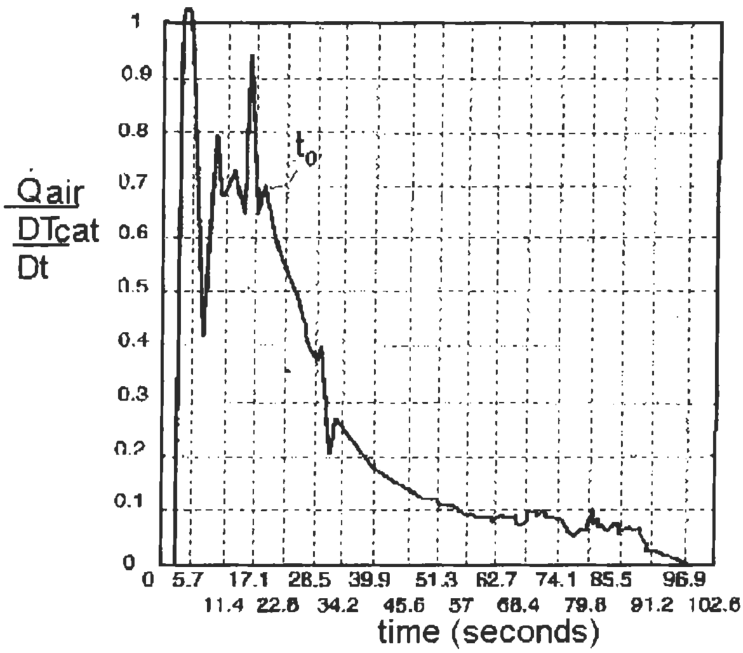


Fig. 121 (from GB2282467)

In **US5431012 (1995)**, the monitor of the performance of a catalytic converter takes place by measuring the temperature on the catalytic converter by means of a thin-resistive device. The device comprises an electrically insulated substrate, a thin layer of an electrically conductive material and metal oxides applied on the surface of the substrate, a wash-coat carried on a surface of the electrically conductive material, and a catalyst carried on a surface of the wash-coat. An electrical circuit is connected to the thin-film resistive device in order to determine the change in the electrical resistance of the electrically conductive material during conversion of the exhaust gases in the catalytic converter.

Fig. 122 shows the measuring engine layout of the method presented in **US5626014 (1997)** where the exhaust pipe of the internal combustion engine comprises a first pipe, a three-way catalytic converter and a second pipe. The first pipe includes an exhaust manifold for transporting exhaust gas from combustion chambers of the engine to the catalytic converter. The engine includes an engine coolant temperature (ECT) sensor for detecting the temperature of engine coolant circulating within the engine. The ECT sensor preferably takes the form of a thermistor which transmits an ECT signal, which is indicative of engine coolant temperature, to Electronic Engine Controller (EEC). A Mass Air Flow (MAF) sensor is positioned before the intake manifold of the engine to detect the mass flow rate of air entering the intake manifold. The MAF sensor preferably takes the form of a hot wire anemometer which transmits a MAF signal, which is indicative of the mass flow rate of air entering the intake manifold, to the EEC. A Heated Exhaust Gas Oxygen (HEGO) sensor positioned upstream of the catalytic converter on the first pipe detects the equilibrium concentration of oxygen in the exhaust gas generated by the engine and transmits a representative HEGO signal to the EEC. A Malfunction Indicator Light (MIL) which is preferably positioned in the passenger compartment of the vehicle, on the instrument panel, provides, in response to a malfunction signal, an indication to a driver of the vehicle of a malfunction as determined by the EEC. The EEC performs a variety of engine control and diagnostic functions including control of fuel injection and spark timing via a plurality of signals.

The EEC preferably includes a central processing unit, a read-only memory (ROM) for storing control programs, a random-access memory (RAM) for temporary data storage, a keep-alive-memory (KAM) for storing learned values, and a conventional data bus and I/O ports for transmitting and receiving signals to and from the engine.

A temperature sensor module connects to a plurality of temperature sensors, which sense the temperature at spaced intervals of a catalyst material in the catalytic converter. Each of the temperature sensors generates a signal which is indicative of the temperature in the catalyst material at the location of the temperature sensor and transmits a representative signal to the temperature sensor module which time multiplexes the signals received from each of the temperature sensors and transmits a multiplexed temperature signal to the EEC. A temperature sensor is additionally installed upstream of the catalytic converter to measure the temperature of the exhaust gases entering the catalytic converter.

The determination of the HC conversion-efficiency of the converter is carried out as follows:
1) checking at least a first operating parameter to determine if the engine is operating within a predetermined operating range (e.g. engine operating temperature). If the condition is satisfied then
2) measuring the temperature of the exhaust gas entering the catalytic converter
3) measuring the temperature of the catalyst substrate in the catalytic converter at the plurality of cross sections for a predetermined number of time intervals
4) generating as a function of the measured temperature of the exhaust gas entering the catalytic converter and the measured temperature of the catalyst substrate, an energy value indicative of the total energy generated in the converter over the predetermined number of time intervals (thermal power model)
5) comparing the generated total energy value to a predetermined total energy value
6) providing an indication of the HC conversion-efficiency of the catalytic converter if the total energy value deviates from the predetermined energy value by more than a predetermined deviation amount

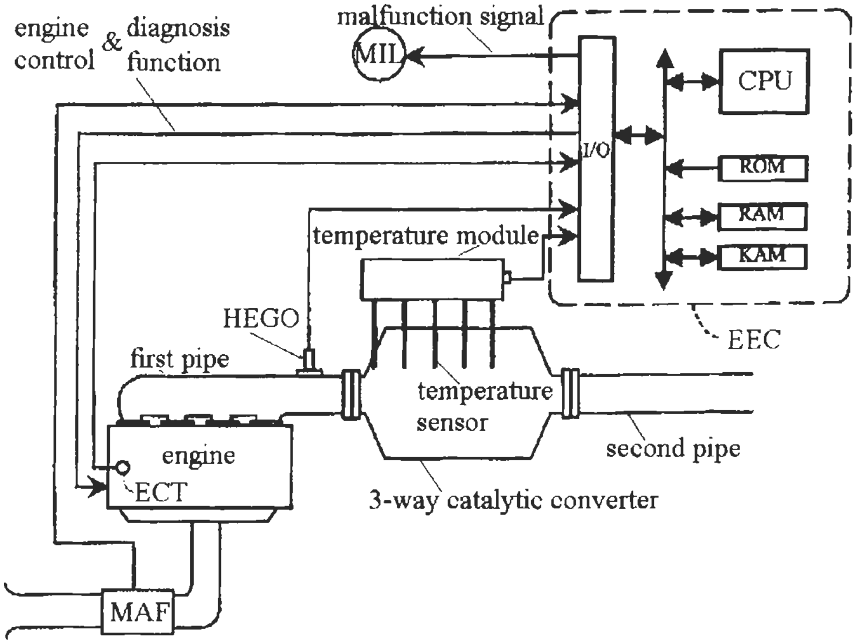


Fig. 122 from US5626014)

Chapter 2.6

Siemens AG - Siemens Automotive SA - Bayerische Motoren Werke AG - Mercedes Benz AG

In the method of **EP0262558 (1988)**, which is applied to a series of catalytic converters used in the exhaust system of industrial applications, a reducing gas (NH_3 or CO) is injected in the exhaust gases to promote NO_x reduction on the catalytic converters. Temperature sensors are provided upstream and downstream of individual layers of the catalytic converters, and a differential amplifier coupled with the sensor reads the difference in temperature among the layers to provide information about the efficiency of the catalytic layers by comparing the actual readings with predetermined values.

In the method of **FR2690203 (1993)** a sharp enrichment of the exhaust gases with unburned fuel is produced by releasing the accelerator pedal without cutting the fuel feed to the engine. This produces an exothermic reaction of the oxidation of the hydrocarbons present in the exhaust and a release of heat in the catalytic converter. The detection of this heat upstream and downstream of the catalytic converter is a measure of the deterioration state of the catalytic converter. In order to measure the temperature downstream of the catalytic converter a special oxygen sensor is used. The sensor has a film of dioxide of titanium deposited on a support and it is equipped with a heating resistance and means of regulation of its temperature to a predetermined temperature. The intensity of the electric current used for heating the resistance permits measurement of the temperature of the exhaust gases.

Figs. 123a,b show the temperature evolution in time upstream and downstream of the catalytic converter as measured for the cases of a non-deteriorated and a deteriorated catalytic converter respectively from the moment the accelerator pedal is released (t_0). When the catalytic converter is deteriorated (fig. 123b) no exothermic reaction takes place and the two distributions of temperature are similar and decrease in time. In the contrary for a non-deteriorated catalytic converter (fig. 123a), a strong exothermic reaction takes place causing an increase of temperature downstream of the catalytic converter until a certain point. If the difference in temperature between the downstream temperature at a predetermined time point after time point t_0 and the downstream temperature at time point t_0 is positive the catalytic converter is considered as non-deteriorated. If this difference is negative, the catalytic converter is considered as deteriorated.

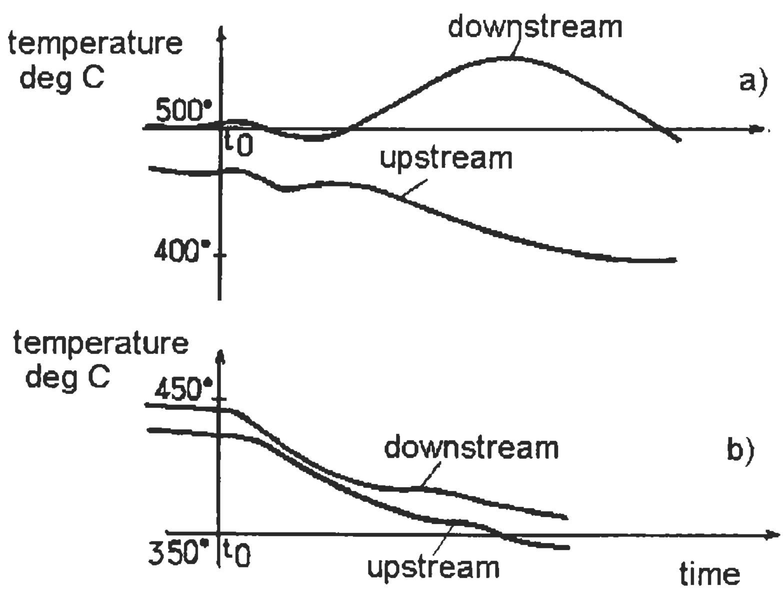


Fig. 123 (from FR2690203)

The method of **WO9421901 (1994)** monitors the condition of a secondary catalytic converter installed upstream of a main catalytic converter. The temperature is measured upstream (T_1) and/or downstream (T_2) of the secondary catalytic converter. The monitoring takes place during an idling phase of 10 sec following an overrun phase. Four criteria are assessed individually or in combination and in which the catalytic converter is considered as efficient. The criteria are:

1) the difference $\Delta T(=T_2-T_1)$ between the temperature downstream and upstream of the catalytic converter increases during the test period (fig. 124a)
2) the temperature T_2 downstream of the catalytic converter lies in a predetermined range. If the temperature falls out of the range defined from curves ε_1 and ε_2, the catalytic converter is considered as exhausted (fig. 124b)
3) the difference $\Delta T(=T_2-T_1))$ between the temperature downstream and upstream of the catalytic converter exhibits a minimum difference ε (fig. 124c)
4) the magnitude of the temperature gradient for the temperature downstream of the catalytic converter is smaller than a threshold value ε (fig. 124d).

The temperature T_1 upstream of the secondary catalytic converter can be directly measured by means of a temperature sensor or it can be estimated by means of a temperature model in function of the operating parameters of the engine.

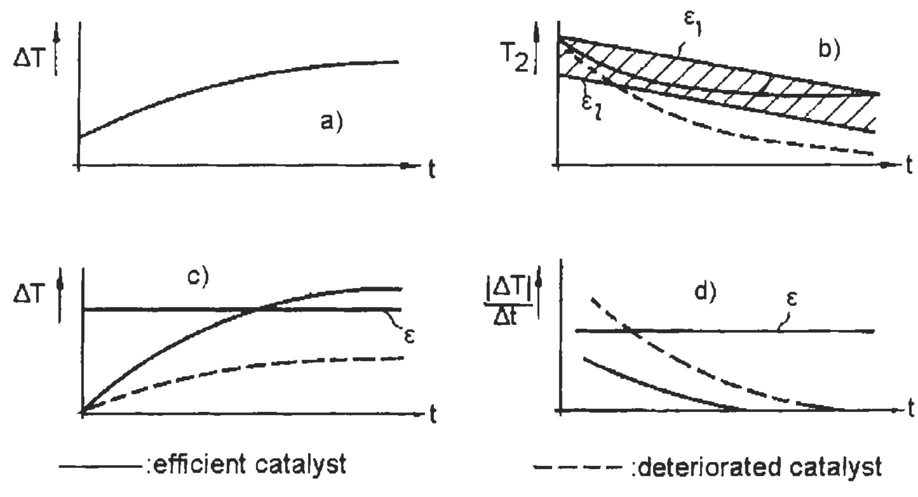


Fig. 124 (from WO9421901)

The method of **WO9517588 (1995)** monitors the condition of a secondary catalytic converter installed upstream of a main catalytic converter and comprises the following steps:

1) measuring the temperature downstream of the secondary catalytic converter at the beginning and end of a predetermined idling phase, over a predetermined number of idling phases, following a power phase under predetermined operating conditions of the engine
2) forming the temperature difference between the temperatures measured at the beginning and end of each predetermined idling phase
3) forming the sum of the results of temperature differences calculating the total duration of the idling phases
4) forming an average temperature quotient from the sum of temperature differences and the total duration of the idling phases
5) comparing the average temperature gradient thus formed with a predetermined threshold
6) assessing the deterioration of the catalytic converter when the average temperature gradient is higher than the predetermined threshold

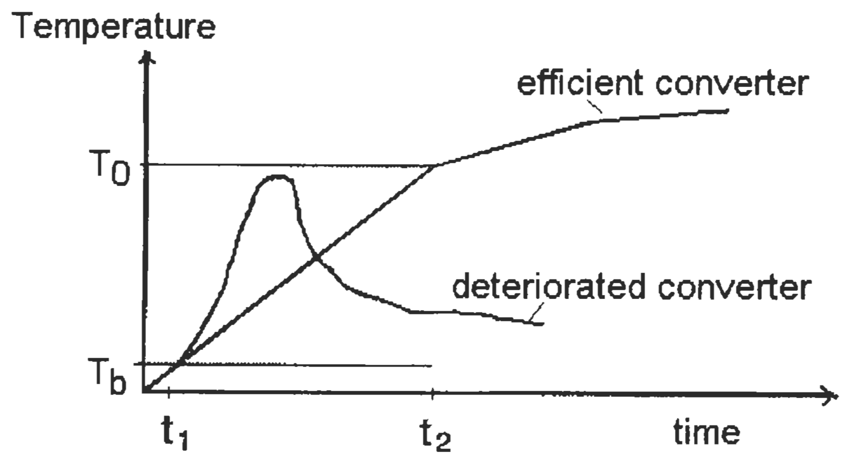


Fig. 125 (from DE4437655)

The method of **DE4437655 (1996)** assesses the effectiveness of a heating device (fuel burner) of a catalytic converter. It comprises the following steps:

1) starting the engine at cold conditions
2) detecting the starting point t_1 (fig. 125) of the fuel burner by achieving
   a) a predetermined temperature T_b or
   b) a predetermined temperature rise rate of the exhaust gases between the burner and the catalytic converter

3) measuring the temperature T_2 of the heated exhaust gases between the burner and the catalytic converter at a time point t_2
4) comparing the measured temperature T_2 with a predetermined threshold T_0
5) determining that the system is deteriorated when $T_2 < T_0$.

Fig. 126 shows an alternative embodiment, where the distribution in time of the temperature of the exhaust gas between the burner and the catalytic converter is compared to a predetermined temperature distribution. The greater the difference A between the two curves at time point t_2 the higher the deterioration of the heating device is. The curve G corresponds to a factor of importance vs. time of the difference A between the two curves. As long as the catalytic converter is heated up the factor G is not so important, whereas close to the burner start up an already small value of A is important for the determination of the performance of the system.

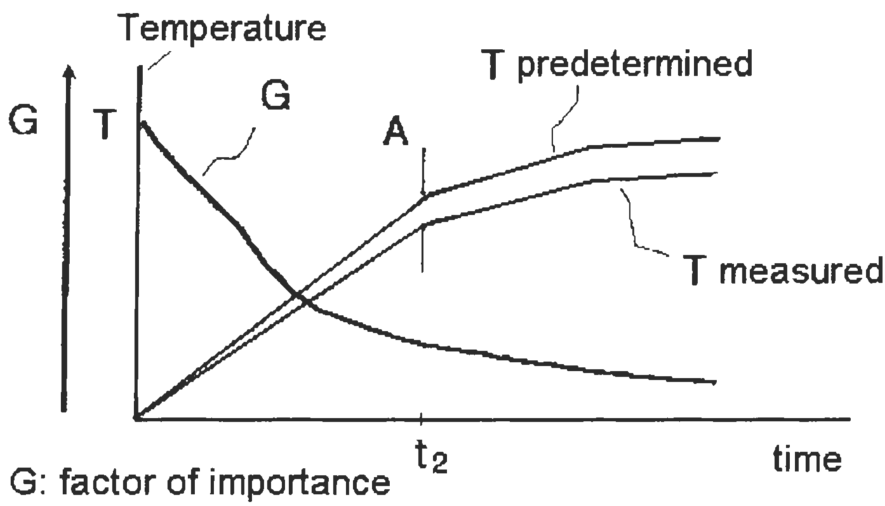


Fig. 126 (from DE4437655)

The method of **EP0773355 (1997)** assess whether an electrically heated catalytic converter (EHC) reaches its activation temperature within a predetermined time interval after a cold start-up. This is achieved by means of two λ probes which are installed upstream and downstream of the converter respectively. The downstream probe is of a heated type. This probe remains unheated during the cold start-up and measures the temperature of the exhaust gases downstream of the converter for checking whether the activation temperature is reached within the predetermined time interval.

Chapter 2.7

Toyota Motor Co. Ltd.

The method of **EP0498598 (1992)** is applied for the layout of fig. 127.
As illustrated in fig. 127, an engine capable of fuel combustion at lean air-fuel ratios (lean burn engine) has an exhaust conduit where a lean NO_x catalytic converter is installed. An exhaust gas temperature control device is installed in a portion of the exhaust conduit upstream of the lean NO_x catalytic converter. When the exhaust gas temperature changes, a catalytic converter temperature of the lean NO_x catalytic converter changes according to the change in the exhaust gas temperature. A portion of engine cooling water is led to the exhaust gas temperature control device and the circulation amount of cooling water is controlled by a control valve so that the exhaust gas temperature control device can control the exhaust gas temperature. The engine cooling water-type exhaust gas temperature control device may be replaced by:

a) a device using introduction of secondary air
b) a device using an air-fuel ratio control or
c) a device using an ignition timing control

For the case of diesel engines the exhaust gas temperature control device may be replaced by:

a) a device using a charging pressure control or
b) a device using an intake throttle valve control .

The operation of the exhaust gas temperature control device is controlled by an electronic control unit (ECU).

In the portion of the exhaust conduit upstream of the lean NO_x catalytic converter, a hydrocarbon supply device (HC supply device) is provided. The HC supply device includes a HC source, a HC supply port for introducing the HC (for NO_x reducing purposes) from the HC source into the portion of the exhaust conduit upstream of the lean NO_x catalytic converter, and a HC control valve for controlling the amount of HC supplied into the exhaust conduit. The control valve is driven by a valve drive device which is controlled by the ECU.

A first exhaust gas temperature sensor is installed in the portion of the exhaust conduit upstream of the lean NO_x catalytic converter, and a second exhaust gas temperature sensor is installed in a portion of the exhaust conduit downstream of the lean NO_x catalytic converter. Further, an NO_x sensor is installed in the portion of the exhaust conduit downstream of the lean NO_x catalytic converter.

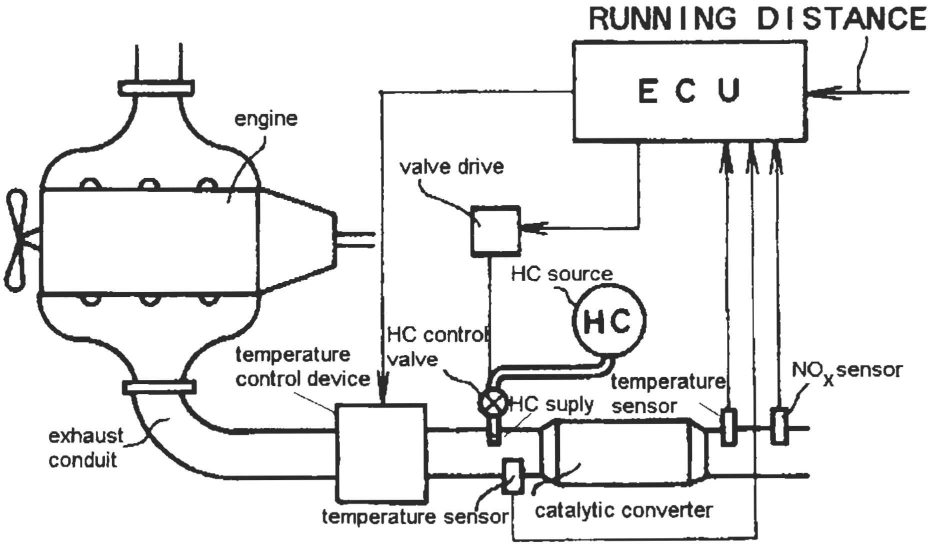


Fig. 127 (from EP0498598)

The output signals of these sensors are fed to the ECU. Also, a signal of a running distance of the automobile to which the engine is mounted, and signals of an engine load and an engine speed are fed to the ECU. The ECU is constituted by a micro-computer which includes an input interface, an output interface, an analog/digital (A/D) converter for converting analog signals to digital signals, a read-only memory (ROM), a random access memory (RAM), and a central processor unit (CPU) for conducting calculation. The ROM stores flow charts and maps (e.g. maps of engine load vs. engine speed). Calculations are executed in the CPU.

When an accumulated running distance of the vehicle is exceeded then a reference temperature difference between inlet exhaust gas and outlet exhaust gas of the catalytic converter at non-degraded state is calculated from an engine load vs. engine speed map. A current temperature difference between the inlet exhaust gas and outlet exhaust gas of the catalytic converter is also detected by means of the upstream and downstream temperature sensors. A degradation extent of the catalytic converter is then detected based on the difference between the detected current temperature and the reference temperature difference.

The degradation of the catalytic converter can be also based on the comparison of the actually measured NO_x content of the exhaust gases downstream of the catalytic converter and the stored NO_x value for a certain accumulated running distance of the vehicle.

Fig. 128 shows the NO_x purification of the converter vs. the temperature of the converter. The points T_1 and T_2 of fig. 128 correspond to a lower temperature limit and to an upper temperature limit respectively of a temperature range, where the lean NO_x converter can work with a high NO_x purification rate for a certain accumulated running distance. In fig. 128, T_1 and T_2 correspond to a lean NO_x converter at an initial state (no running distance).

When it is determined, based on the accumulated running distance, that the lean NO_x catalytic converter has been degraded, the HC amount is increased by the means for increasing the HC amount in accordance with the degradation extent of the lean NO_x catalytic converter . The more degraded the catalytic converter is, the less the NO_x purification rate of the catalytic converter is, and the more the HC amount supplied to the catalytic converter is, the more the NO_x purification rate of the catalytic converter is.

Therefore, even if the NO_x purification characteristic shifts from a to b, and from b to c in fig. 128, due to degradation of the catalytic converter, the characteristic line is raised, as shown by a broken line in fig. 128, by increasing the amount of HC supplied to the catalytic converter.

Further, if the catalytic converter temperature is changed to a higher side, together with the above-described HC amount increase, the NO_x purification rate of the lean NO_x catalytic converter is further increased. More particularly, even if the lean NO_x catalytic converter is degraded, accompanied by a shift of the NO_x purification rate peak temperature, to a higher temperature side, the catalytic converter temperature also is changed to the higher side corresponding to the degradation extent of the catalytic converter, so that the lean NO_x catalytic converter is always used at or near its NO_x purification rate peak temperature and the NO_x purification ability of the lean NO_x catalytic converter can be extended for a long period of time.

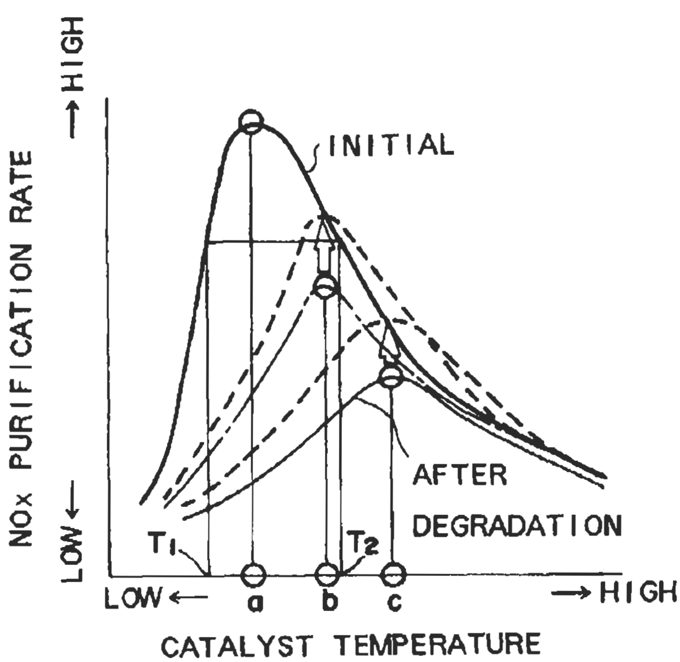


Fig. 128 (from EP0498598)

In **JP5202735 (1993)**, when the engine starts up, a heater is turned on to heat the catalytic converter. The temperature of the catalyst bed is then detected and when the temperature of the bed remains lower than a threshold for a certain time, the heater is turned off and a malfunction signal is produced.

In **US5447696 (1995)**, a method is presented to assess the efficiency of a plurality of electrically heated catalytic converters (EHC) of the heater-converter type located upstream of a plurality of main catalytic converters. Each electrically heated catalytic converter and each main catalytic converter are located in the exhaust passage of a corresponding cylinder bank. For simplicity reasons only two cylinder banks will be used further in the presentation of the method (fig. 129).

As shown in fig. 129, each catalytic converter comprises a cylindrical casing, a heater-converter and a main converter, both disposed in said cylindrical casings. The heater-converters are electrically heated converters having metal substrates, which also act as electric heaters. When the engine starts, electric currents are fed to the heater-converters and the temperatures of the heater-converters increase rapidly and reach the activating temperature within a short time. Thus, the catalysts carried on the heater-converters are activated and start to purify the exhaust gas of the engine as soon as the engine starts.

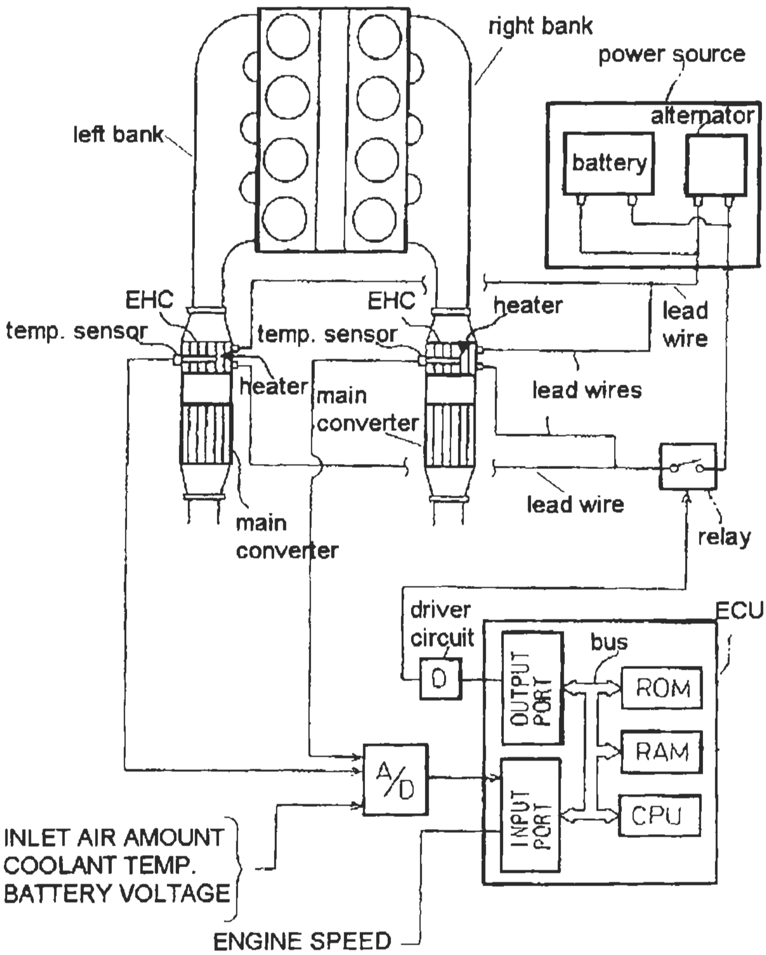


Fig. 129 (from US5447696)

Main converters are common type catalytic converters having metal or ceramic honeycomb type substrates and having larger capacities than the heater-converters,. Since the main converters are disposed downstream of the heater-converters, when the heater-converters reach the activating temperature and the catalytic action starts in the heater-converters, the exhaust gas which is heated by the oxidation of HC and CO components in the exhaust gas in the heater-converters flows into the main converters. Thus the temperatures of the main converters also reach the activating temperature in a short time after the engine starts.

The heaters are connected in parallel to an electric power source via lead wires. The electric power source consists of a battery and an alternator of the engine. Also, a common relay is provided on the lines. The relay is set ON and OFF by the signal from an electronic control unit (ECU) in such a manner that ON and OFF of the heaters can be controlled simultaneously. The ECU controls fuel injections and ignition timing of the engine and ON/OFF operation of the heaters of the heater-converters.

To perform such controls, various signals, are fed to the input port of ECU via an A/D converter. These signals are, for example, a voltage signal proportional to an amount of intake air which is generated by an airflow meter (not shown) disposed on an intake air passage of the engine, a voltage signal proportional to a temperature of the engine coolant which is generated by a coolant temperature sensor (not shown) disposed on a water jacket of the engine and a signal corresponding to a voltage of the battery. Also, a pulse signal from an engine speed sensor (not shown) disposed on a distributor of the engine which represents an engine speed and an ON/OFF signal of a starter motor (not shown) from starter switch (not shown) are fed to the input port.

Further, temperature sensors are embedded in the catalyst beds of the heater-converters or are installed upstream of the converters. Output signals of these temperature sensors are fed to input port of the ECU via the A/D converter.
The output port of the ECU is connected to the relay via a driver circuit to control ON/OFF operation of the heaters and of the heater-converters.

The method comprises the following steps:

1) electrically heating the EHC converters after the engine starts
2) detecting parameters relating to a temperature of each of the two EHC converters. The parameters can be one of the following:
    a) the measured temperatures of the catalyst beds of the converters
    b) the rates of increase of the measured temperatures of the catalyst beds of the converters
    c) the differences between the temperatures of each catalyst bed and the temperature of the stream of exhaust gases flowing into each of the converters
    d) the electric currents flowing through the heating means of each of the EHC converters
    e) the electric voltages applied to the heating means of each of the EHC converters
3) collating the values of the detected parameters of the two converters

4) determining a failure of the EHC converter system when a difference between the values of the detected parameters of the two EHC converters exceeds a predetermined value
5) determining which of the EHC converters has failed when it is determined that the catalytic converter system has failed

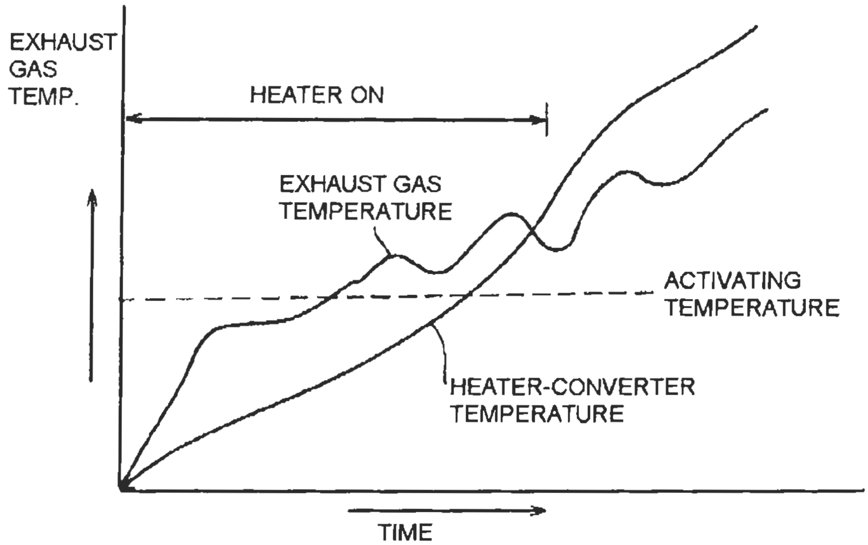


Fig. 130 (from US5447696)

Fig. 130 shows an embodiment of this method. When the engine starts, the exhaust gas temperature starts to increase. The heating of the heater converter also starts to increase and the difference between the exhaust gas temperature and the temperature of the heater converter is maintained relatively small. After an appropriate time, the temperature of the heater-converter reaches the activating temperature of the catalyst, then the temperature of the heater-converter increases rapidly and becomes higher than the exhaust gas temperature. Therefore, if the temperature of the heater converter is lower than the exhaust gas temperature by more than a predetermined value even after the heater is ON, it can be considered that the converter system has failed.

The method described in patent application **WO9636863 (1996)** concerns a durability test of a catalytic converter. A relationship between the catalyst bed temperature and deterioration rate of the catalyst is formed. The durability test takes place at a bed temperature higher than the temperature in field conditions of the vehicle. The period of time for the test is determined from the relationship between the catalyst bed temperature and the deterioration of the catalyst so as to obtain the same extent of deterioration as that under field conditions. So the time of the test can be much shorter than that under field conditions of the vehicle.

The method of **JP8270438 (1996)** comprises the following steps:

1) measuring the actual temperature of a catalytic converter by means of a temperature sensor
2) estimating the temperature of the converter, if the converter has a predetermined deterioration grade, based on the actual operating condition of the engine and the external environment of the converter
3) calculating the difference between the actual and the estimated temperature values of the converter
4) assessing the efficiency of the catalytic converter from the calculate temperature difference of step 3.

The method of **JP8284648 (1996)** is based on the fact that the activation time of a deteriorated catalytic converter is longer than the activation time of an efficient catalytic converter. An oxygen sensor is installed downstream of the catalytic converter. The time required for the sensor to be warmed up to its activation temperature is measured starting from cool engine conditions. The catalytic converter is judged as deteriorated when the measured value of activation time of the sensor is larger than a predefined threshold.

The method of patent application **EP0756071 (1997)**comprises the steps of:

1) measuring the temperature T_2 in the center portion of the downstream side of the catalytic converter
2) assuming a temperature T_2' in the center portion of the downstream side of the catalytic converter on the basis of the operation condition of the engine
3) calculating a ratio of a varying value of the measured temperature T_2 (step 1) to a varying value of the assumed temperature T_2' (step 2)
4) determining that the catalytic converter is deteriorated when said ratio is smaller than a predetermined value.

Fig. 131 shows the relationship between the assumed temperature T_2' and the measured temperature T_2 according to the invention. As shown by the solid line, when the catalytic converter is new, the assumed and measured temperatures are almost equal. For deteriorated converters (dashed line), the purification becomes so poor so that the measured temperature thereof is always lower than the assumed temperature thereof after the converter starts the purification reaction.
When the slope of the dashed line becomes smaller than a threshold slope, the catalytic converter is considered as deteriorated.

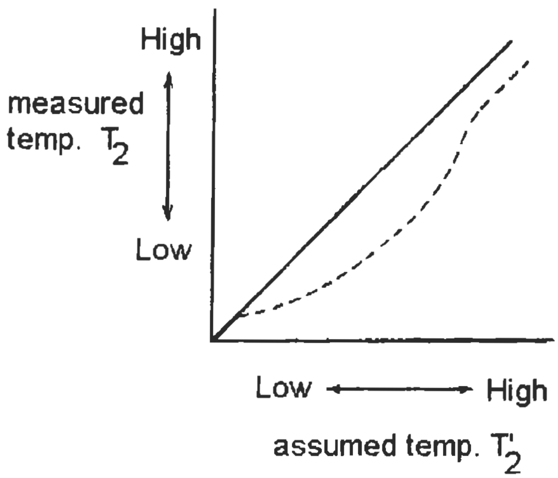


Fig. 131 (from EP0756071)

In the method of **DE19701355 (1997)**, an electric heater is installed upstream of the catalytic converter to heat the exhaust gas during light-off of the catalytic converter. When the engine idles and certain engine predetermined deterioration operating conditions (except the activation temperature of the converter) are satisfied, the electrical heater is supplied with electric current to heat the catalytic converter to its activation temperature. When the duration of time that the electrical heater needs to maintain the operation of the converter is longer than a predetermined time duration then the catalytic converter is considered as deteriorated.

The methods of **EP0770768 (1997)** and **EP0786586 (1997)** comprise the following steps:

1) detecting the temperature of the exhaust gases downstream of the catalytic converter by means of a temperature sensor
2) detecting the oxygen concentration of the exhaust gases upstream of the catalytic converter by means of an oxygen sensor
3) calculating a degree of performance of the catalytic converter in a predetermined period based on the detected temperature and oxygen concentration of the exhaust gases

4) cumulatively adding the degree of performance of the catalytic converter in the predetermined period to obtain an accumulative value
5) evaluating the deterioration of the catalytic converter on the basis of the accumulative value

The degree of performance of step 3 in the predetermined period is calculated based on a rate of performance deterioration K of the converter. K is calculated from one of the following methods:

1) from the equation:

$$\ln K = k_1 - k_2 \cdot \frac{1}{T} + \alpha \ln[O_2]$$

where:
k_1, k_2, α: constants
T: temperature of the exhaust gases
$[O_2]$: concentration of oxygen in the exhaust gases

2) is expressed by a rate of change of a purification ratio ψ of the exhaust gases shown by the equation:

$$\psi = \psi_0 - A \cdot \exp\left(\frac{-B}{T}\right) \cdot [O_2]^{\alpha} \cdot t^m$$

where:
ψ_0: a purification ratio of the exhaust gas at the time of start of use of the converter
A, B, α: constants
T: temperature of the exhaust gases
$[O_2]$: concentration of oxygen in the exhaust gases
t: an operating time
m: a positive value of not more than 1.0

3) is expressed by a rate of change of a degree of decrease $ln(1/\psi)$ of a purification ratio ψ of the exhaust gas shown by the equation:

$$\ln\left(\frac{1}{\psi}\right) = k \cdot t^m$$

where:
k: constant
t: an operating time
m: a positive number

Next, an explanation will be made of the method of evaluating the deterioration of the three-way catalytic converter based on the strictly found purification ratio ψ of the exhaust gas. As explained above, the strictly found purification ratio ψ of the exhaust gas is given by the following equation:

$$\psi = \psi_0 - A \cdot \exp\left(\frac{-B}{T}\right) \cdot [O_2]^{\alpha} \cdot t^{m}$$

Here, the constants A, B, alpha , and m are found from experimental values. The curves ψ_1, ψ_2, ψ_3, ψ_4, and ψ_5 shown in Fig. 132 show the purification ratios of the exhaust gas calculated based on the above equation.

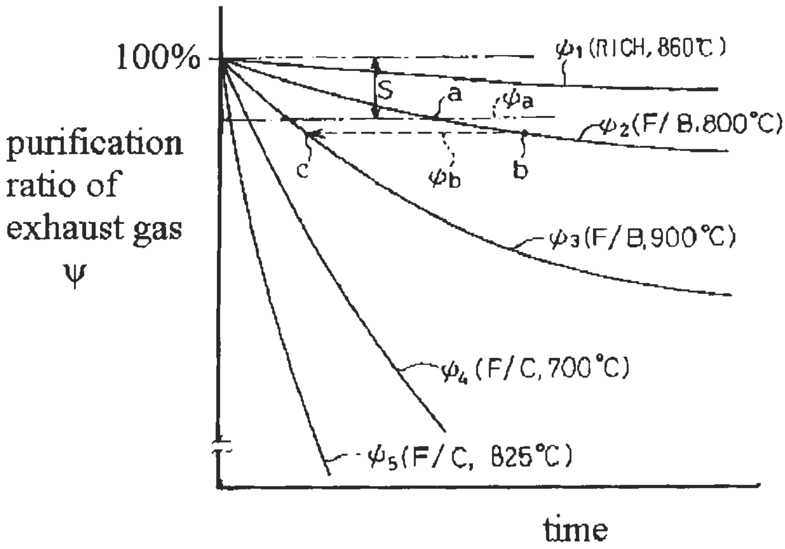


Fig. 132 (from EP0786586)

Focusing on any one of the curves in Fig. 132, for example, the curve ψ_2, the inclination

$$-\frac{d\psi_2}{dt}$$

of the curve ψ_2 gradually becomes smaller along with the operating time. Therefore, the rate of deterioration K, which is expressed by this inclination also becomes smaller along with the operating time. In other words, the rate of deterioration K becomes smaller as the purification ratio ψ of the exhaust gas becomes lower. Accordingly, when evaluating the deterioration of the three-way catalytic converter based on the strictly found purification ratio ψ of the exhaust gas, the rate of deterioration K becomes a function of the temperature T of the catalytic converter, the concentration of oxygen in the exhaust gas, and the operating time or the purification ratio ψ of the exhaust gas.

The method of **EP0786656 (1997)** tests the durability of an exhaust gas catalytic converter by creating the same state of deterioration of the exhaust gas catalytic converter as if a vehicle were actually market driven for a predetermined target driving distance or target driving time. The method comprises the following steps:

1) obtaining in advance a relationship between a magnitude of stress causing deterioration of an exhaust gas purification catalytic converter and a representative value indicative of the degree of deterioration of the performance of the catalytic converter. The stress causing deterioration of the performance of the catalytic converter is the temperature of the catalytic bed whose increase causes an increase of the degree of deterioration of the performance of the catalytic converter. The representative value indicative of the degree of deterioration of the performance of the catalytic converter is the rate of deterioration K of the performance of the catalytic converter which becomes faster with an increase of the temperature of the catalytic bed.
2) obtaining a shortened deterioration time taken for the catalytic converter to reach about the same degree of deterioration as when the vehicle is market driven for the target driving distance or target driving time under a higher stress than the catalytic converter has when the vehicle is market driven from the above relationship
3) applying high stress to the catalytic converter over the shortened deterioration time in operating the engine or the vehicle.

The rate of deterioration K of the performance of the catalytic converter is determined by making use of the method of the patent disclosure **EP0770768 (1997)** mentioned above.

Chapter 2.8

NGK Insulators Ltd.

The method of **EP0779416 (1997)** presented below is applied to the engine layout of fig. 133. The exhaust gas system of fig. 133 comprises a 2.0 liter in-line four-cylinder engine, a 600 cc light-off catalytic converter connected to the engine and a 1.700 cc main catalytic converter connected to the light-off catalytic converter. The light-off catalytic converter is provided at a position 500 mm from the discharge port of the engine; and the main catalytic converter is provided at a position 400 mm from the lower end of the light-off catalytic converter. Temperature sensors are fitted upstream and downstream of the light-off catalytic converter. Further upstream of the light-off catalytic converter is fitted an oxygen sensor for air/fuel control. The outputs of the temperature sensors are sent to an electronic control device unit (ECU) for measurement, control and calculation.

The exhaust gas generated in the engine passes through the light-off catalytic converter and is discharged. The ECU reads the signals sent from the temperature sensors, calculates the cumulative value of generated heat amount and, depending upon the level of the value, issues a signal for lighting of a Malfunction Indicator Light (MIL) or the like.

More specifically, the performance reduction of the light-off catalytic converter is achieved by:

1) detecting a decrease in the heat amount E_g, which is generated from a unit volume of the exhaust gas in a unit time by the reaction of the exhaust gases treated by the converter, or
2) detecting a decrease in the cumulative heat amount E_g, which is generated from the exhaust gas in a predetermined temperature range taken by the converter during its temperature increase. The cumulative heat amount is obtained by cumulating each average heat amount which is generated from a unit volume of the exhaust gas in a

unit time by the reaction of the exhaust gases treated by the converter. The lower limit of the predetermined temperature range is 100-200 °C and the upper limit is 200-400 °C.

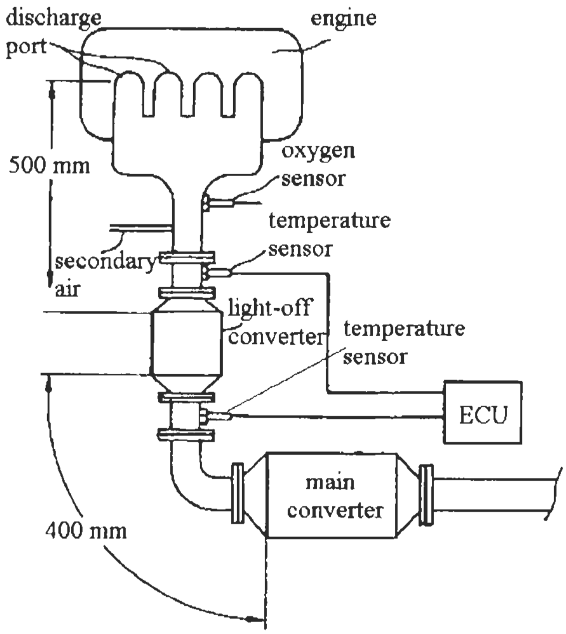


Fig. 133 (from EP0779416)

Fig. 134 shows the heat balance of a catalytic converter. E_{in} is the heat amount possessed by an exhaust gas entering the converter per unit time; E_{out} is the heat amount possessed by an exhaust gas leaving the converter per unit time; E_r is the heat amount released from the converter per unit time; and E_c is the heat amount required to change the temperature of the converter. The following formula holds:

$$E_{out} = E_{in} + E_g - E_c - E_r$$

where

$$E_{in}(cal/\sec) = Q \cdot H_s \cdot T_1$$

$$E_{out}(cal/\sec) = Q \cdot H_s \cdot T_2$$

H_s is the specific heat of the exhaust gas
Q is the volume of the exhaust gas per unit time
T_1 is the temperature of the exhaust gas entering the catalytic converter and
T_2 is the temperature of the exhaust gas leaving the catalytic converter

E_r can be calculated by the following formula, when the engine is operated in a steady state with no noble metal supported on the converter

$$E_r(cal/\sec) = Q \cdot H_s \cdot (T_1 - T_2)$$

A plurality of E_r is determined in various steady states of different catalyst temperatures. A relation between catalyst temperature and E_r can then be obtained.

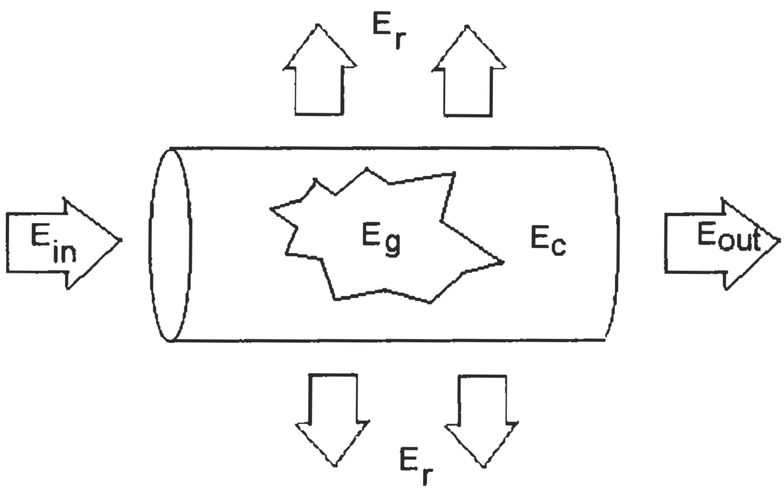


Fig. 134 (from EP0779416)

E_g is calculated as follows:

When the engine is operated with no noble metal supported on the catalytic converter, only Eg can be regarded as zero during the period after engine start but before steady state. Hence, the heat balance formula becomes

$$E_c = E_{in} - E_{out} - E_r$$

or

$$\Sigma E_c = \Sigma(E_{in} - E_{out} - E_r)$$

By measuring T_1, T_2, Q and the temperature of the catalyst per each unit time during the period after engine start but before steady state and by using E_r, ΣE_c in certain temperature range can be calculated from the above mentioned formula. By preparing a graph showing a relation between the temperature of the converter and ΣE_c and determining the inclination thereof, E_c can be determined.

Thus, E_{in}, E_{out}, E_r and E_c can be calculated from various measurement values. Consequently E_g can be calculated from the determined values of E_{in}, E_{out}, E_r and E_c.

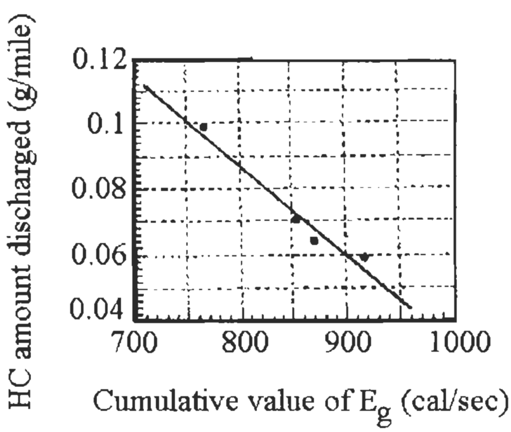


Fig. 135 (from EP0779416)

Fig. 135 shows a relation between the cumulative value of generated heat amounts E_g and the amount of HC discharged. The coefficient of correlation between the cumulative value of generated heat amounts E_g and the amount of HC discharged is 0.956 and the correlation between them is high. The HC limit for new ULEV in the FTP test cycle is 0.04 g/mile. The cumulative value of generated heat amounts E_g when the hydrocarbon amount discharged has reached 1.5 times the above HC limit i.e. 0.06 g/mile, can be obtained from fig. 135. Thus a malfunction indication lamp (MIL) can be lighted when the cumulative value of E_g of a vehicle has reached the value obtained above from fig. 135.

The method of **EP0780551 (1997)** is applied on the upstream front side of a light-off catalytic converter installed upstream of a main converter (fig. 133). The performance reduction of the light-off catalytic converter is achieved by detecting the increase in activation temperature of the light-off converter i.e. by detecting an increase in the temperature of an exhaust gas flowing into the light-off catalytic converter, necessary for its activation. More specifically, the activation of the light-off converter is detected by examining whether the difference between the temperature of the exhaust gases upstream and downstream of the light-off catalytic converter has reached a predetermined level (-50 °C to 200 °C).

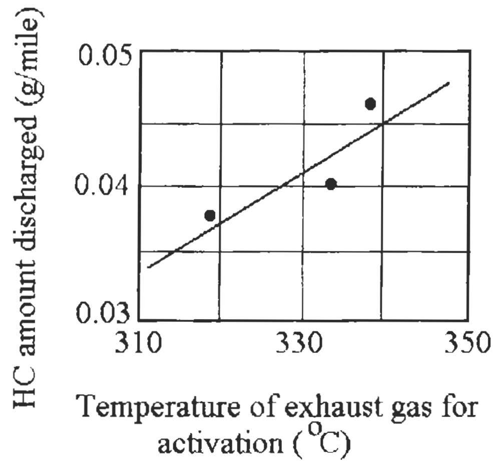


Fig. 136 (from EP0780551)

Fig. 136 shows a relation between the exhaust gas temperature for activation and the HC amount discharged when the difference in temperature between the downstream face and the upstream face of the upstream light-off catalytic converter has reached 50 °C (at this temperature difference, the catalytic converter is judged to have been activated). The coefficient of correlation between the exhaust gas temperature for activation and the hydrocarbon amount discharged is 0.861 and the correlation between them is high.

As discussed in the previous method, the HC limit for new ULEV in the FTP test cycle is 0.04 g/mile. The exhaust gas temperature for activation when the hydrocarbon amount discharged has reached 1.5 times the above HC limit i.e. 0.06 g/mile, can be obtained from fig. 136. Thus a malfunction indication lamp (MIL) can be lighted when the exhaust gas temperature for activation of a vehicle has reached the value obtained above from fig. 136.

Chapter 2.9

General Motors Corporation

The method of **US5444974 (1995)** comprises the following steps:

1) producing an electrical signal from a calorimetric sensor located downstream of the catalytic converter. The sensor comprises a first element bearing an oxidation catalyst for CO and HC and an adjacent second catalyst-free element but otherwise identical in mass and exhaust gas profile to the first element. The electrical signal is directly related to a temperature difference between the two elements
2) monitoring the engine air/fuel ratio, the calorimetric sensor temperature and the exhaust gas flow rate
3) deciding the efficiency judgement of the catalytic converter when the engine air/fuel ratio, the calorimetric sensor temperature and the exhaust gas flow rate are of predetermined values
4) repeating steps 2-3 many times and collecting the data produced
5) assessing the condition of the catalytic converter by statistically analyzing the collected data and comparing the statistical results to predetermined ones

The method of **US5630315 (1997)** comprises the following steps:

1) measuring a first temperature of the engine exhaust gas flowing into the catalytic converter before the gas enters the catalytic converter catalyst
2) measuring a second temperature of the catalytic converter catalyst
3) determining a first value of mass air flow into the engine
4) determining a second value indicative of exothermic activity of the catalytic converter responsive to the first and second temperatures

5) storing the first and second values in respective first and second tables, each table having at least n table locations
6) repeating steps 1 to 5 until the first and second tables are filled
7) comparing a first difference between a first minimum and a first maximum of the first values stored in the first table to a first predetermined threshold
8) comparing a second difference between a second minimum and a second maximum of the second values stored in the second table to a second predetermined threshold and if the first and second differences are respectfully less than the first and second predetermined thresholds, then:
9) updating a filtered exotherm value according to the second value indicative of exothermic activity and
10) comparing the filtered exotherm value to a threshold, wherein filtered exotherm values below the threshold are indicative of an improperly operating catalytic converter.

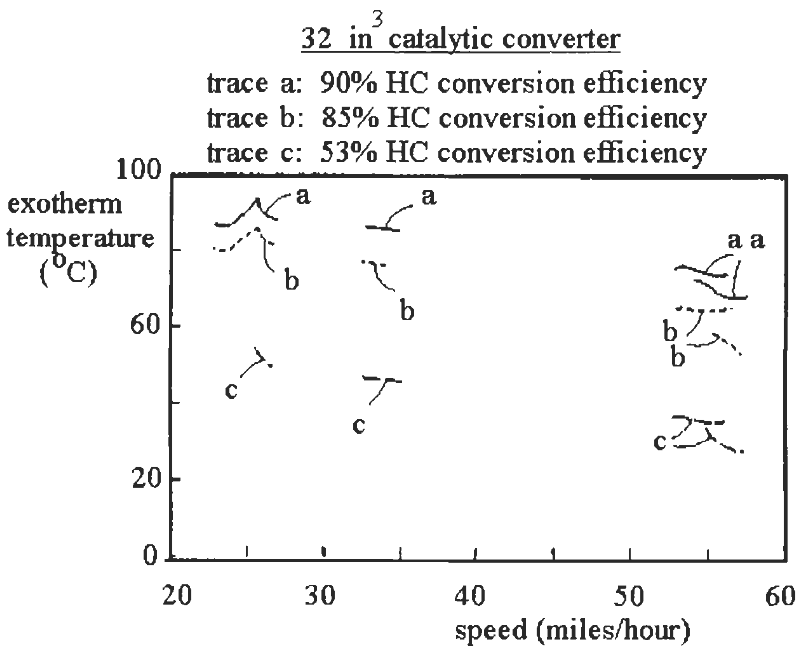


Fig. 137 from (US5630315)

Fig. 137 illustrates example catalytic converter operating efficiencies for a 32 cubic inches catalytic converter. The plotted traces a illustrate the exotherm temperature for a test vehicle with a catalytic converter having 90% HC conversion during the test procedure. The exotherms are plotted against vehicle speed that is recorded when the exotherm is recorded. Plot traces b and c illustrate the exotherms of the same converter having 85% and 53% conversion efficiency respectively. Fig. 137 demonstrates the correlation between measured exotherm and converter efficiency according to the method of **US5630315 (1997)**. This correlation determines the operating status of the catalytic converter. The exotherm satisfying the stabilization criteria appears to decrease with increased vehicle speed or, alternatively, increasing flow rates. This decrease in the exotherm is due to a combination of decreasing emissions emitted from the engine with increased speed as well as decreased conversions in the catalytic converter volume being diagnosed which results from increased space velocity in the monitored volume. This change in the exotherm is accounted for to minimize the variability of the sampled exotherms.

Chapter 2.10

Other Methods

• *Audi AG*

In the method of **DE3516981 (1986),** the temperature is measured upstream and downstream of the catalytic converter. Then it is checked if the absolute variations in time of the two temperature signals lie within predetermined ranges and if the absolute variation in time of the speed of the engine exceeds a predefined threshold. If both conditions are satisfied, then the difference between the downstream temperature and the upstream temperature is formed. The magnitude of this temperature difference defines the criterion for determining the condition of the catalytic converter.

• *Hitachi Ltd.*

In the method of **JP3121240 (1991),** the temperature of the exhaust gases downstream of the catalytic converter is stored in a map in relation to the engine speed and the air/fuel ratio supplied to the engine. If, for certain operating conditions, the measured temperature of the exhaust gases downstream of the catalytic converter is found to be smaller than the one calculated from the stored map, then the catalytic converter is judged to be deteriorated.

- ***FIAT Auto S.p.A.***

The method described in **EP0236659 (1987)** makes use of two temperature sensors installed upstream and downstream of the catalytic converter. When the temperature difference indicated by the two sensors surpasses a first threshold then an intermittent alarm indication signal is produced after a predetermined delay. The indication signal continues as long as the temperature difference does not fall below a second threshold lower than the first one. If on the contrary the temperature difference rises further and surpasses a third threshold, which is greater than the first one, then a continuous alarm indication signal is produced.

- ***Universal Oil Products Co.***

In **US3696618 (1972)**, the indication of the performance of the catalytic converter is assessed by measuring the difference in temperature between the gases entering the catalytic converter and a representative temperature of the converter itself.

- ***Willard R. Calvert, Sr.***

In **US4315243 (1982)**, the indication of the performance of the catalytic converter is also achieved by measuring the difference in temperature of the exhaust gases upstream and downstream of the catalytic converter respectively. The temperature is measured by means of thermocouples.

- ***Phywe Systeme Gmbh***

The method of **DE3710268 (1988)** is similar to the one of **US4315243 (1982)** described above.

- ***Lucas Industries PLC***

The method of **EP0442648 (1991)** assesses the performance of a catalytic converter only when a temperature of the engine is greater than a predetermined temperature, or when the speed of the engine is substantially constant and comprises the following steps:

1) measuring the temperature of the exhaust gases upstream of the catalytic converter
2) measuring the temperature of the exhaust gases downstream of the catalytic converter
3) forming the difference between the upstream and downstream temperature
4) multiplying the difference by a rate of mass flow of the exhaust gases to form a product
5) subjecting the product to processing by a transfer function having an integral term to provide a measure of converter operation. The processing step comprises performing an integration or low pass filtering
6) comparing the measure of operation of the converter with a threshold and
7) determining that the catalytic converter is deteriorated when the measure of operation exceeds this threshold

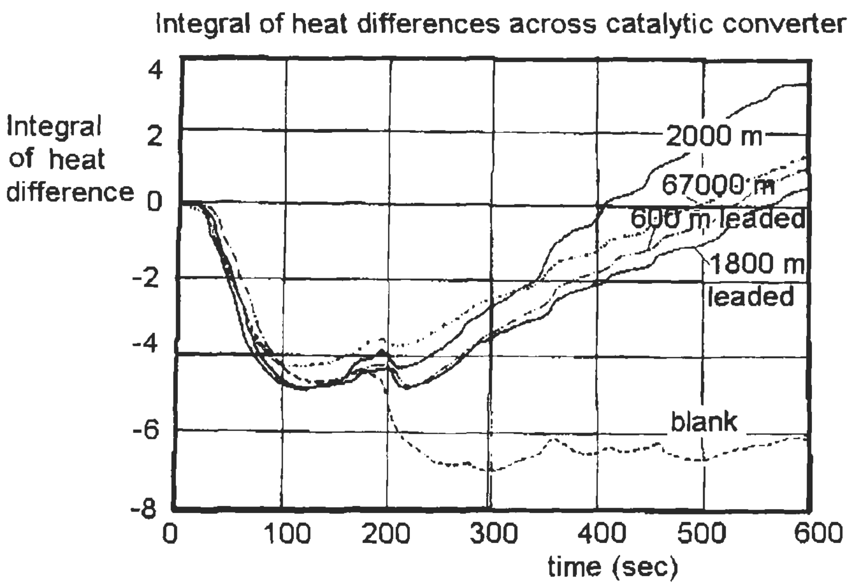


Fig. 138 (from EP0442648)

Fig. 138 shows the integral of heat differences across the catalytic converter vs. time for a catalytic converter subjected to use over 2000 miles, 67000 miles, 600 miles on leaded fuel, 1800 miles on leaded fuel and for a catalytic converter without catalytic substance (blank). The heat differences are calculated as described above in steps 1 to 5. The slope of the curves of fig. 138 is a measure of performance of the catalytic converter. The steeper the slope of the curves the more efficient the catalytic converter is.

- ***Mazda Motor Corp.***

In the method of **JP4060106 (1992)**, a temperature increasing gradient of the catalytic converter is calculated. The gradient is calculated from the temperature of the catalytic converter detected at normal operation and from the temperature of the catalytic converter detected after the air/fuel ratio of the engine is shifted to a rich side when compared to the stoichiometric value. The catalytic converter is considered as deteriorated when the calculated temperature increasing gradient is not in a specified allowable range.

The method of **JP5312024 (1993)** described already in chapter 1.8 can be also applied.

- ***Roth-Technik GmbH & Co. Forschung für Automobil- und Umwelttechniek***

In the method of **DE4228536 (1994)**, the efficiency of a catalytic converter is monitored by means of two temperature sensors, which are located directly on the working surface of the catalyst by means of a thick-film procedure. One sensor is located at the inlet portion of the catalytic converter and the other at the outlet portion of the catalytic converter. The electrical signals produced from the two sensors are proportional to temperature.

- ***Unisia Jecs Corp.***

In **JP7080249 (1995)** a special sensor is used to determine the activity of a catalytic converter. The sensor is installed in the exhaust system and encloses isophthalic acid on which a pair of electrodes are provided in opposite orientation through the isophthalic acid. An active or inactive state of the catalytic converter is discriminated on the basis of the comparison of value of the electric current flowing across the electrodes when constant voltage is applied across the electrodes of the sensor element with a reference electric current value. The flow of electric current depends on the temperature of the exhaust gases.

- ***NGK Spark Plug Co. Ltd.***

The method described in **JP3267517 (1991)** makes use of a sensor installed downstream of the catalytic converter. The sensor comprises two thermistors separated by an insulating layer. On the surface of one of the thermistors, a catalytic layer is formed. When the catalytic converter is effective then both thermistors indicate a similar temperature. When the catalytic converter is deteriorated, then the untreated pollutants react with the catalytic layer of one of the thermistors. When the difference in temperature between the two thermistors becomes high then it is an indication of a deteriorated catalytic converter.

- ***Honda Motor Co. Ltd.***

The method of **US555725 (1996)** assess the efficiency of an electrically heated catalytic converter (EHC). The method comprises the following steps:

1) detecting the voltage applied to the electrically heated catalytic converter
2) detecting electric current flowing through the electrically heated catalytic converter
3) making a changeover between supply and interrupt of power to the electrically heated catalytic converter
4) calculating a parameter indicative of an operative state of the electrically heated catalytic converter, based on the detected current and voltage. The detected voltage is compared with a predetermined reference voltage value, and the detected current is compared with a predetermined reference current value, to calculate the parameter indicative of the operative state of the electrically heated catalytic converter. The parameter can be:
    a) the temperature of the catalytic converter, or
    b) the power consumed by the electrically heated catalytic converter, or
    c) the resistance of the electrically heated catalytic converter
5) detecting the operative state of the electrically heated catalytic converter, based on the parameter thus calculated
6) controlling operation of the switch means, based on an output from the detected operative state of the catalytic converter
7) detecting abnormality of the electrically heated catalytic converter by comparing the detected operative state with predetermined reference values.

- ***Other methods***

Other methods to assess the functionality of catalytic converters by means of temperature measurements can be found in [4], [16] and [23].

The method of [16] attempts to define a method applicable during each driving scenario. Resistance sensors are specially integrated between the metallic foils of the catalytic converter in order to measure the temperature of the exhaust gases. Initially, the deceleration fuel cut-off phase is considered to be a reproducible load condition, suitable for on-board diagnostics purposes. During this phase the temperature difference between the metal catalyst substrate and the exhaust gas entering the converter is obtained. Due to the very small temperature differences during a fuel cut-off phase, it is necessary to intensify the signals so as to enable a clearer distinction between the new and the deteriorated converter. To this end, a well-aimed quantity of fuel can be injected with the help of the fuel injection system with turned off ignition. The goal of this method is to filter out the disturbance effects on grounds of the dynamic influences in the previous history. The temperature signals obtained can be electronically processed by differentiation to distinguish between a working and a degraded catalytic converter (see also [1]).

PART THREE

OTHER METHODS FOR DIAGNOSING THE EFFICIENCY OF CATALYTIC CONVERTERS

Chapter 3

Other Methods for Diagnosing the Efficiency of Catalytic Converters

This chapter comprises methods for diagnosing degradation of the functionality of catalytic converters by using sensors other than oxygen, or temperature sensors. The sensors used usually measure concentration of nitrogen oxide (NO_x) or carbon monoxide (CO) or hydrocarbons (HC) or combinations thereof. The sensors are installed downstream of the catalytic converter or inside the catalytic converter.

These methods allow a direct evaluation of the performance of a converter whereas methods based on oxygen concentration or temperature of the exhaust gases allow only indirect evaluation methods.

Exhaust gas concentration sensors

Most of the HC sensors known in the prior art, either conductivity or calorimetry, can form the basis for providing a signal.

In a semiconductor HC sensor device, a material absorbs combustible gases (HC and/or CO), which absorption changes the conductivity of the material and thus provides an indication of the quantity of HC in the exhaust gas to which it is exposed.

In a calorimetric device, thermocouples are deployed on a divided sensor substrate, one portion of which is catalytic. Combustion of the surrounding gas by the catalytic coating will raise the temperature of this portion above that of the other portion. Comparison of the temperatures of such thermocouples gives a linear indication of the hydrocarbon surrounding the sensor (**CA2077152 (1993)**).

The main problems of such sensors when they are used for on-board detection of catalytic converters are that:
1) they possess no reference to evaluate the sensor signal
2) the devices are bulky and generally inaccurate
3) they cannot operate at the higher temperatures of automotive exhaust gases or operate continuously
4) the calorimetric sensors need an excess of oxygen to operate properly

A number of sensors have appeared recently in the literature that can measure the concentration of different pollutants in the exhaust gas and that can be used for on-board monitoring of catalytic converters. Some representative examples are presented below.

Fig. 139 is a perspective view of a typical catalytic differential calorimetric sensor having a silicon substrate with two membranes and two resistor elements placed on top of the membrane (**US5265417 (1993)**). These resistor elements are covered by a dielectric layer. A catalytic layer is placed on top of one of the membranes (and the corresponding resistor element and the dielectric layer). The other resistor element on the other membrane is used to measure the temperature of the surrounding gas, while the resistor element with the catalytic layer measures the additional heat generated by the oxidation reactions on the catalytic layer. Both membranes are thermally isolated from each other, because they have a low thermal conductivity and the silicon substrate is a good heat sink.

The resistor elements could be part of a Wheatstone bridge, in which case the sensor output is directly proportional to the amount of combustibles in the gas. An alternative method of operating the sensor is to heat the membranes to a set temperature by passing currents through the resistor elements. The difference in both currents would then be a measure of concentration of combustibles present in the gas. The membranes are typically 1 micrometer in thickness and 1 mm in width and are made of a composite structure of silicon oxide and silicon nitride to reduce residual stress. The temperature sensitive resistor elements are typically made of a sputtered platinum film patterned by lithography and a chemical etching.

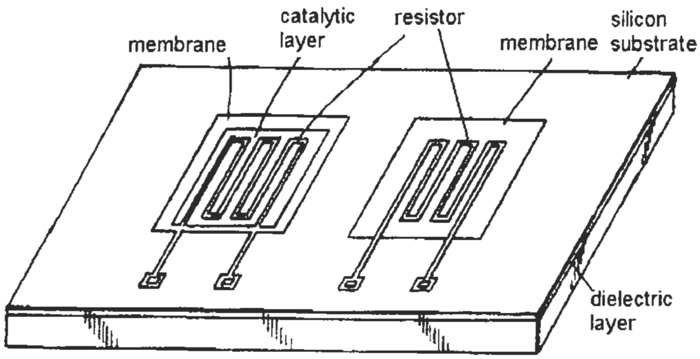


Fig. 139 (from US5265417)

Catalytic layers that may be applied to the catalytic differential calorimetric sensor may be deposited by a variety of techniques such as sputtering, evaporation (E-gun) or by applying a paste. The sensor of fig. 139 is used to monitor the concentration of HC in the exhaust gas.

Fig. 140 illustrates a sensor that can be used for measuring the concentration of hydrogen, CO or HC downstream of a catalytic converter (**US5472580 (1995)**). The sensor comprises an inner electrode which may be platinum, formed on one face of an electrolyte body, and an outer electrode formed on an opposed surface of the electrolyte body. A suitable electrolyte body may be formed from yttria stabilized zirconia. The outer electrode includes a gold-containing layer according to the present invention. For example, the outer electrode may include a platinum electrode and a gold-containing layer formed on top of the platinum electrode.
Alternatively, the outer electrode may be simply a single gold-containing layer. The gold-containing layer may be an alloy which contains at least 28 percent by weight gold.

The gold layer may be deposited by a variety of techniques including sputtering, ink printing, or other thin and thick film deposition techniques. Preferably the thickness of the gold layer ranges from about 0.5 microns to about 12 microns. A protective coating such as spinel may overlay the outer electrode including the gold-containing layer.

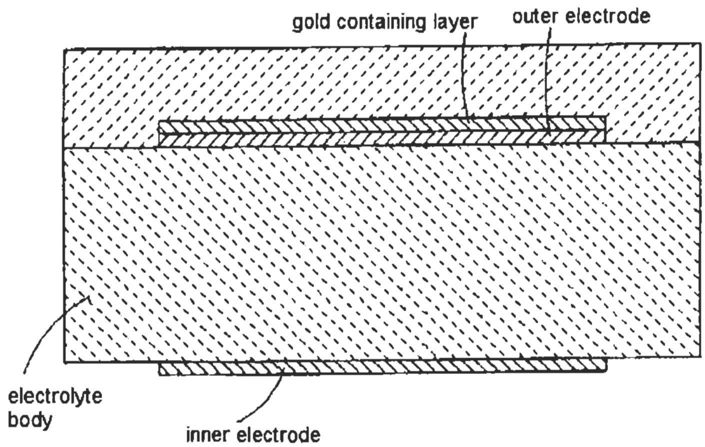


Fig. 140 (from US5472580)

The voltage output produced from the two electrodes of the sensor when they come in contact with the non-combusted pollutants is used for determining the condition of the catalytic converter.

A very promising technique for measuring unburned HC is the use of surface ionization detectors ([25]). The sensor comprises platinum filaments of very small diameter that are kept at high temperatures of about 1000 °C. The platinum filaments produce small currents when subjected to a flow stream containing hydrocarbons. The signal is sensitive to the gas flow rate, the oxygen, hydrogen and carbon monoxide concentrations of the gas, as well as to hydrocarbon molecular structure (fig. 141).

Although the ability of the sensor to detect differences in HC concentration before and after the catalytic converter as well as engine misfires has been demonstrated, significant work remains to be done in order to render the detector feasible for on-board diagnostics purposes. This work concerns detector contamination, processing of very small currents, stability over long-term operation and durability ([1]).

NGK Insulators has presented recently a number of NO_x sensors that can be used for monitoring the automotive exhaust gas. Such a sensor is shown in fig. 142 (**EP0769694 (1997)**). Fig. 142a shows a plan view of the sensor, and fig. 142b shows an enlarged view of principal components, taken along a cross section of A-A shown in fig. 142a.

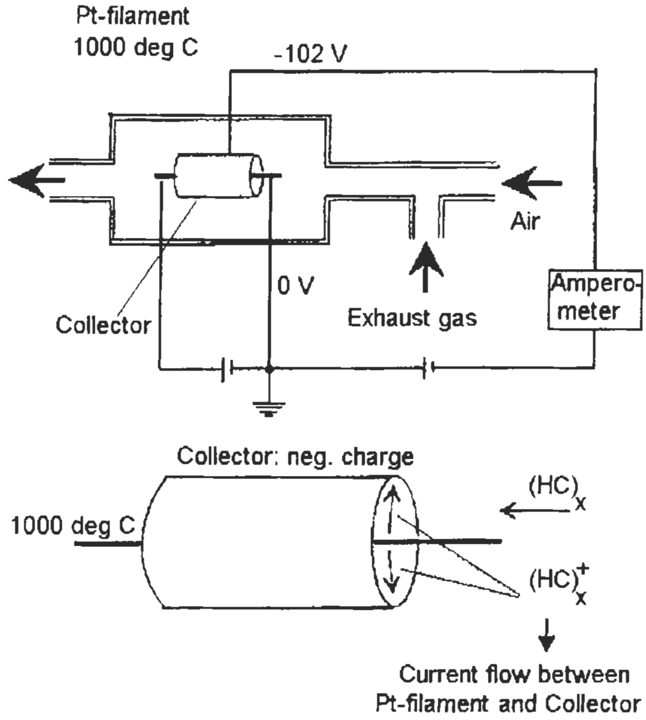


Fig. 141 (from [19], p. 20)

The sensor element comprises a plurality of dense and airtight oxygen ion-conductive solid electrolyte layers (zirconia ceramics) a, b, c, d, e, f stacked up on each other.
It comprises a first internal space into which the exhaust gas is introduced through a first diffusion rate-determining passage, a second internal space arranged with a NO_x reducing catalyst, into which an atmosphere is introduced through a second diffusion rate-determining passage.

An electrochemical pumping cell controls a partial pressure of oxygen in the first internal space by using the first oxygen ion-conductive solid electrolyte a and electrochemical cells provided in contact therewith.
A partial oxygen pressure detecting means detects the partial pressure of oxygen in the first internal space by using the first oxygen ion-conductive solid electrolyte a and electrochemical cells provided in contact therewith.

A first electrochemical sensor cell outputs an electromotive force corresponding to the partial pressure of oxygen in the second internal space. A first potentiometer (voltage detecting means) detects the electromotive force output of the first electrochemical sensor cell.

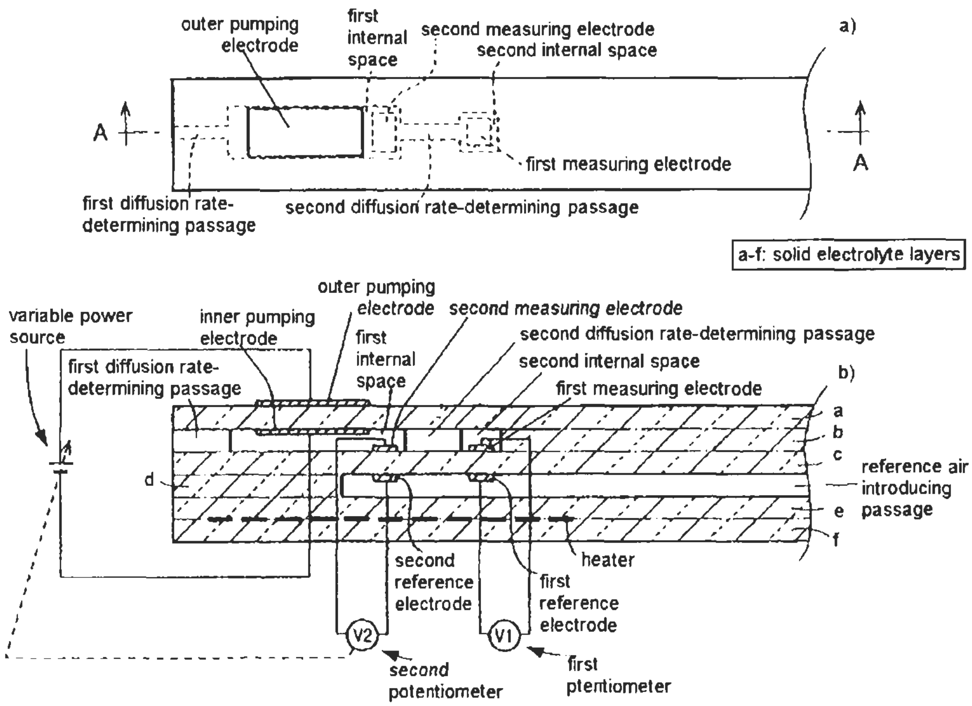


Fig. 142 (from EP0769694)

The NO_x concentration is determined from a value of the electromotive force of the first electrochemical sensor cell detected by the first potentiometer.

Other types of sensors will be presented later in this chapter.

Monitoring and diagnosing set-up

Fig. 143 shows an exemplary monitoring and diagnosing set-up.
In non-OBD methods normally the sensor that measures the content of an exhaust component is introduced in the tail pipe, whereas in OBD methods the sensor is installed downstream or inside the catalytic converter. The system may comprise a λ or oxygen sensor placed upstream of the catalytic converter, additional exhaust gas concentration component sensors installed upstream and/or downstream of the catalytic converter, an exhaust gas analyzer, a control unit (computer) receiving the output signals of all sensors plus information concerning the operation conditions of the engine e.g. engine load, cooling water temperature, intake air flow etc. The control unit processes all the input and can regulate the air/fuel ratio of the mixture fed to the engine as well as the introduction of secondary air in the exhaust system. The control unit may comprise calculation means, integrators, comparators, storage means etc. Air supply means are also controlled to supply the exhaust path with secondary air. Driver warning means are also included for the case where a degraded catalytic converter is detected.

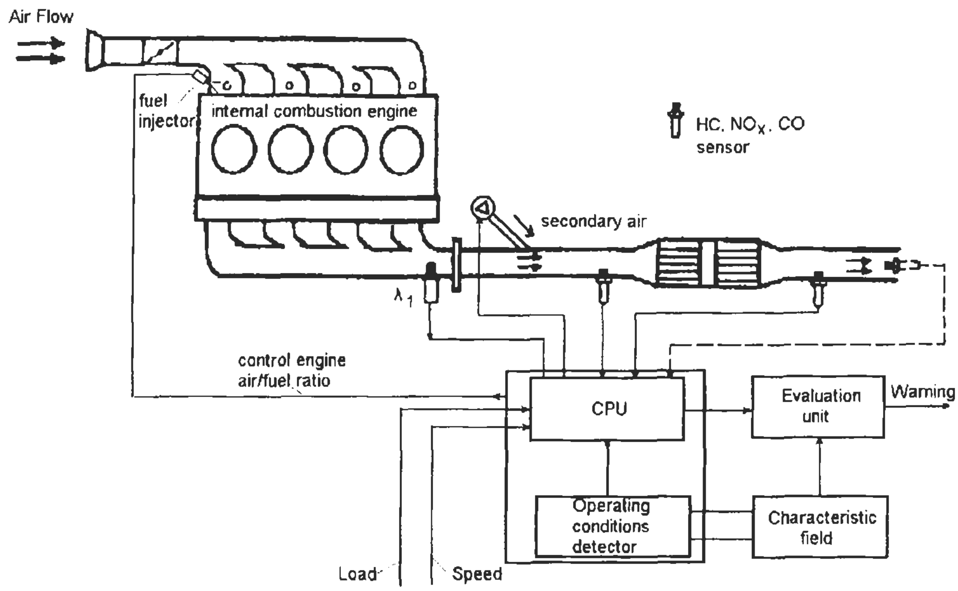


Fig. 143 (from [9], p. 22)

A small number of methods presented in this chapter uses pressure sensing devices in the exhaust pipe of an internal combustion engine in order to assess the functionality of the catalytic converter.

Chapter 3.1

Ford Motor Co. - Ford France SA - Ford Werke AG - Ford Motor Co. Canada - Ford Motor Co. Ltd.

The method of **US5177464 (1993)** and **CA2077152 (1993)** is applied to the set-up of fig. 144. As shown in fig. 144, the on-board monitoring system comprises essentially a test chamber remote from the exhaust stream, means for supplying the test chamber with sampled exhaust gases sequestered from the automobile's engine exhaust stream, a single hydrocarbon sensor exposed to the sequestered exhaust gases in the test chamber to render a signal responsive to the concentration of hydrocarbon in such chamber, and means for comparing the sensed signal with a reference signal.

The means for supplying the chamber particularly comprises a supply channel interconnected between the chamber and the gas stream which is upstream of the catalytic converter, a supply channel independently interconnected between the chamber and the stream which is downstream of the catalytic converter, and valve means for permitting flow-through of no more than one channel to the chamber at any one moment. The valve means may further include a computerized monitoring control module having a routine for alternately opening and closing the valves at a predetermined frequency. Such predetermined frequency may be in the range of 0.1 to 1.0 Hz. The apparatus may further comprise an electronic engine control unit (ECU or EEC) interconnected to the monitoring control module to initiate a catalyst interrogation routine after steady-state conditions and a window of air/fuel, speed/load opportunities are met. These conditions are described in the California Air Resources Board (CARB) regulations designated OBD II. The criteria are specified in these regulations, which are incorporated herein by reference (see Introduction).

The test chamber itself should be relatively small, having a volume sufficient to contain the hydrocarbon sensor surrounded by sufficient volume of sequestered exhaust gas so as to function properly. Such volume may be in the range of 0.2 to 1.0 cubic inch.

To provide reliable operation, a single HC sensor is placed in such chamber so as to eliminate the need for both a hydrocarbon sensor upstream as well as downstream of the catalytic converter, which is costly and leads to durability and reliability problems. The two sensor approach would require that sensor characteristics track over the operating conditions and useful life of the sensors and thereby require some type of jump-back software.

Thus, alternate sampling from upstream and downstream locations communicated to a common test chamber is the approach of this invention. Each sample line connects to remotely located solenoids, the output of which would discharge into the small test chamber. The length and design of the sample lines are chosen to provide adequate cooling of the exhaust gas samples to prevent heat damage to the solenoids of the valves and to the hydrocarbon sensor itself.

It is important that very low sample flow rates be used for proper operation of the invention. Such flow rates may range from as little as 50 cm^3/min to 800 cm^3/min. As a consequence of such low flow rate, deterioration of the hydrocarbon sensor due to the prolonged exposure to exhaust gases will be negligible. The sample flow rate is that of the exhaust gas into the test chamber. In practice, the exhaust gas flow rate into the test chamber would be controlled by connecting the outlet of the chamber to the engine intake manifold through a suitable orifice.

The method comprises the following steps:
1) transferring periodically a downstream sample quantity of gas, taken from a location downstream of the catalytic converter, into the test chamber at a predetermined flow rate.
2) measuring the hydrocarbon content (HC) of the downstream exhaust gas quantity inside the test chamber by means of the hydrocarbon sensor (fig. 144)
3) transferring periodically an upstream sample quantity of gas, taken from a location upstream of the catalytic converter, into the test chamber at a predetermined flow rate. The test chamber should contain at any time exhaust gas from either the upstream or downstream location but not both
4) measuring the hydrocarbon content (HC) of the upstream exhaust gas quantity inside the test chamber by means of the hydrocarbon sensor
5) forming the quotient

$$AZ = \frac{(HC)_1 - (HC)_2}{(HC)_1} x\ 100$$

where:
$(HC)_1$ is the concentration of hydrocarbons upstream of the catalytic converter and
$(HC)_2$ is the concentration of hydrocarbons downstream of the catalytic converter.

6) comparing the quotient AZ with a predetermined quotient, and deciding that the catalytic converter is deteriorated when the difference between the quotient AZ and the predetermined quotient is greater than e.g. 50%.

The transfer of exhaust gas in the test chamber is achieved by alternately closing and opening the two solenoid valves installed in the channels that supply exhaust gas the test chamber.

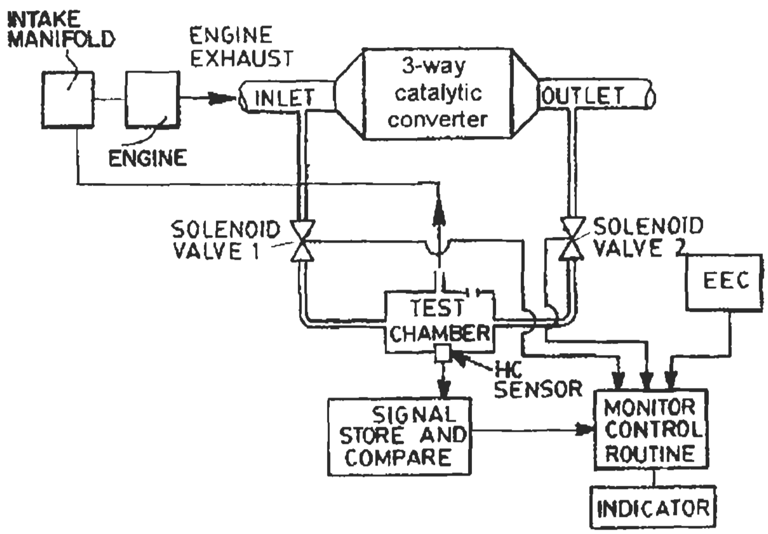


Fig. 144 (from US5177464)

The method of **US5265417 (1993)** uses the configuration of fig. 144 and it is similar to the method of **US5177464 (1993)** described above. The sensor of fig. 139 is also used.

In a first embodiment of the invention a catalytic differential hydrocarbon sensor is used in order to measure the difference in HC content of the exhaust gas samples sequestered upstream and downstream of the catalytic converter.

In a second embodiment two different catalytic sensors are used to measure the HC content of the exhaust gas samples upstream and downstream of the catalytic converter respectively.

In the method of **GB2290883 (1996)** comprises the following steps:

1) training a first neural network to predict the emissions of the exhaust gas upstream of the catalytic converter, by accumulating a plurality of measured exhaust gas emission outputs from a plurality of vehicle operating cycles and from a plurality of vehicles
2) predicting the emissions of the exhaust gas upstream of the catalytic converter by inputting a first set of engine operating condition signals to the first neural network. The first set of signals comprises at least two signals taken from the group consisting of air intake mass flow signal, engine speed signal, upstream oxygen sensor signal, engine fuel signal and exhaust gas recirculation signal
3) training a second neural network to predict the emissions of the exhaust gas downstream of the catalytic converter, by accumulating a plurality of measured exhaust gas emission outputs from a plurality of vehicle operating cycles and from a plurality of vehicles.
4) predicting the emissions of the exhaust gas downstream of the catalytic converter by inputting a second set of engine operating condition signals to the second neural network. The second set of signals comprises at least two signals taken from the group consisting of air intake mass flow signal, engine speed signal, upstream oxygen sensor signal, engine fuel signal, exhaust gas recirculation signal, spark advance signal, downstream oxygen sensor signal and predicted upstream exhaust gas emissions
5) determining the ratio of the predicted emissions upstream of the catalytic converter to the predicted emissions downstream of the catalytic converter
6) comparing this ratio to a predetermined one in order to assess the performance of the catalytic converter.

Chapter 3.2

Volkswagen AG - General Motors Corp.

The method of **DE3809082 (1988)** uses a single gas analyzer for transferring periodically exhaust gas samples from locations upstream and downstream of the catalytic converter (fig. 145). The analyzer measures simultaneously HC, CO and NO_x. A three-way valve is used to deviate the samples from the upstream or downstream locations in the gas analyzer. Depending on the measured noxious content of the exhaust gases, useful conclusions are drawn about the condition of the catalytic converter.

In the method of **DE3935381 (1990)** the catalytic converter is heated to a specified activation temperature by the exhaust gases and then the engine is operated at idling speed. During idling, nitrogen oxide is injected at a controlled rate upstream of the catalytic converter. The nitrogen oxide quantity injected is smaller than the one needed to produce a stoichiometric mixture. The residual concentration of nitrogen oxides downstream of the catalytic converter is then measured by means of an exhaust gas sensor and it is compared with predetermined values to draw conclusions about the condition of the catalytic converter.

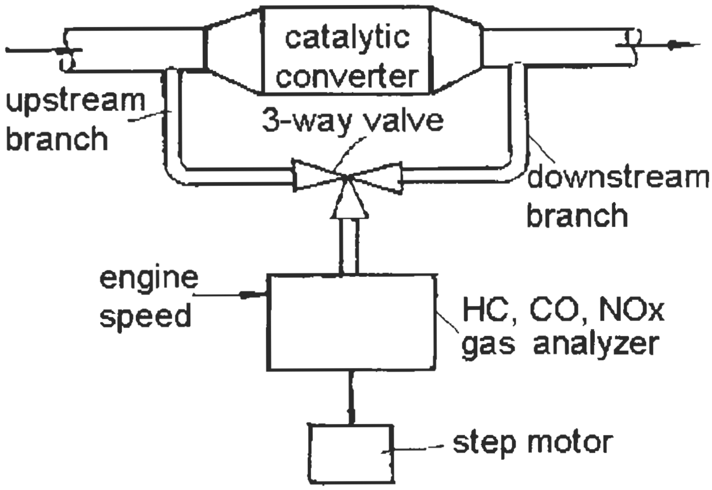


Fig. 145 (from DE3809082)

In the method of **US3766536 (1973)** the pressure of the exhaust gases is measured downstream and inside the catalytic converter. The pressure is proportional to the temperature of the exhaust gases. When the catalytic converter has reached its activation temperature, the pressure difference between the locations downstream and inside the catalytic converter is formed. When the pressure difference is higher than a certain threshold then the catalytic converter is considered as efficient.

The method of **US5431043 (1995)** comprises the following steps:

1) preheating the catalytic converter to its activation temperature
2) disabling the ignition and fuel supply systems of the engine
3) introducing a metered quantity of hydrocarbons (e.g. propane) from a source into the engine upstream of the catalytic converter
4) cycling the engine such that the metered quantity of the hydrocarbons is mixed with air from the engine intake and is pumped, through the cycling of the engine, through the preheated catalytic converter
5) analyzing the levels of hydrocarbons, oxygen and carbon dioxide downstream of the catalytic converter
6) assessing the condition of the catalytic converter from the analysis results

The monitoring method of **US5472580 (1995)** is activated when the combustion engine is operated in a lean air/fuel ratio and comprises the following steps:

1) positioning a sensor in the exhaust gases downstream of the catalytic converter
2) measuring the voltage output from the sensor, responsive to the combustible concentration of hydrogen and/or carbon monoxide in the exhaust gases
3) comparing the voltage output from the sensor with a predetermined value corresponding to known concentration of hydrogen and/or carbon monoxide in the exhaust gases
4) assessing the condition of the catalytic converter from the comparison of the actual and predetermined voltage output values.

The sensor comprises an outer electrode having a first layer comprising a metal, a second layer containing at least 28 percent by weight gold and a solid electrolyte body between the two electrodes (see fig. 140).

In the method of **DE4426788 (1995)** NO_x, or oxygen or temperature sensors are used upstream and downstream of the catalytic converter to determine the efficiency of the converter. Three different cases are then distinguished:

1) When a diminution of the NO_x-reduction capability is observed, then the quantity of the recirculated exhaust gas (EGR) is increased
2) When the deactivation of a heated catalytic converter (EHC) progresses from the exhaust gas intake side of the converter, then the heating process is extended in time
3) When the deactivation of a catalytic converter supplied with secondary air progresses from the exhaust gas intake side of the converter, then the supply of secondary air is extended in time

In the method of **DE19645202 (1997)** a HC sensor is installed downstream of the catalytic converter, whereas an oxygen sensor is installed upstream of the catalytic converter. The method comprises the following steps:

1) starting the engine from cold
2) summing the measured HC emissions downstream of the catalytic converter during a fixed time window after starting the engine from cold
3) storing electronically the summed values of step 2
4) comparing the stored summed value of step 3 with a predetermined threshold
5) triggering a fault signal , when the comparison of step 4 indicates a certain deviation

The method can be explained by means of fig. 146, where the concentration of HC downstream of the catalytic (curves 1,2) as well as the temperature T of the exhaust gases upstream of the converter (curve 3) in function of time t are presented. Curve 1 corresponds to the measured concentration of HC downstream of a new catalytic converter. Curve 2 corresponds to the measured concentration of HC downstream of a deteriorated catalytic converter. Till time point t_1, both curves show a similar behavior, so this region is not suitable for evaluating the efficiency of the catalytic converter.

The time interval dt corresponds to the time window during which the evaluation of the efficiency of the converter takes place. Points t_1 and t_2 correspond to the beginning and end of the time window. The shaded area corresponds to the summated concentration of HC downstream of the catalytic converter. The area measured for the case of a new converter (curve 1) is used as the threshold for comparison of step 4. Large areas correspond to highly deteriorated catalytic converters (curve 2).

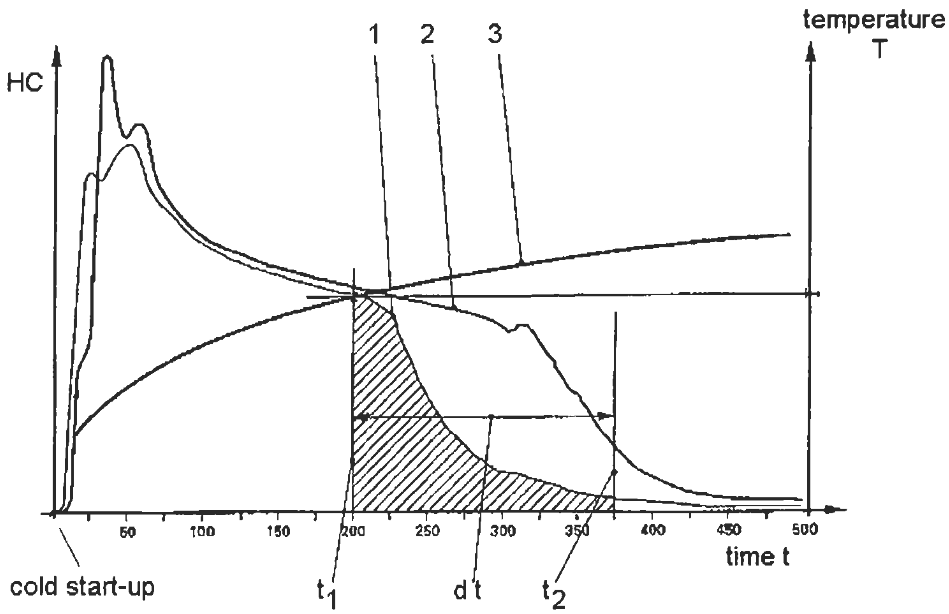


Fig. 146 (from DE19645202)

Chapter 3.3

Hitachi America Ltd. - Hitachi Ltd.

The method of **DE4402850 (1994)** detects the functionality of a nitrogen oxide (NO_x) catalytic converter installed downstream of a three-way catalytic converter of an exhaust system. Two NO_x concentration sensors are installed in the exhaust pipe to measure the concentration of NO_x in the exhaust gases during testing. A first NO_x sensor is installed between the three-way converter and the NO_x converter whereas the second sensor is installed downstream of the NO_x converter. The output signals of the two sensors are determined and the following efficiency coefficient is calculated:

$$AZ = \frac{(NOx)_1 - (NOx)_2}{(NOx)_1}$$

where:
$(NO_x)_1$ is the NO_x concentration of the exhaust gases upstream of the catalytic converter and
$(NO_x)_2$ is the NO_x concentration of the exhaust gases downstream of the catalytic converter.

If the efficiency coefficient value AZ is less than a threshold ε the catalytic converter is considered as deteriorated.

The method of **DE19708225 (1997)** is applied on the layout of fig. 147. An air filter, an air intake mass sensor, a throttle valve sensor and an ISC idling valve to regulate the air during idling are installed in the air intake of the engine. A fuel injector injects fuel in the air intake and a spark plug ignites the air/fuel ratio in the engine cylinder. The speed of the engine is measured by means of a crank angle sensor and the cooling water temperature is measured by means of a water temperature sensor. Upstream of the catalytic converter, an air/fuel ratio sensor measures the air/fuel ratio content of the exhaust gases in order to feedback-control the engine air/fuel ratio, whilst a HC sensor downstream of the converter measures the content of HC in the exhaust gases. In place of a HC sensor, a NO_x or an air/fuel sensor can be used.

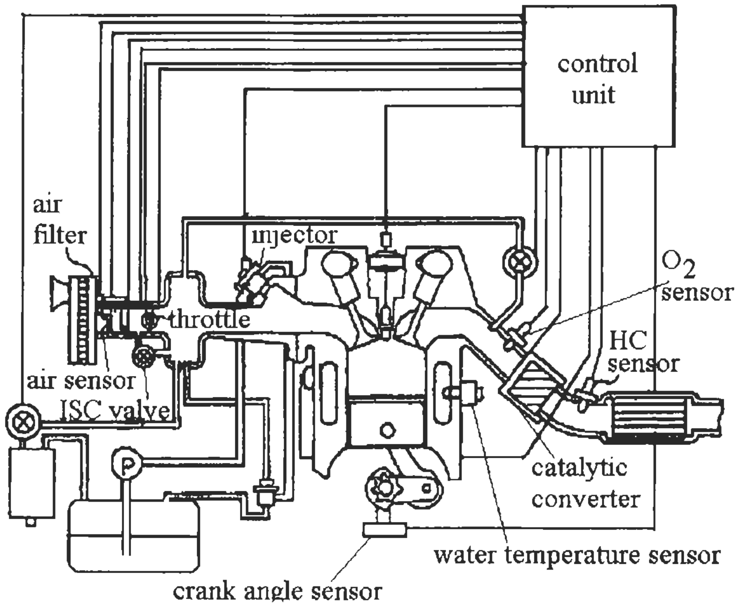


Fig. 147 (from DE19708225)

A control unit receives the output signals of all sensors and it controls the fuel injection and the ignition of the air/fuel ratio in the cylinder. Additionally, the control unit determines whether or not the operating conditions of the engine are appropriate for a catalytic converter efficiency diagnosis and determines the efficiency of the catalytic converter.

The method comprises the following steps:

1) measuring the HC or the air/fuel ratio or the NO_x content of the exhaust gases downstream of the catalytic converter by means of the HC sensor or the air/fuel ratio sensor or the NO_x sensor respectively
2) determining the temperature of the catalytic converter and/or the operating conditions of the engine and when the temperature of the converter and/or the operating conditions of the engine satisfy certain conditions then
3) integrating the measured output signal of the downstream sensor
4) averaging the integrated value calculated at step 3
5) determining the efficiency of the catalytic converter by comparing the averaged integrated value with a predetermined threshold

If a HC sensor is used downstream of the catalytic converter, then an averaged value of the integral calculated at step 3 can be expressed as follows:

$$AZ = \frac{\int \left[(HC)_2 \, \dot{Q}_{air} \, \frac{molecular\ weight\ HC}{molecular\ weight\ air} \right] dt}{\int \dot{Q}_{air} \, dt} \quad \text{(in g/Kg), or}$$

$$AZ = \frac{\int \left[(HC)_2 \, \dot{Q}_{air} \, \frac{molecular\ weight\ HC}{molecular\ weight\ air} \right] dt}{\int V \, dt} \quad \text{(in g/Km)}$$

where:
V is the driving speed of the car
$(HC)_2$ is the concentration of HC downstream of the catalytic converter
$\dot{Q}_{air}$ is the intake air volume

When the average value of AZ is greater than a predetermined threshold, then the converter is considered as deteriorated. Only one HC sensor is necessary for the deterioration detection.

Fig. 148 shows the relationship between the temperature of the catalytic converter and the HC purification ability. The behavior of a new converter is shown as well as the behavior of three deteriorated converters (a to c). Converter a) concerns a converter with such a high temperature that can purify 90% of existing HC (as a new converter). Converter (b) concerns a converter with low HC purification ability. Converter c) concerns a converter with low HC purification ability, although the activation temperature of the converter is as high as that of a new converter. T_1 is the time, in which the integrated value of the intake air volume $\dot{Q}_{air}$ lies between certain limits ε_1 and ε_2. T_2 is a predetermined time period, that starts at the time point that the integrated value of the intake air volume $\dot{Q}_{air}$ is equal to ε_2. Both T_1 and T_2 depend on the temperature of the catalytic converter as well as on the time after engine start up.

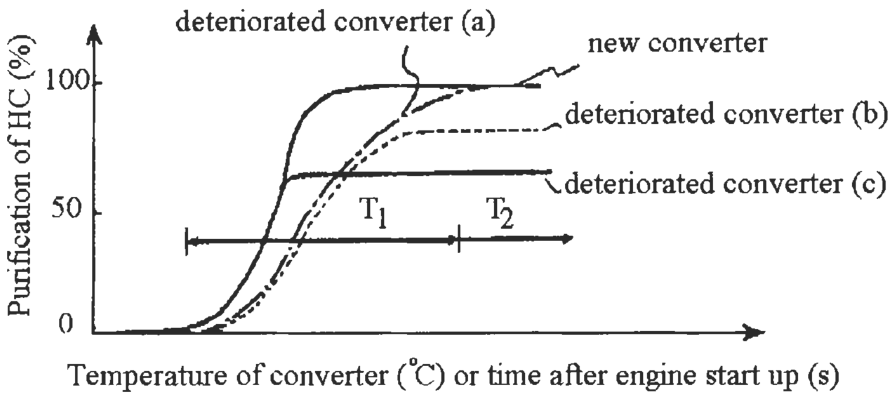


Fig. 148 (from DE19708225)

Fig. 149 shows the averaged values AZ of the HC quantity, that is estimated for each of the deteriorated catalytic converters (a to c) of fig. 148. By choosing suitable integration periods T_1 and T_2 and by setting suitable thresholds of AZ, it is possible to determine the deterioration of the catalytic converter.

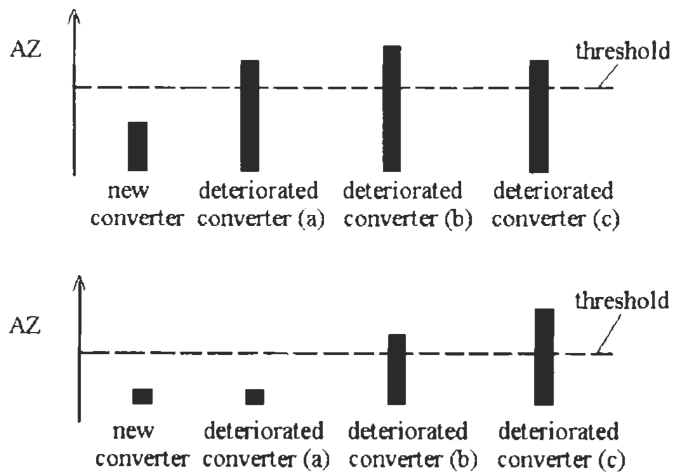


Fig. 149 (from DE19708225)

Chapter 3.4

Robert Bosch GmbH

The method of **DE19537788 (1997)** is applied for the engine layout of fig. 150.
The engine of fig. 150 is a Diesel engine with an a exhaust system comprising an oxidation catalytic converter and/or a reduction catalytic converter. A temperature sensor is installed upstream of the converter and fuel (HC) is supplied to the exhaust gases by means of a fuel metering device. The quantity of hydrocarbons supplied is dependent on the operation parameters of the engine and is used for reduction of NO_x in the catalytic converter. A HC sensor installed downstream of the converter(s) measures the content of HC in the exhaust gases and an air flow meter measures the quantity of intake air. A rotational speed sensor measures the rotational speed of the engine and a fuel metering device meters the fuel injected to the engine. An electronic control unit receives information from the sensors and adjusts the fuel quantity injected in the engine and the quantity of HC supplied to the exhaust pipe. A monitoring device checks the efficiency of the catalytic converter.
In case of a deteriorated converter, the quantity of HC supplied to the exhaust gases does not reduce NOx but contributes to additional pollution.

The method comprises the following steps:
1) checking whether certain operating conditions of the engine which depend on the rotational speed of the engine and the injected fuel quantity are fulfilled, and in case they do
2) measuring the content of HC in the exhaust gases downstream of the catalytic converter by means of the HC sensor

3) determining a first parameter which is a measure of the time interval during which a significant monitoring of the catalytic converter takes place
4) determining a second parameter which is a measure of the time interval during which the catalytic converter works normally. A normal operation of the catalytic converter means that the measured HC content of the exhaust gases downstream of the converter is not higher than a predetermined threshold. This threshold depends on the temperature of the exhaust gases or the injected fuel quantity or the rotational speed or the metered quantity of HC supplied to the exhaust gases
5) determining the deterioration of the catalytic converter by comparing the two parameters

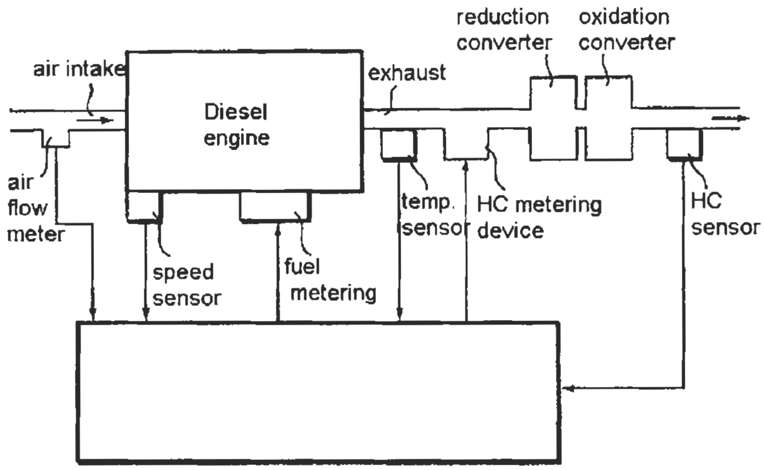


Fig. 150 (from DE19537788)

In the method of **WO9715468 (1997)** it is judged whether the damage to a catalytic converter was due to a critical low level of the fuel in the fuel tank. In such cases and especially when the vehicle goes uphill or downhill, the fuel pump sporadically supplies the engine with gas instead of fuel. As a result of this one or more cylinders of the engine misfire and the non-burnt fuel in the cylinders is burnt in the catalytic converter. Misfiring provokes then overheating of the converter that can lead to damages.

A fuel level indicator indicates the level of the fuel in the tank. The indicated fuel levels together with engine misfires are stored in a memory. Where misfires and critical fuel levels (indicated by a fault indicator light) are found to be present simultaneously, the stored data are linked in the memory so that it is possible when the linked stored data are read out later to ascertain whether or not the misfires were caused by a critical fuel level. In this way it can be proved whether or not the damage to the converter was provoked by a mistake of the driver.

Chapter 3.5

Other Methods

- ***Monsanto Co.***

The method of **US3667914 (1972)** tests a catalyst in a laboratory and comprises the following steps:

1) cyclically passing a combination of oxygen rich and oxygen poor exhaust gases through a catalyst charge for predetermined time intervals at a desired temperature to cause attrition of the catalyst charge
2) adjusting the rate of flow of the exhaust gases in accordance with the kinetic reaction conditions existing during attrition of the catalyst charge
3) periodically passing a catalytically inactive gas through the catalyst charge at a linear flow rate which is substantially higher than the rate of flow of the exhaust gases
4) measuring a pressure drop across the catalyst charge during the passing of the neutral gas through the charge. An increase in pressure drop measured in a time interval span is proportional to the degradation of the catalyst

• *Beckman Industries, Inc.*

In the method of **US4116053 (1978)**, secondary air is injected upstream of the catalytic converter in order to create a thermal reaction of the exhaust gases and to dilute the HC and CO existing in the exhaust gases. A dilution factor *DF* is estimated from the formula

$$DF = \frac{Injected\ air\ volume}{Total\ exhaust\ volume}$$

A family of working curves graphing the conversion efficiency of the whole exhaust system against the CO at the tailpipe as a function of the various oxygen dilution levels to be found in the exhaust gases is used in conjunction with the present test procedure. The method comprises the following steps:

1) disabling secondary air injection
2) verifying that the engine is running properly at curb idle speed
3) adjusting the carburetor air/fuel ratio to achieve an oxygen level in the emissions of about 1%
4) enabling secondary air injection
5) reading the oxygen level in the emissions
6) disabling secondary air injection
7) injecting a continuous flow of additional fuel (propane) into the air intake in an amount sufficient to cause the CO level in the emissions from the exhaust system to achieve a level of about 2%
8) enabling secondary air injection
9) reading the CO level in the emissions while maintaining the flow of additional fuel
10) determining the efficiency of the exhaust system as a function of the CO level read in step (9) from the family of working curves graphing the conversion efficiency of the whole exhaust system against the CO at the tailpipe as a function of the various oxygen dilution levels. The efficiency is 100% when the content in CO is 0% and the efficiency is 0% when the CO content is 10% and the oxygen read in step (5) is 21%.

The method of **US4175427 (1979)**, uses a hydrocarbon (HC) sensor, a carbon monoxide (CO) sensor and an oxygen sensor to assess whether the engine or the catalytic converter is malfunctioning. The sensors are installed in the exhaust system of the engine. An idling and a non-idling operating condition of the engine are used for the tests, which comprise the following steps:

A. idle speed

1) sensing CO emissions and producing a first output when the CO emissions exceed a first predetermined maximum and the CO emissions exceed the oxygen emissions, while producing a second output if the oxygen emissions exceed the CO emissions

2) sensing the HC emissions and producing a third output if the HC emissions are greater than a second predetermined maximum and the CO emissions are greater than the oxygen emissions, while producing a fourth output when the oxygen emissions are greater than the CO emissions

B. off-idle speed
1) sensing CO emissions and producing a fifth output when the CO emissions exceed a third predetermined maximum and the CO emissions exceed the oxygen emissions, while producing a sixth output when the oxygen emissions exceed the CO emissions
2) sensing the HC emissions and producing a seventh output when the HC emissions are greater than a fourth predetermined maximum and the CO emissions are greater than the oxygen emissions, while producing an eighth output when the oxygen emissions are greater than the CO emissions

Display means produce information about the condition of different parts of the engine in response to the above mentioned first, second, third, fourth, fifth, sixth, seventh and eighth outputs.
The catalytic converter needs to be replaced as indicated by one of high CO emissions with oxygen emissions greater than CO emissions or high HC emissions with oxygen emissions greater than CO emissions.

• *Technische Universität "Otto von Guericke" Magdeburg*

The method of **DD269673 (1989)** comprises the following steps:
1) operating the engine at idling with a speed which is higher than the normal one
2) measuring simultaneously the temperature and the oxygen content of the exhaust gases upstream of the catalytic converter, by means of a temperature sensor and an oxygen sensor respectively
3) comparing the measured temperature of the exhaust gases with the activation (light-off) temperature of the catalytic converter
4) activating an exhaust gas heating apparatus, if the measured temperature is lower than the light-off temperature of the catalytic converter, till the light-off temperature is achieved
5) correcting the oxygen content of the exhaust gases, if it is measured to be low, by regulating the carburetor
6) measuring the content of the exhaust gases in CO upstream of the catalytic converter and regulating the carburetor to produce a normal low content of pollutants in the exhaust
7) assessing the functionality of the catalytic converter by measuring the exhaust gas content in HC at the exit of the exhaust pipe and by comparing the measured value to a predetermined threshold

- ***Toshiba Corp.***

The catalytic activity of a catalytic converter, as disclosed in **JP3050406 (1991)**, is assessed by measuring the temperature of the exhaust gases upstream of the catalytic converter and by measuring the pressure drop (loss) across the catalytic converter. A lowering in the activity of the catalytic converter results in a decrease of temperature of the catalytic converter and it also results in a decrease of the exhaust gas flow velocity passing through the converter. Thus the pressure loss across the converter is also reduced.

- ***Gutmann Messtechnik AG***

The method of patent application **EP0409013 (1991)** is a non-OBD diagnostic method and comprises the steps of:

1) memorizing first signals which are transmitted by a λ sensor located upstream of the catalytic converter during idling of the engine at approximately 1000 RPM
2) sampling the exhaust gases downstream of the catalytic converter and generating second signals denoting the content of the exhaust gases in CO and HC
3) storing reference signals denoting the desired parameters of exhaust gases
4) comparing the stored reference signals with the first and second signals and assessing a first efficiency of the converter
5) repeating the steps 1-4 of memorizing, sampling and comparing while the engine is operated under no-load conditions at approximately 3000 RPM and assessing a second efficiency of the converter
6) determining the efficiency of the catalytic converter from the results of the comparison tests at 1000 and 3000 RPM. If there is no appreciable difference between the ascertained first and second efficiencies following the tests at 1000 and 3000 RPM, then the operation of the converter is considered as satisfactory.

- ***Nissan Motor Co. Ltd.***

The method of **JP3073839 (1991)** demands that the engine attains a preset operating condition. This preset condition is achieved by detecting different operating parameters of the engine (cooling water temperature, rotational speed and suction negative pressure of the engine) and by judging that these parameters fall within certain ranges. The concentration of NO_x downstream of the catalytic converter is then measured and compared to a predetermined threshold. When the measured concentration of NO_x is found to be bigger than the threshold then the catalytic converter is considered as deteriorated.

In the method of **JP7054641 (1995)** two NO_x sensors are installed on either side of a catalytic converter which is capable of purifying NO_x in an oxygen excessive state. The concentrations of NO_x upstream and downstream of the converter are measured and the following ratio is formed

$$AZ = \frac{(NOx)_2}{(NOx)_1}$$

where:
$(NO_x)_1$ is the NO_x concentration of the exhaust gases upstream of the catalytic converter and
$(NO_x)_2$ is the NO_x concentration of the exhaust gases downstream of the catalytic converter.

Next a reference value of AZ is calculated based on the engine speed and the basic fuel injection amount to the cylinders of the engine. The measured value of AZ and the calculated reference value of AZ are compared and an alarm signal is produced when a decrease of the NO_x conversion ratio is judged on the basis of the comparison.

The method of **JP9088560 (1997)** diagnoses the efficiency of a NO_x adsorbing catalytic converter that adsorbs NO_x during lean operation of the engine and reduces adsorbed NO_x during stoichiometric operation of the engine (lean-burn engine). The method comprises the following steps:
1) feedback-controlling the engine air/fuel ratio by means of an oxygen sensor installed upstream of the catalytic converter under a stoichiometric condition
2) open-controlling the engine air/fuel ratio under a lean condition
3) determining the NO_x content of the exhaust gases downstream of the catalytic converter by means of a NO_x sensor
4) measuring the time interval that the measured NO_x content needs to reach a predetermined slice level after the engine air/fuel ratio changes from stoichiometric to lean
5) determining the deterioration of the NO_x adsorption capability of the converter when the measured time interval is smaller than a predetermined threshold

- ***ABB Patent GmbH***

The method of patent application **DE4039429 (1992)** carries out the monitoring of the catalytic converter at a defined temperature of the measuring sensors and comprises the following steps:
1) detecting hydrogen and CO downstream of the catalytic converter by means of a sensor disposed in the exhaust path downstream of the converter
2) detecting the oxygen content of the exhaust gases by means of an oxygen sensor disposed upstream of the catalytic converter

3) feedback controlling the air/fuel ratio of the engine by making use of the output signal of the oxygen sensor
4) forming a differential signal of the output signals of the two sensors, which corresponds to the content of hydrogen and CO of the exhaust gases
5) indicating a deteriorated catalytic converter if the differential signal exceeds a defined threshold value

- ***Blanke, J. D.***

The method of patent **US5175997 (1991)** comprises the following steps:
1) injecting secondary air into the exhaust system upstream of the catalytic converter
2) feedback controlling the engine air/fuel ratio by means of an oxygen sensor located upstream of the catalytic converter and the system for injecting air to the exhaust system
3) calibrating an exhaust gas analyzer, which measures the content of CO, oxygen and HC downstream of the catalytic converter
4) disabling the injection of air and providing a signal to the engine air/fuel control to produce an oxygen level in the exhaust stream downstream of the catalytic converter of about one percent
5) enabling the injection of air and determining the oxygen level in the exhaust stream downstream of the catalytic converter using the analyzer
6) disabling the injection of air and providing a signal to the engine air/fuel control to produce a CO level in the exhaust stream downstream of the catalytic converter of about two percent
7) determining the HC level in the exhaust stream downstream of the catalytic converter using the analyzer
8) enabling the injection of air and determining the CO and HC levels in the exhaust stream downstream of the catalytic converter using the analyzer
9) calculating catalytic converter efficiency using the oxygen level in step 5, the HC levels determined in steps 7 and 8, and the CO levels produced in step 6 and determined in step 8.

- ***Effort Mijdrecht B.V.***

In the method of **DE4207079 (1992)**, a λ probe is installed upstream of the catalytic converter and a gas concentration sensor for measuring CO or CO_2 or HC or oxygen is installed in the exit of the exhaust pipe. The engine operates for a certain time in order to warm up, and during the test it runs with a constant speed of 3000 RPM. The output signals of the λ probe and the gas concentration sensor are retrieved and compared to predetermined values stored in the form of histograms. From this comparison, useful information is extracted concerning the functionality of the catalytic converter.

• *Keesmann, T.*

In the German Patent Utility Model **DE9202966U (1992)** an experimental measuring set-up is presented. A specially designed flange, installed upstream of the catalytic converter, carries all the necessary instrumentation (electric and pneumatic) to determine the efficiency of the converter. Such instrumentation comprises temperature, oxygen and CO sensors and tubes to blow oxygen into the exhaust. At the tail pipe, the CO or/and HC content of the exhaust gases is measured.

• *Honda Motor Co. Ltd.*

The method of **US5179833 (1993)** comprises the following steps:

1) measuring the HC content of the exhaust gases upstream of the catalytic converter by means of a first HC sensor
2) measuring the HC content of the exhaust gases downstream of the catalytic converter by means of a second HC sensor
3) calculating the ratio of the measured HC content downstream of the catalytic converter to the measured HC content upstream of the catalytic converter
4) determining that the catalytic converter is deteriorated when this ratio is larger than a predetermined value

• *Iris-GmbH Infrared & Intelligent sensors*

The method of patent application **WO9409266 (1994)** comprises two similar sensors installed upstream and downstream of the catalytic converter. Each of the two sensors has an infrared emitting part and an infrared receiving part and they can measure the concentration or the variation in time of the concentration of an exhaust gas component. The measured concentration or variation in time of the concentration of this exhaust gas component upstream and downstream of the catalytic converter are used as a measure of the performance of the catalytic converter.

• *Hagen & Schildkamp Techniek B.V.*

The method of patent application **FR2719116 (1995)** uses a simple pressure gauge upstream of a catalytic converter, in order to measure the pressure upstream of the catalytic converter while the engine is running. This simple quantitative procedures determines the degree of blockage of the catalytic converter.

- ***Roth-Technik GmbH & Co. Forschung für Automobil- und Umwelttechniek***

In the method of **DE4441432 (1996)** an HC sensor is installed downstream of the catalytic converter to verify the performance of both the catalytic converter and the λ sensor which is installed upstream of the converter. In predetermined operating modes of the engine the measured data are compared to stored data and useful conclusions are drawn about the condition of the catalytic converter and the λ sensor. The system also controls secondary air injected in the exhaust to vary the quantity of air present in the catalytic converter to a preset value.

- ***NGK Insulators Ltd.***

The method of **EP0743431 (1996)** uses an oxygen concentration measuring apparatus comprising an electrochemical oxygen pumping cell downstream of the catalytic converter (fig. 151) and comprises the following steps:

1) introducing the exhaust gases downstream of the catalytic converter into a processing zone under a predetermined diffusion resistance and detecting an oxygen partial pressure of the exhaust gas within the processing zone.
2) energizing the electrochemical pumping cell to perform an oxygen pumping action for pumping oxygen out of said processing zone to thereby control an oxygen concentration in the exhaust gas within the processing zone to a predetermined value at which a combustible gas component (e.g. CO, HC, H_2) of the exhaust gas cannot be substantially burned. More specifically, the voltage applied between the pair of electrodes of the electrochemical cell is controlled on the basis of a monitor voltage which corresponds to the detected oxygen partial pressure within the processing zone, such that this detected oxygen partial pressure is held at a predetermined value
3) detecting a pumping current (limiting current) flowing through the electrochemical pumping cell during activation of the electrochemical pumping cell
4) determining a degree of deterioration of the catalytic converter according to an oxygen concentration in said combustion exhaust gas which is obtained on the basis of the detected pumping current

The processing zone, the diffusion control passage and the electrochemical oxygen pumping cell are integrally provided in a sensing element, which includes an oxygen ion conductive solid electrolyte layer as an integral part thereof.

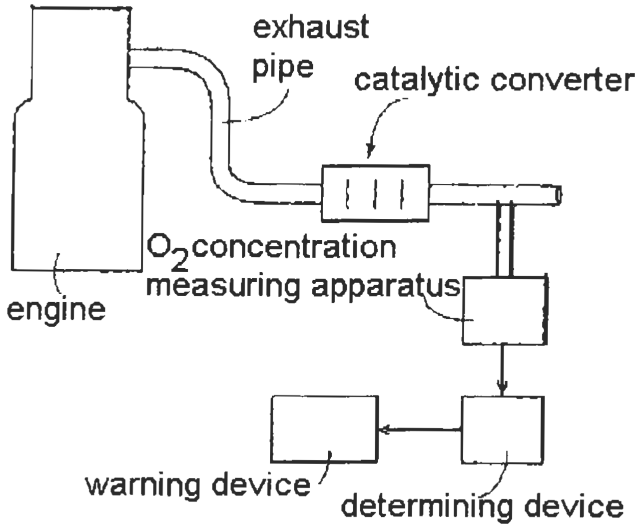


Fig. 151 (from EP0743431)

In the method of **EP0751390 (1997)** a temperature exhaust gas sensor is presented that can be used for detecting deterioration of a catalytic converter. The sensor has a pair of temperature sensor sections, where one of the temperature sensor sections is covered with porous oxidizing catalytic layers for oxidizing the exhaust gas, whereas the other is not covered with oxidizing catalyst layers. The catalyst present on one of the sensor sections burns the exhaust gas and in the other temperature sensor section, the temperature of the gas to be measured is compensated. When a difference between temperatures of the pair of sensor sections or a difference between powers fed to the pair of sensor sections exceeds a predetermined threshold, it is judged that the catalytic converter is deteriorated.

Fig. 152 shows the correlation between a value obtained by accumulating power differences between the two temperature sensor sections (resistors) every second at the time of self-heating of the sensor sections at 500 °C and an amount of the exhausted hydrocarbons. From the output of the sensor, the lighting of the malfunction indicator lamp (MIL) can be judged.

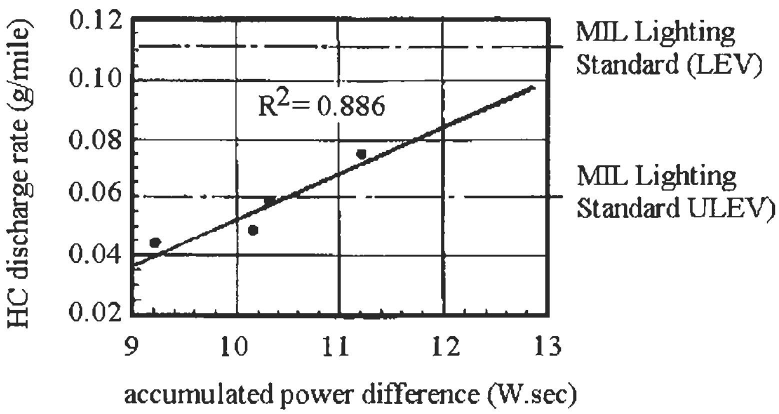


Fig. 152 (from EP0751390)

- ***Fuji Heavy Ind. Ltd.***

In **JP7180535 (1995)** a lean NO_x catalytic converter is monitored to assess whether it is deteriorated. For this reason a NO_x concentration sensor is mounted in the exhaust pipe downstream of the converter in a position that is not influenced by the ambient air at the tail pipe region. At certain operating conditions of the engine and for a specific time interval, the output concentration of NO_x measured by the sensor is integrated. The integral value is compared to a predetermined value to decide whether the converter is deteriorated.

- ***Toyota Motor Co Ltd.***

In the method of **JP5113157 (1993)**, a NO_x sensor is installed downstream of a lean NO_x catalytic converter. The measured NO_x content of the exhaust gas is compared to a reference value to determine whether or not the catalytic converter is deteriorated. When it is judged that the catalytic converter is deteriorated, the exhaust gas recirculation amount (EGR) is increased.

The method of **JP8338297 (1996)** comprises the following steps:
1) detecting the current purification capacity of a catalytic converter by means of a purification capacity detector mounted in the exhaust pipe
2) determining a threshold of the purification capacity of the catalytic converter according to the current temperature of the converter
3) calculating a difference between the measured current purification capacity of the converter and the calculated threshold value
4) comparing this calculated difference with a predetermined value
5) determining that the catalytic converter is deteriorated when the calculated difference exceeds the predetermined value

In the method of **JP9041950 (1997)** a HC sensor is mounted in the exhaust pipe downstream of the catalytic converter. A deterioration index is calculated, based on the measured concentration of HC in the exhaust pipe. A threshold value of the deterioration index is calculated and corrected based on the current velocity of the exhaust gases in the converter. The corrected threshold value is compared to the deterioration index and the deterioration of the converter is determined from this comparison.

- ***Forskarpatent I Linköping AB***

In the method of **WO9715751 (1997)**, momentarily during engine operation a suitable amount of thin oil is fed to the intake of the engine, which is burned on the surface of the converter. A gas sensor sensitive to thin oil is placed downstream of the catalytic converter. The sensor indicates the presence of thin oil in the exhaust gases and thereby the functionality of the converter.

- ***Komatsu Ltd.***

In **WO9713058 (1997)** a hydrocarbon sensor is installed downstream of a NO_x reducing catalytic converter of a Diesel engine. A reducing agent (fuel) is fed to the exhaust system upstream of the converter. Operation parameters like the rotational speed of the engine, the engine load and the HC content of the exhaust gases are fed to a deterioration detecting means. The determination of deterioration of the NO_x catalytic converter is based on the change in an amount of HC in the exhaust gases with the passage of time when the operating condition of the engine (determined from the rotational speed and the load) meets a predetermined condition. To compensate the deterioration of the catalytic converter, the quantity of reducing agent (fuel) fed to the exhaust gases is increased.

- ***Leybold AG***

The method of **EP0294715 (1988)** is a non-OBD diagnosis method and comprises the following steps:

1) supplying a mixture of nitrogen oxide (NO_x) and an inert gas (Argon) in the exhaust gases upstream of the catalytic converter. The NO_x /Ar ratio is 1:1
2) measuring the NO_x and inert gas concentration of the exhaust gas downstream of the catalytic converter by means of a mass spectrometer
3) determining the efficiency of the catalytic converter by comparing the mixture of NO_x and Argon (Ar) upstream and downstream of the catalytic converter

An efficient converter reduces more than 90% of the NO_x whereas the Argon remains unaffected.

- ***Osaka Gas Co. Ltd.***

The method of **JP59119247 (1984)** detects the deterioration of a catalytic converter by analyzing the noble metal catalyst (e.g. Ru) deposited on a carrier of alumina, titanium dioxide, zirconia etc. by means of a photoelectric spectrum analysis. X-rays are applied to a certain specimen of the catalyst, and the energy distribution of the electrons released from the specimen by a photoelectric effect is measured. The position of the peak in the photoelectric spectrum of the actual catalyst is detected and compared with the position of the O-peak value in the photoelectric spectrum of the metal catalyst. The comparison allows the extraction of conclusions about the efficiency of the converter.

- ***Sun Electric UK Ltd.***

The non-OBD method of **GB2310044 (1997)** comprises the measuring system of fig. 153 that is inserted in the exhaust pipe of a motor vehicle to determine the efficiency of a catalytic converter. The system comprises a gas analysis apparatus that analyzes the concentrations of four gas components in the exhaust emissions from the engine, namely hydrocarbons, oxygen, carbon monoxide and carbon dioxide. A data processing apparatus samples data from the gas analysis apparatus and determines the rate of change of the individual gas concentrations with time and identifies a time instant or period at which the rate of change of concentrations changes in accordance with a predetermined pattern or rate characteristic of the activation of the catalytic converter ("light-off"). A display provides a signal indicative of the "light-off" of the converter. The system includes further a data-processing function, a data-storage function, a computation function and a display function. A projecting probe is inserted in the exhaust pipe to sample the exhaust gases.

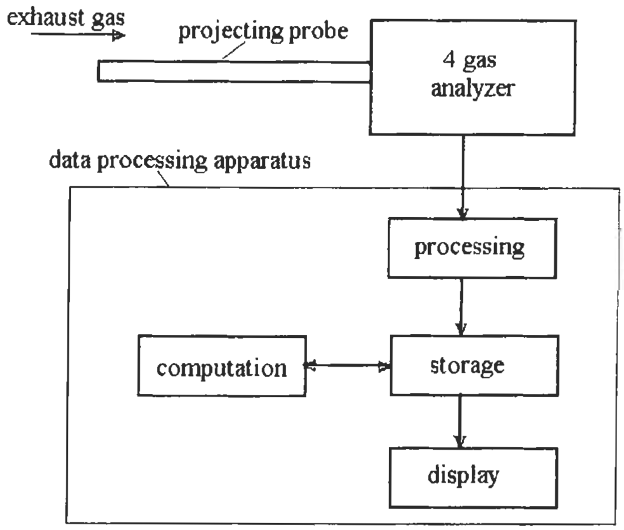


Fig. 153 (from GB2310044)

The method comprises the following steps:

1) sampling exhaust gas delivered by the internal combustion engine
2) determining data relating to the concentration of at least three gases therein
3) identifying, by means of a data processing algorithm, changes in the concentrations of at least two of the exhaust gas components indicative of the state of operation of a catalytic system provided in the engine exhaust delivery system. A time instant or period is identified at which the rate of change of concentrations for at least two of the gases in the emissions is in accordance with a predetermined pattern or rate or configuration characteristic of activation or deactivation of the catalytic converter
4) providing a signal indicative of the state of operation of the catalytic system

The different phases of the present analysis are shown in fig. 154. In phase "engine-off", the concentrations of the gases (HC, CO, CO_2 and O_2) are at the values indicated corresponding to substantially zero except in the case of oxygen, which is at its atmospheric level. In phase "engine-start", the oxygen level dips sharply at 30, rises likewise sharply at 32 and then plateaus and commences a gentle decrease in 34.

Hydrocarbons and carbon monoxide increase at 36, then plateau and commence a corresponding shallow decline at 38. Carbon dioxide likewise rises at 40 to a generally horizontal plateau 42. The plateaus 34, 38 and 42 extend across the "catalytic converter warming" phase.

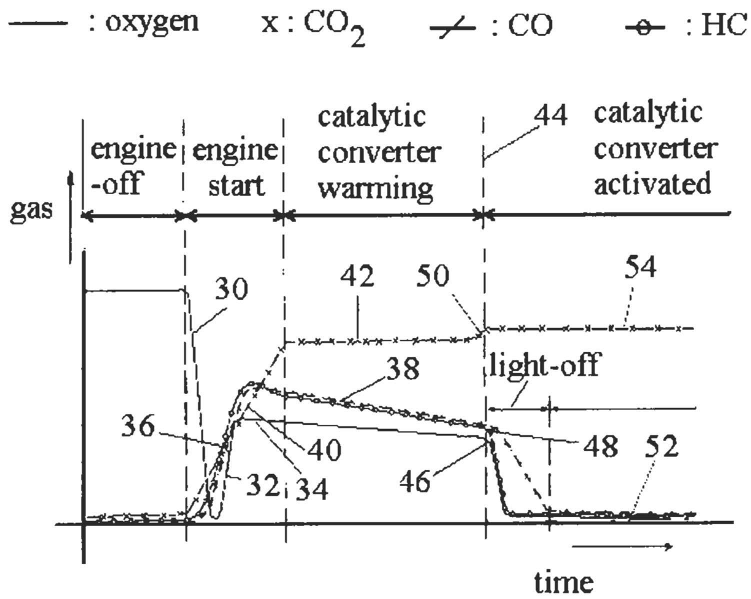


Fig. 154 (from GB2310044)

Finally, each plot undergoes at the interface 44 between "catalytic converter warming" and "catalytic converter activated" phases a sudden increase in the rate of change (plateaus 46, 48, 50). This region of change may be identified as a distinct phase called "catalytic converter light-off" phase. The concentrations then settle down to plateaus 52 (CO, HC, O_2) and 54 (CO_2).

A suitable algorithm detects then the changes of slope at 46, 48 and 50 for each of the four gas components. The calculated values are compared to effectively stored values of the system in order to determine when the system has reached the interface 44 and the plateaus at 52 and 54, whereupon a signal can be triggered to indicate that the converter is activated. In the event that this final stage is not reached, then a failure signal is activated after a short time interval corresponding to the maximum time required for the system to reach the interface 44.

- ***Other methods***

A method to test the performance of a catalytic converter at a specialized workshop is presented in [26].

According to the method, the converter is warmed up by operating the vehicle under high idle conditions for a period of 3 to 5 minutes. After the vehicle is shut off the spark and fuel to the engine are disabled by removing the appropriate fuses. Gaseous propane is then introduced in the exhaust system upstream of the converter e.g. through the secondary air ports and the engine is cranked. The cranking of the engine transports the propane and air through the catalytic converter, where oxidation of the propane occurs. A gas analyzer bench is used to measure the concentration of HC and CO_2 emitted from the tailpipe of the vehicle. The determination of the converter efficiency is based on the measured concentrations of HC and CO_2.

By measuring both HC and CO_2 concentrations, the efficiency determination is independent of the flow rate of the propane, the cranking speed and the engine displacement.

The method of **SU1741880 (1992)** is based on the fact that when dust is deposited on the surface of a porous catalytic material, the speed of the gas through the material is changed and consequently the intensity of produced noise is also changed. The noise produced is detected by means of suitable measuring equipment, it is analyzed and compared to predetermined values to determine the efficiency of the catalytic converter.

The method of [29] compares two non-OBD diagnostic methods. The first method is a non-intrusive propane injection catalytic converter test procedure developed by General Motors and the second method uses a fiber-optic borescope to visually assess the condition of the catalytic converter substrate.

The method of **DE4019572 (1992)** has been already discussed in chapter 1.16.

PART FOUR

DISCUSSION AND COMPARISON OF EXISTING METHODS

Chapter 4

Discussion and Comparison of Existing Methods

This chapter summarizes the principles of the three main categories for monitoring and diagnosing the degradation of catalytic converters placed in the exhaust systems of modern vehicles. Advantages and disadvantages of all three methods are discussed and are compared to each other. Similar summaries can be also found in [1], [9] and [19].

Use of λ or oxygen sensors

The diagnosing methods of the deterioration of a catalytic converter by means of conventional λ or oxygen sensors have the big disadvantage that the diagnosis is achieved in an indirect way. Instead of measuring directly the composition of the exhaust gases, a rather switch-type response output signal indicating deviation from stoichiometry of the air/fuel ratio in the exhaust gases is obtained.

The sensor exhibits a complex response due to species diffusion effects through its outer surface. Such diffusion effects can cause long and random response times when switching between rich and lean air/fuel ratio. 'Memory effects', that is change in response time due to air/fuel preconditioning, further complicates the interpretation of the sensor output signal.

This type of indirect diagnosis is based on the oxygen storage capacity of the catalytic converter, which has been proved in the literature not to be always directly correlated with overall deficiency of the converter, as the aging mechanisms in the two phenomena are not generally identical. In some cases, converters which have lost nearly all of their oxygen storage capacity due to high temperature aging still retain HC conversions near 90% ([27]). Especially, small volume light-off catalytic converters lose their oxygen storage capacity due to high temperature aging, but their FTP HC efficiency is very high resulting in a very low decrease in efficiency of the combination light-off and main catalytic converters ([28]).
Furthermore, stability of oxygen storage capacity is very much dependent on washcoat formulation (use of appropriate stabilizers).

For example, errors may appear when the slope of the output signal of the downstream oxygen sensor is processed to determine the oxygen storage of the converter (the signal processing is such that the slope of the downstream oxygen sensor signal will give the oxygen storage capacity of the catalytic converter). Then the system functions in the manner depicted by the following equations (**EP0799984 (1997)**):

Hypothesis:

x = A/D output signal value of downstream oxygen sensor
x_f = filtered output signal value of downstream oxygen sensor
O_2 index = oxygen storage capacity of the converter
t = time instant
15.6 msec = duration between two time instants
α = filter coefficient of x to generate x_f.

Thesis:

O_2 index is related to the slope of the downstream oxygen sensor

Demonstration:

O_2 index $(t) = x(t) - x_f(t)$ current diagnostic

$x_f(t) = x_f(t-1) - \{\alpha\,(x_f(t-1) - x(t)\}$ current diagnostic

$x_f(t) = (1-\alpha)\, x_f(t-1) + \alpha\; x(t)$

O_2 index $(t) = x(t) - \{(1-\alpha)\, x_f(t-1) + \alpha\; x(t)\}$

O_2 index $(t) = (1-\alpha)\, x(t) - (1-\alpha)\; x_f(t-1)$

O_2 index $(t) = (1-\alpha)\; \{x(t-1) - \; x_f(t-1)\}$

The filter coefficient on the downstream oxygen sensor is high. Since the loop time is constant the O_2 index value at its maximum will be very close to the slope of the downstream oxygen sensor signal.

The result of this analysis is shown in fig. 155. It will be apparent that the oxygen sensor index is a measure of the downstream oxygen sensor slope. The slope is related to the response time of the sensor but not to the storage capacity of the converter. Thus, anything which can affect the response time of the sensor will generate an incorrect oxygen sensor index. Factors which can affect sensor response time are, for example, poisoning of the exhaust gases, aging of the sensor, air/fuel ratio control, location of the sensor and so on. Experience has shown that a lazy downstream oxygen sensor can make an inert converter appear to function properly.

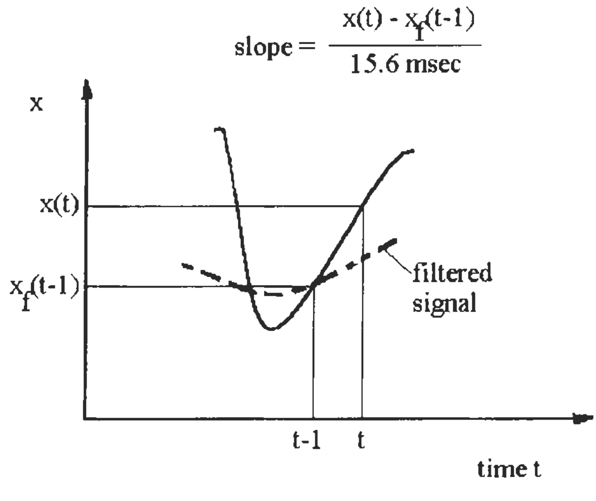


Fig. 155 (from EP0799984)

As already mentioned, an important factor that influences the precision of assessment of the efficiency of the catalytic converter is the deterioration or aging of the oxygen sensors installed upstream or downstream of the catalytic converter.
Particularly, the upstream oxygen sensor, which is directly exposed to hot exhaust gases, undergoes faster deterioration than the downstream oxygen sensor. The rate at which the determination proceeds is thus different between the upstream and downstream oxygen sensors, which results in an error in the result of deterioration determination. For this reason, modern methods for assessing the functionality of catalytic converters comprise simultaneous assessment of degradation of oxygen sensors and compensation of the errors that occur from this degradation. Certain types of fuel additives, carbon particles, engine oil and naturally occurring chemicals can adversely affect the performance of the measuring sensors.

The sensors installed upstream and downstream of the catalytic converter may have different characteristics, due to manufacturing tolerances. These tolerances must be taken into account during the assessment of the condition of the catalytic converter.

Two oxygen sensors installed upstream and downstream of the catalytic converter of a certain type of vehicle can give much different output signals when it is used in the exhaust system of another type of vehicle [19].

The temperature of the catalytic converter is also an important factor that can influence the correct determination of the deterioration of a catalytic converter by means of oxygen or air/fuel sensors. The oxygen storage capacity of the catalytic converters in general varies with a change in the temperature, which causes a variation in the indication of the sensor placed downstream of the catalytic converter. Additionally, the high operating temperature of the sensors (>250 °C) requires that special filtration should be applied, to avoid using 'lower temperature signals' for OBD purposes. The measurement of temperature of the exhaust gas would probably be required that would result in an increase of the total cost of the monitoring set-up. This problem can be solved by correlating the temperature of the converter with other operating parameters of the engine. This correlation is pre-stored in a memory part of the monitoring set-up and allows an estimation of the temperature of the converter by referring to the correspondence information on the basis of detected results of the operating state of the engine (**US5649420 (1997)**).

Oxygen sensors cannot monitor the malfunction of catalytic converters during cold start-up, which is most critical for modern OBD technology vehicles.

During injection of secondary air in the exhaust system to enhance oxidation of unburned HC and CO in the exhaust manifold, the exhaust gas arriving at the catalytic converter is lean for the warm-up phase (air injection phase). During this period no voltage could be generated by a normally operating downstream λ or oxygen sensor, thus precluding any catalytic converter efficiency detection.

During the deterioration diagnosis procedure, the engine air/fuel ratio is controlled in such a way as to achieve certain predetermined operating conditions. Great attention should be paid not to increase the emissions of the internal combustion engine during this deterioration diagnosis procedure.

Deterioration detection prohibiting means must be also included in the measuring set-up to exclude an erroneous deterioration detection when predefined engine operation parameters are not satisfied.

Universal air/fuel ratio heated exhaust gas oxygen sensors (UEGO) seem to be more promising for use in OBD systems because of their proportional output characteristic (unlike the switch-type response of conventional oxygen sensors). However, their cost compared to HEGO sensors still lies an order of magnitude higher. An even more promising oxygen sensor for use in OBD systems is the so-called NEEGO sensor presented in [19].

In general the use of dependable linear oxygen sensors gives more reliable results although there is no direct evaluation of CO, HC and NO_x concentrations in the exhaust.

In [30] it has been proven that oxygen or λ sensors can give a satisfactory assessment of the efficiency of a catalytic converter for the case of LEV or EURO III standards.

Use of temperature sensors

The diagnosing methods of the deterioration of a catalytic converter by means of temperature sensors has the big disadvantage that the diagnosis is achieved in an indirect way. The methods do not measure directly the concentration of pollutants downstream of the catalytic converter, but they try to determine the condition of the converter by measuring the exothermic reaction taking place inside the converter. This makes it difficult to accurately detect deterioration of the converter (**US5179833 (1993)**).

However, the results of temperature sensors used to verify catalytic converter efficiency diagnosis evaluated by means of the dual-oxygen sensor technique have shown that dual oxygen-sensor measurements for catalytic converter efficiency become questionable with introduction of ULEV standards ([22]).

Additionally, in **WO9420738 (1994)** it is claimed that it is difficult to produce a signal qualitatively representative of the efficiency of a catalytic converter based on the output signals of an upstream and a downstream air/fuel sensor and this presents the vehicle manufacturer with a serious dilemma. If a high efficiency threshold is set, then the driver will be frequently given false warnings of failure of the catalytic converter and apart from the nuisance to the driver this could result in the warning signals being totally disregarded when the alarm is genuine. On the other hand, if a low threshold is set and the vehicle should fail to comply with the legislative requirements then the manufacturer could face serious financial penalties. For these reasons, it is proposed in **WO9420738 (1994)** to use temperature measurements techniques to assess the functionality of a catalytic converter.

Problems can arise in the diagnosis of a converter by means of temperature measurements, because the measured temperature difference can fall, and even become negative, for an efficient converter during certain operating conditions of an internal combustion engine (see **EP0442648 (1991)**).

In [4] it has been proven that the use of only the downstream exotherm of an underfloor catalytic converter is not sufficient to assess the efficiency of the catalytic converter during transient state driving. The exotherm requires excessive amounts of time to stabilize after a transient maneuver (approximately 5 minutes following a deceleration from 60 to 30 miles/hour).

In **EP0751390 (1996)** and **EP0779416 (1997)** it is claimed that the methods that measure the exothermic reaction in a catalytic converter by making use of two temperature sensors upstream and downstream of the catalytic converter are reliable only after the vehicle has been operated several minutes at a constant speed of 40-60 Km/h to stabilize the exhaust gas thermally, because the catalyst has a large capacity. Additionally, the measurement of the performance of the converter at a higher accuracy, longer-time operation at the above constant speed is necessary. However, under actual running conditions of the vehicles where acceleration and deceleration are repeated, the above-mentioned requirement of the running at constant speed can hardly be met, and therefore it is difficult to detect the deterioration with high precision. Furthermore, a sufficient temperature difference cannot be obtained unless the temperature sensors are inserted into an exhaust tube so that they may be close to the central axis of the exhaust tube, and hence this method has a drawback that the pressure of the exhaust gas is increased and the output power of the engine is consequently reduced.

When a throttle valve controlling the admission of a combustible mixture to the engine is opened, the temperature of exhaust gas entering the converter can rise dramatically but, because of thermal lags, the temperature of exhaust gas leaving the converter rises more slowly. This can result in an indication of incorrect operation of a converter which is actually operating efficiently.

Similar problems can occur during other modes of operation of the engine giving rise to spurious or transient temperature differences which are detected as indicating inefficient operation of the converter.

An additional problem for detecting correctly the efficiency of an exhaust gas catalytic converter is a possible deterioration of a temperature sensor. The output of such a deteriorated sensor must be corrected during the diagnosis procedure in order to avoid erroneous results.

Existing temperature sensor elements have a drastically reduced life duration, when they suffer very often from very fast and big temperature variations.

Linear temperature sensors become more attractive if they are used simultaneously for monitoring other emission control functions (exhaust gas ignition, catalyst temperature management) or detection of engine misfire ([24]).

A new generation of temperature sensors like fiber optics pyrometers is under investigation. These sensors have a very fast response time but they still suffer from signal output instabilities ([19]).

In general, durable production-feasible temperature sensors which can be mounted either inside the catalytic converter substrate or on its external surface are lacking and need to be developed [23].

The main problem with the temperature measurement techniques remains the lack of universally valid monitoring methods, principally applicable during each driving scenario.

However according to [31], the temperature measurements in combination with a suitable algorithm is a very reliable, inexpensive and readily available method of assessment of the condition of a catalytic converter.

Use of exhaust gas concentration sensors

Direct measurements of HC, CO and NO_x is the most obvious way to monitor the efficiency of a catalytic converter. The feasibility of this technique, however, strongly depends on the development of such sensors applicable for vehicle exhaust systems at a rational cost.

Calorimetric and semiconductor HC sensors suffer from the following:
1) they possess no reference to evaluate the sensor signal
2) the devices are bulky and generally inaccurate
3) they cannot operate at the higher temperatures of automotive exhaust gases or operate continuously
4) the calorimetric sensors need an excess of oxygen to operate properly

Potentiometric thick-film HC sensors have good properties and have shown satisfactory correlation with measured HC concentrations by gas analyzers. These sensors could eventually be used for monitoring catalytic converters after their cost becomes affordable.

Surface ionization detectors are also a possible future solution for OBD purposes, but for the time being they suffer from considerable drawbacks.

In [31], the use of a conventional HC sensor for a catalytic converter assessment system is not recommended since the HC content signal is not very sensitive to catalytic converter efficiency, especially when the converter operates at high temperatures. On the contrary, the use of a CO sensor to assess the efficiency of a catalytic converter in combination with a simple algorithm is straightforward under the condition that reliable and inexpensive CO sensors are reliable [30].

NO_x sensors are still under investigation and they have been used in the literature in a limited number of cases for OBD purposes.

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Priority: DE951037788 11.10.95
Applicant: BOSCH GMBH ROBERT (DE)
Inventor: SCHENK RENE (DE)
Title: Verfahren und Vorrichtung zur Überwachung der Funktionsweise eines Katalysators
Family: DE19537788 A 17.04.97
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DE19539024 A 25.04.96 **203**
Priority: JP940254062 20.10.94
Applicant: NISSAN MOTOR (JP)
Inventor: NAKAJIMA YUKI (JP); UEMA HIDEKI (JP)
Title: Katalysatorschädigungs-diagnosesystem für einen Verbrennungsmotor
Family: DE19539024 A 25.04.96
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DE19540673 A 07.05.97 **174**
Priority: DE951040673 31.10.95
Applicant: SIEMENS AG (DE)
Inventor: LEMIRE BERTRAND (DE); SCHÜRZ WILLIBALD (DE)
Title: VERFAHREN ZUR ÜBERPRÜFUNG EINES KATALYSATORS MIT EINEM SAUERSTOFFSENSOR
Family: DE19540673 A 07.05.97
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Priority: DE951045693 07.12.95
Applicant: VDO SCHINDLING (DE)
Inventor: STAUFENBERG ULRICH (DE); OLEJNIK PETER (DE)
Title: Verfahren zur Überprüfung des Wirkungsgrades eines Katalysators in einer Brennkraftmaschine
Family: DE19545693 A 12.06.97

DE19605103 A 14.08.96 **194**
Priority: JP950023181 10.02.95; JP950023182 10.02.95
Applicant: MITSUBISHI MOTORS CORP
Inventor: MATSUMOTO TAKUYA (JP); HASHIMOTO TORU (JP); MIYAKE MITSUHIRO (JP); NOMURA TOSHIRO (JP); KANAO HIDETSUGU (JP)
Title: Vorrichtung zur Verschlechterungsdiagnose eines Abgasreinigungskatalysators
Family: DE19605103 A 14.08.96
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DE19620417 A 28.11.96 **158; 159**
Priority: JP950122171 22.05.95
Applicant: HITACHI LTD (JP); HITACHI CAR ENGINEERING CO (JP)
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Family: DE19620417 A 28.11.96
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Priority: DE961023335 12.06.96
Applicant: BOSCH GMBH ROBERT (DE)
Inventor: SCHNEIDER ERICH (DE)
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Inventor: KÖNIG AXEL
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Applicant: BOSCH GMBH ROBERT
Inventor: RIEGER FRANZ; LINDER ERNST ; SCHMIDT PETER J.
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Priority: DE762643739 29.09.76
Applicant: BOSCH GMBH ROBERT
Inventor: WÖSSNER GÜNTER
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Applicant: AUDI NSU AUTO UNION AG
Inventor: VRANG K. (DE); ZAHL J. (DE); MEIER M. (DE); SEUFER T.
Title: Verfahren zum Überprüfen der Funktionsfähigkeit eines Abgaskatalysators
Family: DE3516981 A 13.11.86

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Applicant: PHYWE SYSTEME GMBH
Inventor: PRAEKELT ERICH (DE)
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Applicant: VOLKSWAGENWERK AG
Inventor: KLINGENBERG HORST (DE)
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Priority: DE883811732 08.04.88
Applicant: DEUTSCHE FERNSPRECHER GMBH (DE)
Inventor: HEDER HANS-JOACHIM (DE); PETRI SIEGFRIED (DE)
Title: Schaltungsanordnung zur Funktionsprüfung des Katalysators von Kraftfahrzeugen
Family: DE3811732 A 19.10.89
DE3811732 C 21.11.91

DE3830515 A 22.03.90 **217**
Priority: DE883830515 08.09.88
Applicant: BAYERISCHE MOTOREN WERKE AG (DE)
Inventor: HUNDERTMARK D. (DE)
Title: Verfahren zur Überprüfung der Funktion des Abgaskatalysators einer Brennkraftmaschine
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Priority: DE893935381 24.10.89;

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DE4039762 A 17.06.92 **45; 46**
Priority: DE904039762 13.12.90
Applicant: BOSCH GMBH ROBERT (DE)
Inventor: SCHNAIBEL EBERHARD (DE); RAFF LOTHAR (DE)
Title: Verfahren und Vorrichtung zum Überprüfen des Alterungszustandes eines Katalysators
Family: DE4039762 A 17.06.92
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Priority: DE914100241 07.01.91; DE904000611 11.01.90
Applicant: VOLKSWAGENWERK AG
Inventor: MEIER-GROTRIAN J.(DE); WITTIG F-M (DE)
Title: Katalysatoranordnung, insbesondere für das Abgassystem einer Brennkraftmaschine
Family: DE4100241 A 18.07.91

DE4100397 A 14.08.91 **266**
Priority: DE914100397 09.01.91; DE904004066 10.02.90
Applicant: VOLKSWAGENWERK AG
Inventor: GEIGER ISTVAN (DE)
Title: Verfahren und Anordnung zur Überwachung des Konvertierungsgrads eines Katalysators
Family: DE4100397 A 14.08.91
US5133184 A 28.07.92

DE4101616 A 14.08.91 **117; 118**
Priority: JP900013219 22.01.90; JP900281290 18.10.90
Applicant: NIPPON DENSO CO (JP)
Inventor: NAKANE HIROAKI (JP); NAKABAYASHI KATSUHIKO (JP); KURITA NORIAKI
Title: Einrichtung zum Messen von Katalysator-Reinigungsfaktoren
Family: DE4101616 A 14.08.91
US5154055 A 13.10.92

DE4112478 A 22.10.92 **47; 48**
Priority: DE914112478 17.04.91
Applicant: BOSCH GMBH ROBERT (DE)
Inventor: SCHNAIBEL EBERHARD (DE); SCHNEIDER ERICH (DE)
Title: Verfahren und Vorrichtung zum Beurteilen des Alterungszustandes eines Katalysators
Family: DE4112478 A 22.10.92
FR2675539 A 23.10.92
US5267472 A 07.12.93

DE4112479 A 22.10.92 **48; 49**
Priority: DE914112479 17.04.91
Applicant: BOSCH GMBH ROBERT (DE)
Inventor: SCHNAIBEL EBERHARD (DE); SCHNEIDER ERICH (DE)
Title: Verfahren und Vorrichtung zum Bestimmen des Alterungszustandes eines Katalysators
Family: DE4112479 A 22.10.92
US5303580 A 19.04.94
IT1258314 B 22.02.96

DE4112480 A 22.10.92 **50; 51**
Priority: DE914112480 17.04.91
Applicant: BOSCH GMBH ROBERT (DE)
Inventor: RICHTER W. (DE); STUBER A. (DE); HEPPNER B. (DE)
Title: Verfahren und Vorrichtung zum Bestimmen des Alterungszustandes eines Katalysators
Family: DE4112480 A 22.10.92
FR2675538 A 23.10.92

DE4122787 A 30.01.92 **266**
Priority: DE914122787 10.07.91; DE904023364 23.07.90
Applicant: VOLKSWAGENWERK AG
Inventor: MEIER-GROTRIAN J. (DE)
Title: Einrichtung zur Überwachung des Konvertierungsgrads eines Katalysators
Family: DE4122787 A 30.01.92

DE4128823 A 04.03.93 **51; 52**
Priority: DE914128823 30.08.91
Applicant: BOSCH GMBH ROBERT (DE)

JP7509551T T 19.10.95
DE4227207 C 31.10.96
US5610844 A 11.03.97

DE4228536 A 03.03.94 308
Priority: DE924228536 27.08.92
Applicant: ROTH TECHNIK GMBH (DE)
Inventor: HAEFELE EDELBERT (DE)
Title: Verfahren zur Überwachung der Funktionsfähigkeit von Katalysatoren in Abgasanlagen
Family: DE4228536 A 03.03.94
EP0589169 A 30.03.94
EP0589169 B 21.02.96
DE59301674G G 28.03.96

DE4233977 A 15.04.93 189
Priority: JP910264312 14.10.91
Applicant: MITSUBISHI ELECTRIC CORP
Inventor: MAEDA MIE (JP); OHUCHI HIROFUMI (JP)
Title: Gerät zur Erfassung der Verschlechterung eines Katalysators für einen Verbrennungsmotor
Family: DE4233977 A 15.04.93
DE4233977 C 19.05.94
US5417061 A 23.05.95

DE4234102 A 15.04.93 90; 91
Priority: JP910263859 11.10.91
Applicant: TOYOTA MOTOR CO LTD
Inventor: SHIMIZU YASUHIRO (JP); KOBAYASHI NOBUYUKI (JP)
Title: Einrichtung und Verfahren zum Feststellen einer Verschlechterung eines Katalysators
Family: DE4234102 A 15.04.93
US5303548 A 19.04.94
DE4234102 C 27.02.97

DE4238807 A 27.05.93 150
Priority: JP910301519 18.11.91
Applicant: HITACHI LTD (JP)
Inventor: ASANO SEIJI (JP); ISHII TOSHIO (JP); KANEYASU MASAYOSHI (US); AWANO KAZUYA (JP); MUKAIHIRA TAKASHI (JP)
Title: Steuereinrichtung für Verbrennungsmotoren mit Abgasreinigungs-Katalysator und Verfahren und Einrichtung zur Überwachung der Verschlechterung des Katalysators
Family: DE4238807 A 27.05.93

DE4243339 A 24.06.93 150; 153
Priority: JP910338220 20.12.91
Applicant: HITACHI LTD (JP)
Inventor: KURIHARA NOBUO (JP); ISHII TOSHIO (JP); MUKAIHIRA TAKASHI (JP); KAWANO KAZUYA (JP); TAKAKU YUTAKA (JP)
Title: System für die Überwachung einer Abgasreinigungseinrichtung eines Motors und für die Überwachung eines Sensors
Family: DE4243339 A 24.06.93
US5341642 A 30.08.94

DE4302779 A 04.08.94 250; 251
Priority: DE934302779 02.02.93
Applicant: PORSCHE AG (DE)
Inventor: PELTERS STEPHAN (DE); SCHWARZENTHAL DIETMAR
Title: Verfahren zur Überprüfung der Funktionstüchtigkeit von im Abgasstrang, von mit einer Brennkraftmaschine ausgerüsteten Kraftfahrzeugen eingesetzten Abgaskatalysatoren
Family: DE4302779 A 04.08.94
EP0609527 A 10.08.94
US5435172 A 25.07.95
DE4302779 C 05.10.95

DE4308661 A 22.09.94 250
Priority: DE934308661 18.03.93
Applicant: EMITEC EMISSIONSTECHNIK
Inventor: MAUS W. (DE); SWARS H. (DE); BRÜCK ROLF (DE)
Title: Verfahren und Vorrichtung zur Funktionsüberwachung eines katalytischen Konverters
Family: DE4308661 A 22.09.94
WO9421902 A 29.09.94
EP0689641 A 03.01.96
BR9405949 A 19.12.95
US5560200 A 01.10.96
JP8506161T T 02.07.96
EP0689641 B 28.05.97
DE59402923G G 03.07.97
CN1119464 A 27.03.96
ES2104360T T 01.10.97

DE4322341 A 05.01.94 122
Priority: JP920177229 03.07.92

NEUMANN HARALD (DE); RIEGEL JOHANN (DE); STANGLMEIER FRANK
Title: SENSOR ZUR BESTIMMUNG GASKOMPONENTEN IN GASGEMISCHEN
Family: DE4408504 A 21.09.95
WO9525277 A 21.09.95
AU1754295 A 03.10.95
EP0698208 A 28.02.96
JP8510840T T 12.11.96
CN1124522 A 12.06.96

DE4412191 A 13.10.94 153
Priority: JP930083326 09.04.93
Applicant: HITACHI LTD (JP)
Inventor: TAKAKU YUTAKA (JP); ISHII TOSHIO (JP)
Title: Diagnoseeinrichtung für eine Abgasreinigungsvorrichtung
Family: DE4412191 A 13.10.94
DE4412191 C 10.04.97

DE4426020 A 01.02.96 264
Priority: DE944426020 22.07.94
Applicant: BOSCH GMBH ROBERT (DE)
Inventor: SCHNAIBEL EBERHARD (DE); SCHNEIDER ERICH (DE); BLISCHKE FRANK
Title: Verfahren zur Überwachung der Funktionsfähigkeit eines Katalysators im Abgaskanal einer Brennkraftmaschine
Family: DE4426020 A 01.02.96
SE9502681 A 23.01.96
JP8061047 A 05.03.96

DE4426788 A 23.02.95 327
Priority: DE944426788 28.07.94; DE934326534 07.08.93
Applicant: VOLKSWAGENWERK AG
Inventor: DONNERSTAG ACHIM (DE)
Title: Verfahren zur Berücksichtigung des aktuellen Konvertierungsgrads einer Abgasreinigungsvorrichtung
Family: DE4426788 A 23.02.95

DE4437655 A 02.05.96 280; 281
Priority: DE944437655 21.10.94
Applicant: BAYERISCHE MOTOREN WERKE AG (DE); DAIMLER BENZ AG (DE)
Inventor: MISSY STEPHAN (DE); TIEFENBACHER GERD (DE)
Title: Verfahren zur Überwachung der Funktionsfähigkeit einer Katalysatorheizvorrichtung
Family: DE4437655 A 02.05.96

DE4441432 A 23.05.96 342
Priority: DE944441432 22.11.94
Applicant: ROTH TECHNIK GMBH (DE)
Inventor: HAEFELE EDELBERT (DE)
Title: Anordnung zur Überwachung der Funktionsfähigkeit von Katalysatoren und/oder Lambda-Sonden
Family: DE4441432 A 23.05.96
WO9616257 A 30.05.96
CZ9603517 A 12.03.97
EP0793770 A 10.09.97

DE9202966U U 30.07.92 341
Priority: DE929202966U 920306; DE914108436 15.03.91
Applicant: KEESMANN T.
Inventor: KEESMANN T.
Title: Katalysatoranlage für eine Brennkraftmaschine
Family: DE9202966U U 30.07.92

EP0236659 A 16.09.87 306
Priority: IT860067029 14.01.86
Applicant: FIAT AUTO SPA (IT)
Inventor: DI NUNZIO VITTORIO; BONARDO RINALDO
Title: Device for protecting the catalyst in a catalytic silencer for motor vehicles.
Family: EP0236659 A 16.09.87
BR8700227 A 01.12.87
EP0236659 B 20.12.89
DE3667700G G 25.01.90
ES2012359 B 16.03.90
IT1187855 B 23.12.87

EP0262558 A 06.04.88 277
Priority: DE863633283 30.09.86
Applicant: SIEMENS AG (DE)
Inventor: BALLING LOTHAR; SPITZNAGEL GÜNTHER
Title: Katalysatoranordnung zur Minderung der Stickoxide in Rauchgasen
Family: EP0262558 A 06.04.88
NO8704061 A 02.05.88

EP0498598 A 12.08.92 **16; 283; 284; 286**
Priority: JP910033366 04.02.91; JP910045662 20.02.91
Applicant: TOYOTA MOTOR CO LTD
Inventor: HIROTA SHINYA (JP); KATOH KENJI (JP)
Title: Exhaust gas purification system for an internal combustion engine.
Family: EP0498598 A 12.08.92
JP4255521 A 10.09.92
US5201802 A 13.04.93
EP0498598 B 26.04.95
DE69202163E E 01.06.95

EP0505720 A 30.09.92 **11**
Priority: DE914109626 23.03.91
Applicant: EBERSPÄCHER J (DE)
Inventor: SCHUMACHER HERBERT (DE); WÖRNER SIEGFRIED
Title: Halterung eines Trägerkörpers in Abgasanlagen von Fahrzeugen.
Family: DE4109626 A 24.09.92
EP0505720 A 30.09.92
EP0505720 B 17.05.95
DE59202191G G 22.06.95

EP0510498 A 28.10.92 **16**
Priority: US910688967 22.04.91; US920856848 30.03.92
Applicant: CORNING INC (US)
Inventor: LACHMAN IRWIN MORRIS ; PATIL MALLANAGOUDA DYAMANAGOUD; SWAROOP SRINIVAS HOSDURG (US); WILLIAMS JIMMIE LEWIS (US)
Title: Catalytic reactor system.
Family: EP0510498 A 28.10.92
AU8898891 A 29.10.92
AU1491592 A 29.10.92
BR9201433 A 30.03.93
JP5131118 A 28.05.93
AU650120 B 09.06.94
EP0510498 B 29.01.97
DE69217108E E 13.03.97

EP0521641 A 07.01.93 **71**
Priority: US910724399 28.06.91
Applicant: FORD MOTOR CO (GB); FORD FRANCE (FR); FORD WERKE AG (DE)
Inventor: HAMBURG DOUGLAS RAY (US); COOK JEFFREY ARTHUR (US)
Title: Method and apparatus for detecting catalyst malfunctions.
Family: EP0521641 A 07.01.93
EP0521641 B 21.02.96
DE69208401E E 28.03.96

EP0536789 A 14.04.93 **90**
Priority: JP910263892 11.10.91
Applicant: TOYOTA MOTOR CO LTD
Inventor: SHIMIZU YASUHIRO (JP); KOBAYASHI NOBUYUKI (JP)
Title: A device for determining deterioration of a catalytic converter for an engine.
Family: EP0536789 A 14.04.93
EP0536789 A 07.07.93
US5301501 A 12.04.94
EP0536789 B 23.08.95
DE69204250E E 28.09.95

EP0537968 A 21.04.93 **16**
Priority: JP910298252 16.10.91
Applicant: TOYOTA MOTOR CO LTD
Inventor: OSHIMA YUJIRO (JP); MURAKI HIDEAKI (JP); YOKOTA KOJI (JP); NAKANISHI KIYOSHI (JP)
Title: Nitrogen oxides decreasing apparatus for an internal combustion engine.
Family: EP0537968 A 21.04.93
JP5106430 A 27.04.93
US5412946 A 09.05.95
EP0537968 B 24.01.96
DE69207854E E 07.03.96

EP0546318 A 16.06.93 **54; 55**
Priority: DE914140618 10.12.91
Applicant: BOSCH GMBH ROBERT (DE)
Inventor: SCHNAIBEL EBERHARD (DE); SCHNEIDER ERICH (DE); REUSCHENBACH LUTZ (DE); BLISCHKE FRANK (DE)
Title: Verfahren und Vorrichtung zur Ermittlung der Konvertierungsfähigkeit eines Katalysators.
Family: EP0546318 A 16.06.93
DE4140618 A 17.06.93
US5317868 A 07.06.94
EP0546318 B 12.07.95

DE59202872G G 17.08.95
ES2074793T T 16.09.95

EP0547326 A 23.06.93 **84; 92; 93; 94; 95; 100; 115**
Priority: JP910331810 16.12.91
Applicant: TOYOTA MOTOR CO LTD
Inventor: SHIMIZU YASUHIRO (JP); KOBAYASHI NOBUYUKI (JP)
Title: A device for determining deterioration of a catalytic converter for an engine.
Family: EP0547326 A 23.06.93
US5279116 A 18.01.94
EP0547326 A 18.08.93
EP0547326 B 13.09.95
DE69204807E E 19.10.95

EP0588123 A 23.03.94 **27; 220**
Priority: IT92TO000760 14.09.92
Applicant: FIAT AUTO SPA (IT)
Inventor: COMIGNAGHI EMILIO (IT); PEROTTO ALDO (IT)
Title: System for monitoring the efficiency of a catalyst, in particular for motor vehicles.
Family: EP0588123 A 23.03.94
EP0588123 B 28.02.96
DE69301648E E 04.04.96
IT1257100 B 05.01.96
US5627757 A 06.05.97

EP0588324 A 23.03.94 **137**
Priority: JP920275405 18.09.92
Applicant: HONDA MOTOR CO LTD (JP)
Inventor: OGAWA KEN (JP); KATO ATSUSHI (JP); OSHIMA YOSHIKAZU (JP)
Title: Catalyst deterioration-detecting device for internal combustion engines.
Family: EP0588324 A 23.03.94
US5357754 A 25.10.94
EP0588324 B 11.12.96
DE69306511E E 23.01.97

EP0595044 A 04.05.94 **114**
Priority: JP920261840 30.09.92; JP920263746 01.10.92
Applicant: TOYOTA MOTOR CO LTD
Inventor: SHIMIZU YASUHIRO (JP)
Title: A device for detecting deterioration of a catalytic converter for an engine.
Family: EP0595044 A 04.05.94
US5417058 A 23.05.95
EP0595044 A 15.02.95
EP0595044 B 29.01.97
DE69307824E E 13.03.97

EP0602468 A 22.06.94 **99**
Priority: JP920329405 09.12.92
Applicant: TOYOTA MOTOR CO LTD
Inventor: SHIMIZU YASUHIRO (JP)
Title: A device for detecting deterioration of a catalytic converter for an engine.
Family: EP0602468 A 22.06.94
US5359853 A 01.11.94
EP0602468 B 19.06.96
DE69303258E E 25.07.96

EP0602963 A 22.06.94 **22**
Priority: JP920335937 16.12.92
Applicant: NGK INSULATORS LTD (JP)
Inventor: ABE FUMIO (JP); SUZUKI JUNICHI (JP); OGAWA MASATO (JP)
Title: Exhaust gas purification method and apparatus therefor.
Family: EP0602963 A 22.06.94
JP6185343 A 05.07.94
US5662869 A 02.09.97

EP0619420 A 12.10.94 **63; 64; 74**
Priority: US930043713 08.04.93
Applicant: FORD MOTOR CO (GB); FORD FRANCE; FORD WERKE AG
Inventor: ORZEL DANIEL V (US)
Title: An air/fuel control system providing monitoring of activity of a catalytic converter.
Family: EP0619420 A 12.10.94
US5357751 A 25.10.94
EP0619420 B 02.10.96
DE69400626E E 07.11.96

EP0626506 A 30.11.94 **172**
Priority: EP930108615 27.05.93
Applicant: SIEMENS AG (DE)
Inventor: ACHLEITNER ERWIN (DE)
Title: Verfahren zur Überprüfung des Katalysatorwirkungsgrades.
Family: EP0626506 A 30.11.94
WO9428292 A 08.12.94
EP0626506 B 21.02.96
DE59301687G G 28.03.96
ES2083793T T 16.04.96

JP8510811T T 12.11.96
US5673555 A 07.10.97

EP0626507 A 30.11.94 **153**
Priority: JP930099765 26.04.93
Applicant: HITACHI LTD (JP)
Inventor: MUKAIHIRA TAKASHI (JP); MIURA KIYOSHI (JP); ISHII TOSHIO (JP); AWANO KAZUYA (JP)
Title: System for diagnosing deterioration of catalyst.
Family: EP0626507 A 30.11.94
US5526643 A 18.06.96
US5649420 A 22.07.97

EP0627548 A 07.12.94 **13; 14; 15**
Priority: JP930129513 31.05.93
Applicant: TOYOTA MOTOR CO LTD
Inventor: TAKESHIMA SHINICHI (JP)
Title: An exhaust gas purification device for an engine.
Family: EP0627548 A 07.12.94
US5448887 A 12.09.95
EP0627548 B 20.11.96
DE69400941E E 02.01.97

EP0634567 A 18.01.95 **174**
Priority: EP930111479 16.07.93
Applicant: SIEMENS AG (DE)
Inventor: ACHLEITNER ERWIN (DE)
Title: Anpassung von Verfahren zur Katalysatorwirkungsgrad-überprüfung an Katakysatoren mit unterschiedlichem Wirkungsgrad.
Family: EP0634567 A 18.01.95
EP0634567 B 18.09.96
DE59303885G G 24.10.96

EP0636771 A 01.02.95 **215**
Priority: GB930015918 31.07.93
Applicant: LUCAS IND PLC (GB)
Inventor: SINDANO HECTOR (GB); BIRKETT PAUL WILLIAM
Title: Method of and apparatus for monitoring operation of a catalyst
Family: EP0636771 A 01.02.95
JP7150931 A 13.06.95
US5602737 A 11.02.97
EP0636771 B 21.05.97
DE69403288E E 26.06.97

EP0641920 A 08.03.95 **153**
Priority: JP930223613 08.09.93
Applicant: HITACHI LTD (JP); HITACHI AUTOMOTIVE ENG (JP)
Inventor: NUMATA AKIHITO (JP); MUKAIHIRA TAKASHI (JP); ISHII TOSHIO (JP); TAKAKU YUTAKA (JP); KAWANO KAZUYA (JP)
Title: Malfunction diagnosis apparatus for internal combustion engine.
Family: EP0641920 A 08.03.95
US5557933 A 24.09.96

EP0668438 A 23.08.95 **124**
Priority: JP940020909 18.02.94; JP940273509 08.11.94; JP940324693 27.12.94
Applicant: NIPPON DENSO CO (JP)
Inventor: FUKAYA KENJI (JP); HAYASHI KAZUO (JP); HORI MAKOTO (JP); HAMAYA MASAHIRO (JP); OHTA MINORU (JP)
Title: Catalyst degradation detecting apparatus
Family: EP0668438 A 23.08.95
CA2142744 A 19.08.95
US5545377 A 13.08.96
JP8189343 A 23.07.96
EP0668438 B 03.09.97
DE69500627E E 09.10.97

EP0690213 A 03.01.96 **102; 103**
Priority: JP940149446 30.06.94
Applicant: TOYOTA MOTOR CO LTD
Inventor: KIHARA TETSURO (JP); KATOH KENJI (JP); ASANUMA TAKAMITSU (JP); IGUCHI SATOSHI (JP)
Title: Exhaust purification device of internal combustion engine
Family: EP0690213 A 03.01.96
JP8014030 A 16.01.96
US5577382 A 26.11.96

EP0709129 A 01.05.96 **16**
Priority: US940331410 31.10.94
Applicant: GENERAL MOTORS CORP
Inventor: CHO BYONG KWON (US)
Title: Method of reducing NO_x emissions from lean-burn combustion engines
Family: EP0709129 A 01.05.96
US5609022 A 11.03.97

EP0748927 A 18.12.96 **104**
Priority: JP950144690 12.06.95; JP950191527 27.07.95; JP960055891 13.03.96
Applicant: TOYOTA MOTOR CO LTD
Inventor: MITSUTANI NORITAKE (JP); ADACHI SHIN (JP)
Title: A device for determining deterioration of a catalytic converter for an engine
Family: EP0748927 A 18.12.96
JP8338232 A 24.12.96
JP9041951 A 10.02.97

EP0751390 A 02.01.97 **343; 344; 358**
Priority: JP950159683 26.06.95
Applicant: NGK INSULATORS LTD (JP)
Inventor: IKOMA NOBUKAZU (JP); NISHIKAWA SATOSHI (JP); MIYASHITA TAKEYA
Title: Combustible gas sensor and method for detecting deterioration of catalyst
Family: EP0751390 A 02.01.97
JP9015186 A 17.01.97

EP0756071 A 29.01.97 **290; 291**
Priority: JP950189154 25.07.95
Applicant: TOYOTA MOTOR CO LTD
Inventor: HANAFUSA TORU (JP); OHASI MICHIHIRO (JP)
Title: A device for determining an abnormal degree of deterioration of a catalyst
Family: EP0756071 A 29.01.97
JP9032535 A 04.02.97

EP0756072 A 29.01.97 **104**
Priority: JP950190803 26.07.95
Applicant: TOYOTA MOTOR CO LTD
Inventor: HANAFUSA TORU (JP); OHASHI MICHIHIRO (JP)
Title: A device for determining an abnormal degree of deterioration of a catalyst
Family: EP0756072 A 29.01.97
JP9041949 A 10.02.97

EP0756073 A 29.01.97 **105; 106**
Priority: JP950190573 26.07.95
Applicant: TOYOTA MOTOR CO LTD
Inventor: MITSUTANI NORITAKE (JP)
Title: A device for determining deterioration of a catalytic converter for an engine
Family: EP0756073 A 29.01.97
JP9041948 A 10.02.97

EP0769694 A 23.04.97 **316; 318**
Priority: JP950272458 20.10.95
Applicant: NGK INSULATORS LTD (JP)
Inventor: KATO NOBUHIDE (JP)
Title: NO_x sensor and method of measuring NO_x
Family: EP0769694 A 23.04.97
JP9113482 A 02.05.97

EP0770767 A 02.05.97 **107**
Priority: JP950279344 26.10.95; JP950281803 30.10.95
Applicant: TOYOTA MOTOR CO LTD
Inventor: MITSUTANI NORITAKE (JP)
Title: Catalyst deterioration detection device for internal combustion engine
Family: EP0770767 A 02.05.97
JP9119309 A 06.05.97
JP9125936 A 13.05.97

EP0770768 A 02.05.97 **291; 294**
Priority: JP950277780 25.10.95
Applicant: TOYOTA MOTOR CO LTD
Inventor: TANAHASHI TOSHIO (JP); SANADA MASAKATSU (JP); YOKOTA KOJI (JP); MATSUNAGA SHINICHI (JP)
Title: Device for evaluating catalyst performance deterioration
Family: EP0770768 A 02.05.97
JP9177544 A 08.07.97

EP0773355 A 14.05.97 **281**
Priority: DE951041903 10.11.95
Applicant: BAYERISCHE MOTOREN WERKE AG (DE)
Inventor: ZIMMER RAINER (DE); HUNDERTMARK DIETMAR
Title: Überwachungssystem für die Abgasreinigung einer Brennkraftmaschine
Family: EP0773355 A 14.05.97
DE19541903 A 15.05.97

EP0779416 A 18.06.97 **295; 296; 297; 298; 358**
Priority: JP950326959 15.12.95

Priority: NL940000655 25.04.94
Applicant: HAGEN SCHILDKAMP TECHNIEK BV (NL)
Inventor: VAN ROOTSELAAR GERRIT
Title: Werkwijze en meter voor het testen van katalysator van een verbrandingsmotor.
Family: FR2719116 A 27.10.95
NL9400655 A 01.12.95

FR2739139 A 28.03.97 225
Priority: FR950011060 21.09.95
Applicant: PEUGEOT (FR)
Inventor: PIRALI FREDERIC
Title: DISPOSITIF DE DIAGNOSTIC DE L'EFFICACITE D'UN CATALYSEUR DE GAZ D' ECHAPPEMENT D'UN MOTEUR A COMBUSTION CYLINDRES
Family: FR2739139 A 28.03.97

FR2746142 A 19.09.97 228
Priority: FR960003350 18.03.96
Applicant: RENAULT (FR)
Inventor: AIMARD FRED.; SORINE M.
Title: PROCEDES DE SURVEILLANCE DU FONCTIONNEMENT ET DU CATALYTIQUE DE VEHICULE AUTOMOBILE ET PROCEDE DE COMMANDE DU MOTEUR
Family: FR2746142 A 19.09.97

GB1373826 A 13.11.74 253
Priority: JP710071096U 09.08.71
Applicant: NISSAN MOTOR
Inventor: NISSAN MOTOR
Title: MOTOR VEHICLE EXHAUST SYSTEM INCLUDING A CATALYTIC CONVERTER
Family: GB1373826 A 13.11.74

GB2177513 A 02.08.89 217
Priority: DE853524592 10.07.85
Applicant: PIERBURG GMBH & CO KG
Inventor: ROTH ANDREAS; LAMPE G.
Title: Process for testing the functional effectiveness of a catalytic reactor
Family: DE3524592 C 25.09.86
GB2177513 A 21.01.87
FR2584818 A 16.01.87
GB2177513 B 02.08.89

GB2178857 A 18.02.87 61
Priority: DE853527175 30.07.85
Applicant: DAIMLER BENZ AG (DE)
Inventor: ABTHOFF JORG (DE); SCHUSTER HANS DIETER (DE); LANGER HANS JOACHIM (DE); ZAHN W. (DE); EBINGER GÜNTHER (DE)
Title: Process for the determination of the ageing condition of an exhaust-gas catalyst for an internal combustion engine which is fitted with λ-controlled regulation of the fuel/air ratio
Family: DE3527175 A 12.02.87
GB2178857 A 18.02.87
AU6040786 A 05.02.87
FR2585767 A 06.02.87
SE8603227 A 31.01.87
US4691562 A 08.09.87
CH670284 A 31.05.89
DE3527175 C 17.08.89
GB2178857 B 20.09.89
SE465587 B 30.09.91
IT1214697 B 18.01.90

GB2225860 A 13.06.90 61
Priority: DE883841685 10.12.88
Applicant: DAIMLER BENZ AG (DE)
Inventor: DURSCHMIDT FERRY; KOLB HARTMUT; STRAUSS W.
Title: Method for detecting the condition of catalytic converters
Family: GB2225860 A 13.06.90
DE3841685 A 13.06.90
FR2640383 A 15.06.90
DE3841685 C 20.09.90
US5018348 A 28.05.91
GB2225860 B 23.06.93
IT1237223 B 27.05.93

GB2254939 A 21.10.92 46
Priority: DE914112477 17.04.91
Applicant: BOSCH GMBH ROBERT (DE)
Inventor: SCHNEIDER ERICH; SCHNAIBEL EBERHARD
Title: SIMULATION OF A LAMBDA VALUE FOR ENGINE CATALYTIC CONVERTER.
Family: GB2254939 A 21.10.92
DE4112477 A 22.10.92
US5214915 A 01.06.93

Priority: JP880180336 21.07.88
Applicant: TOYOTA MOTOR CORP
Inventor: KASHIWANUMA NOBUAKI; BESSHO HIRONORI; FURUHASHI MICHIO; SAWAMOTO HIROYUKI; SONODA YUKIHIRO; OSAWA KOICHI
Title: DEVICE FOR DISCRIMINATING CATALYTIC DEGRADATION OF INTERNAL COMBUSTION ENGINE
Family: JP2033408 A 02.02.90

JP2091440 A 30.03.90 **86**
Priority: JP880242481 29.09.88
Applicant: TOYOTA MOTOR CORP
Inventor: SONODA YUKIHIRO; BESSHO HIRONORI; FURUHASHI MICHIO; IZUMITANI NAOHIDE; SAWAMOTO HIROYUKI; HOSHI KOICHI; OSAWA KOICHI
Title: CATALYST DETERIORATION DETERMINING DEVICE OF INTERNAL
Family: JP2091440 A 30.03.90

JP2136538 A 25.05.90 **117**
Priority: JP880287121 14.11.88
Applicant: NIPPON DENSO CO
Inventor: KATO KATSUSHI
Title: CATALYTIC DEGRADATION DETECTOR
Family: JP2136538 A 25.05.90

JP2207159 A 16.08.90 **86**
Priority: JP890023962 03.02.89
Applicant: TOYOTA MOTOR CORP
Inventor: IZUMITANI NAOHIDE
Title: CATALYST DETERIORATION JUDGING DEVICE FOR INTERNAL COMBUSTION ENGINE
Family: US5088281 A 18.02.92
JP2030915 A 01.02.90
JP2033408 A 02.02.90
JP2207159 A 16.08.90

JP2310453 A 26.12.90 **199**
Priority: JP890132296 25.05.89
Applicant: NISSAN MOTOR
Inventor: NEMOTO KOICHI; MORITA HIROSHI; KANEKO HIROAKI; GOTO TADASHI
Title: DETECTION OF DETERIORATION OF CATALYST
Family: JP2310453 A 26.12.90

JP3031756 A 12.02.91 **189**
Priority: JP890168174 29.06.89
Applicant: MITSUBISHI MOTORS CORP
Inventor: KUME TAKEO; YOSHIDA MICHIYASU
Title: DEVICE FOR DIAGNOSING CLEANING EFFICIENCY OF CATALYST
Family: JP3031756 A 12.02.91

JP3050315 A 04.03.91 **256**
Priority: JP890182517 17.07.89
Applicant: NISSAN MOTOR
Inventor: ARAMAKI TAKASHI
Title: CATALYST DETERIORATION DETECTING DEVICE
Family: JP3050315 A 04.03.91

JP3050406 A 05.03.91 **338**
Priority: JP890184539 19.07.89
Applicant: TOKYO SHIBAURA ELECTRIC CO; TOKYO ELECTRIC POWER CO
Inventor: YAMANAKA CHIKAU; FURUYA TOMIAKI; HAYATA TERUNOBU; FURUSE YUTAKA; TSUCHIYA TOSHIAKI
Title: CATALYTIC COMBUSTION TYPE GAS-TURBINE COMBUSTOR
Family: JP3050406 A 05.03.91

JP3057862 A 13.03.91 **86**
Priority: JP890190632 25.07.89
Applicant: TOYOTA MOTOR CORP
Inventor: KASHIWANUMA NOBUAKI
Title: CATALYST DETERIORATION DISCRIMINATOR FOR INTERNAL COMBUSTION ENGINE
Family: JP3057862 A 13.03.91

JP3073839 A 28.03.91 **338**
Priority: JP890211158 15.08.89
Applicant: NISSAN MOTOR
Inventor: IWAKIRI YASUNORI

Applicant: MITSUBISHI MOTORS CORP; MITSUBISHI ELECTRIC CORP
Inventor: MIYAKE MITSUHIRO; HASHIMOTO TORU; TAKAHASHI AKIRA; HORIE OSAMU; KATASHIBA HIDEAKI; MAKIKAWA YASUYUKI; NISHIDA MINORU
Title: DIAGNOSIS FOR DETERIORATION OF CATALYST
Family: JP4181149 A 29.06.92

JP4303754 A 27.10.92 **164**
Priority: JP910093519 29.03.91
Applicant: MAZDA MOTOR
Inventor: KOMATSU KAZUYA; NOGUCHI NAOYUKI; KURONISHI KIYOSHI; NISHIMURA HIROBUMI
Title: CLEANING APPARATUS FOR EXHAUST OF ENGINE
Family: JP4303754 A 27.10.92

JP4321744 A 11.11.92 **120**
Priority: JP910090646 22.04.91
Applicant: NIPPON DENSO CO
Inventor: YASUNAGA HISAYO; KURITA NORIAKI; KONDO TOSHIO
Title: CATALYST DETERIORATION DETECTION APPARATUS
Family: JP4321744 A 11.11.92

JP5010181 A 19.01.93 **224**
Priority: JP910160298 01.07.91
Applicant: OSAKA GAS CO LTD
Inventor: MORIYA KOJI; HIRAOKA TSUTOMU; SAKO TAKAHIRO
Title: CATALYST DETERIORATION DETECTOR OF EXHAUST EMISSION CONTROL DEVICE AND METHOD THEREOF
Family: JP5010181 A 19.01.93

JP5018231 A 26.01.93 **224**
Priority: JP910173884 15.07.91
Applicant: OSAKA GAS CO LTD
Inventor: MORIYA KOJI; HIRAOKA TSUTOMU; SAKO TAKAHIRO
Title: CATALYST DETERIORATION DETECTING DEVICE FOR EXHAUST GAS PURIFICATION DEVICE
Family: JP5018231 A 26.01.93

JP5098945 A 20.04.93 **200**
Priority: JP910260833 08.10.91
Applicant: NISSAN MOTOR
Inventor: TAKAHATA TOSHIO
Title: DEVICE FOR DIAGNOSING DETERIORATION OF CATALYST CONVERTER DEVICE OF INTERNAL COMBUSTION ENGINE
Family: JP5098945 A 20.04.93

JP5098946 A 20.04.93 **206**
Priority: JP910260834 08.10.91
Applicant: NISSAN MOTOR
Inventor: TAKAHATA TOSHIO
Title: DEVICE FOR DIAGNOSING DETERIORATION OF CATALYST CONVERTER DEVICE OF INTERNAL COMBUSITON ENGINE
Family: JP5098946 A 20.04.93

JP5113157 A 07.05.93 **344**
Priority: JP910302700 23.10.91
Applicant: TOYOTA MOTOR CORP
Inventor: KIHARA TETSUO; KATO KENJI
Title: EXHAUST GAS PURIFICATION APPARATUS FOUR INTERNAL COMBUSTION ENGINE
Family: JP5113157 A 07.05.93

JP5179935 A 20.07.93 **96**
Priority: JP920153840 12.06.92
Applicant: TOYOTA MOTOR CORP
Inventor: KATSUNO TOSHIYASU; MASUI TAKATOSHI; SATO YASUSHI; NAGAI TOSHINARI
Title: CATALYST DETERIORATION DETECTING DEVICE FOR INTERNAL COMBUSTION ENGINE
Family: JP5179935 A 20.07.93

JP5196588 A 06.08.93 **177**
Priority: JP920157658 17.06.92; JP910307600 22.11.91
Applicant: NGK SPARK PLUG CO

Family: JP6159048 A 07.06.94

JP6193436 A 12.07.94 **138**
Priority: JP920359280 24.12.92
Applicant: HONDA MOTOR CO LTD
Inventor: YANAGA MORIJI; WAKABAYASHI MITSUO; KANEKO TETSUYA; FUKUDA MORIO
Title: DETERIORATION DETECTION DEVICE OF CATALYTIC CONVERTER RHODIUM OF INTERNAL COMBUSTION ENGINE
Family: JP6193436 A 12.07.94

JP6200811 A 19.07.94 **181**
Priority: JP920361521 28.12.92
Applicant: SUZUKI MOTOR CO
Inventor: TOYODA KATSUHIKO
Title: CATALYST DETERIORATION DECIDING DEVICE OF INTERNAL COMBUSTION ENGINE
Family: JP6200811 A 19.07.94

JP6229309 A 16.08.94 **186**
Priority: JP930034598 30.01.93
Applicant: SUZUKI MOTOR CO
Inventor: TOYODA KATSUHIKO; SUZUKI RYOJI
Title: CATALYST DETERIORATION JUDGING DEVICE OF INTERNAL COMBUSTION ENGINE
Family: JP6229309 A 16.08.94

JP6264724 A 20.09.94 **256**
Priority: JP930054033 15.03.93
Applicant: NISSAN MOTOR
Inventor: SATO TATSUO; NISHIZAWA MASAYOSHI
Title: CATALYST DETERIORATION DIAGNOSING DEVICE OF INTERNAL COMBUSTION ENGINE
Family: JP6264724 A 20.09.94

JP6264725 A 20.09.94 **256**
Priority: JP930055506 16.03.93
Applicant: MITSUBISHI ELECTRIC CORP
Inventor: TAKADA TAMOTSU
Title: DETERIORATION DETECTING DEVICE OF CATALYTIC CONVERTER
Family: JP6264725 A 20.09.94

JP6264726 A 20.09.94 **192**
Priority: JP930049757 11.03.93
Applicant: NISSAN MOTOR
Inventor: KISHIMOTO YOICHI
Title: CATALYST DETERIORATION DIAGNOSING DEVICE OF INTERNAL COMBUSTION ENGINE
Family: JP6264726 A 20.09.94

JP6265498 A 22.09.94 **156**
Priority: JP930055425 16.03.93
Applicant: HITACHI LTD; HITACHI AUTOMOTIVE ENG
Inventor: SATO KANEMASA; UENO SADAYASU
Title: STRUCTURE OF CATALYTIC DIAGNOSTIC AIR-FUEL RATIO SENSOR
Family: JP6265498 A 22.09.94

JP6280547 A 04.10.94 **164**
Priority: JP930090941 24.03.93
Applicant: MAZDA MOTOR
Inventor: KAMAKURA TAMOTSU; UCHIUMI IWAO
Title: CATALYST DETERIORATION DETECTING DEVICE
Family: JP6280547 A 04.10.94

JP6280661 A 04.10.94 **164**
Priority: JP930071760 30.03.93
Applicant: MAZDA MOTOR
Inventor: KAMAKURA TAMOTSU; MOMII KATSUHIRO
Title: TROUBLE DETECTION DEVICE OF AIR-FUEL RATIO CONTROLLER
Family: JP6280661 A 04.10.94

JP6280662 A 04.10.94 **164**
Priority: JP930071761 30.03.93
Applicant: MAZDA MOTOR
Inventor: NIIMOTO KAZUHIRO; IWASHITA YOSHIKAZU
Title: TROUBLE DETECTION DEVICE OF AIR-FUEL RATIO CONTROLLER
Family: JP6280662 A 04.10.94

JP63231252 A 27.09.88 **189**

JP7180534 A 18.07.95 **201**
Priority: JP930323563 22.12.93
Applicant: NISSAN MOTOR
Inventor: GOTO KENICHI; KISHIMOTO YOICHI
Title: CATALYST DETERIORATION DIAGNOSTIC DEVICE FOR INTERNAL COMBUSTION ENGINE
Family: JP7180534 A 18.07.95

JP7180535 A 18.07.95 **344**
Priority: JP930324557 22.12.93
Applicant: FUJI HEAVY IND LTD
Inventor: MORIKAWA KOJI
Title: FAILURE DIAGNOSTIC DEVICE FOR EXHAUST EMISSION CONTROL DEVICE
Family: JP7180535 A 18.07.95

JP7180536 A 18.07.95 **257**
Priority: JP930324802 22.12.93
Applicant: NISSAN MOTOR
Inventor: KIKUCHI TSUTOMU
Title: CATALYST DETERIORATION DETECTING DEVICE
Family: JP7180536 A 18.07.95

JP7180537 A 18.07.95 **257**
Priority: JP930324803 22.12.93
Applicant: NISSAN MOTOR
Inventor: KIKUCHI TSUTOMU
Title: CATALYST DETERIORATION DETECTING DEVICE FOR CATALYTIC CONVERTER
Family: JP7180537 A 18.07.95

JP7189664 A 28.07.95 **202**
Priority: JP930337957 28.12.93
Applicant: NISSAN MOTOR
Inventor: MATSUSHIMA HIDEYUKI
Title: CATALYST DETERIORATION JUDGING DEVICE FOR INTERNAL COMBUSTION ENGINE
Family: JP7189664 A 28.07.95

JP7189780 A 28.07.95 **221**
Priority: JP930334408 28.12.93
Applicant: ATSUGI UNISIA CORP
Inventor: UCHIKAWA AKIRA
Title: CATALYST DETERIORATION DIAGNOSIS DEVICE FOR INTERNAL COMBUSTION ENGINE
Family: JP7189780 A 28.07.95

JP7189781 A 28.07.95 **202**
Priority: JP930337958 28.12.93
Applicant: NISSAN MOTOR
Inventor: MATSUSHIMA HIDEYUKI
Title: CATALYST DETERIORATION JUDGMENT DEVICE FOR INTERNAL COMBUSTION ENGINE
Family: JP7189781 A 28.07.95

JP7197807 A 01.08.95 **186**
Priority: JP930354129 29.12.93
Applicant: SUZUKI MOTOR CO
Inventor: TOYODA KATSUHIKO
Title: DEVICE FOR JUDGING DETERIORATION OF CATALYST FOR INTERNAL COMBUSTION ENGINE
Family: JP7197807 A 01.08.95

JP7238824 A 12.09.95 **222**
Priority: JP940028603 25.02.94
Applicant: ATSUGI UNISIA CORP
Inventor: TAKAYAMA KENGO; OSAKI MASANOBU
Title: DIAGNOSIS DEVICE FOR DETERIORATION OF EXHAUST EMISSION CONTROL CATALYST FOR INTERNAL COMBUSTION ENGINE
Family: JP7238824 A 12.09.95

JP7243342 A 19.09.95 **202**
Priority: JP940032577 02.03.94
Applicant: NISSAN MOTOR
Inventor: NAKAJIMA YUKI
Title: CATALYST DETERIORATION DIAGNOSTIC DEVICE FOR INTERNAL COMBUSTION ENGINE
Family: JP7243342 A 19.09.95

JP7247830 A 26.09.95 **202**
Priority: JP940040090 10.03.94
Applicant: NISSAN MOTOR
Inventor: UCHIDA MASAAKI; NAKAJIMA YUKI
Title: CATALYST DETERIORATION DIAGNOSIS DEVICE FOR INTERNAL

INTERNAL
COMBUSTION ENGINE
Family: JP8128317 A 21.05.96

JP8135432 A 28.05.96 223
Priority: JP940303033 11.11.94
Applicant: ATSUGI UNISIA CORP
Inventor: TAKAYAMA KENGO; FURUYA JUNICHI; OSAKI MASANOBU
Title: CATALYST DETERIORATION DIAGNOSTIC DEVICE OF INTERNAL COMBUSTION ENGINE
Family: JP8135432 A 28.05.96

JP8144744 A 04.06.96 140
Priority: JP940308229 17.11.94
Applicant: HONDA MOTOR CO LTD
Inventor: SEKI YASUNARI
Title: CATALYST DETERIORATION DETECTING DEVICE FOR INTERNAL COMBUSTION ENGINE
Family: JP8144744 A 04.06.96
US5636514 A 10.06.97

JP8144745 A 04.06.96 141
Priority: JP940309860 18.11.94
Applicant: HONDA MOTOR CO LTD
Inventor: SEKI YASUNARI
Title: CATALYST DETERIORATION DETECTING DEVICE FOR INTERNAL COMBUSTION ENGINE
Family: JP8144745 A 04.06.96
US5636514 A 10.06.97

JP8177468 A 09.07.96 203
Priority: JP940328464 28.12.94
Applicant: NISSAN MOTOR
Inventor: TAKEYAMA SATORU; NAKAJIMA YUKI
Title: CATALYST DETERIORATION DIAGNOSTIC DEVICE FOR INTERNAL COMBUSTION ENGINE
Family: JP8177468 A 09.07.96

JP8177469 A 09.07.96 203
Priority: JP940327415 28.12.94
Applicant: NISSAN MOTOR
Inventor: OBA HIROSHI; NAKAJIMA YUKI
Title: CATALYST DETERIORATION DIAGNOSTIC DEVICE FOR INTERNAL COMBUSTION ENGINE
Family: JP8177469 A 09.07.96

JP8210126 A 20.08.96 102
Priority: JP950280917 27.10.95
Applicant: TOYOTA MOTOR CORP
Inventor: FURUHASHI MICHIO
Title: CATALYTIC DETERIORATION DISCRIMINATING DEVICE
Family: JP8210126 A 20.08.96

JP8246853 A 24.09.96 204
Priority: JP950049866 09.03.95
Applicant: NISSAN MOTOR
Inventor: NAKAJIMA YUKI; MATSUMOTO MIKIO
Title: CATALYST DEGRADATION DIAGNOSING DEVICE FOR INTERNAL COMBUSTION ENGINE
Family: JP8246853 A 24.09.96

JP8246854 A 24.09.96 125
Priority: JP950051288 10.03.95
Applicant: NIPPON DENSO CO
Inventor: OKAMOTO YOSHIYUKI; SATO KAZUKI
Title: CATALYST DEGRADATION DIAGNOSING DEVICE FOR INTERNAL COMBUSTION ENGINE
Family: JP8246854 A 24.09.96

JP8270438 A 15.10.96 290
Priority: JP950077751 03.04.95
Applicant: TOYOTA MOTOR CORP
Inventor: HANABUSA TORU; OHASHI MICHIHIRO
Title: CATALYST DEGRADATION JUDGING DEVICE
Family: JP8270438 A 15.10.96

JP8284648 A 29.10.96 290
Priority: JP950091061 17.04.95
Applicant: TOYOTA MOTOR CORP
Inventor: KUNIMASA AKIO
Title: CATALYST DETERIORATION DIAGNOSING DEVICE FOR INTERNAL COMBUSTION ENGINE

Inventor: HANABUSA TORU; OHASHI MICHIHIRO
Title: CATALYST DETERIORATION JUDGING DEVICE
Family: JP8338297 A 24.12.96

JP9033478 A 07.02.97 **222**
Priority: JP950182789 19.07.95
Applicant: ATSUGI UNISIA CORP
Inventor: SAKUMA TORU
Title: APPARATUS FOR DIAGNOSING RESPONSE OF OXYGEN SENSOR IN INTERNAL COMBUSTION ENGINE
Family: JP9033478 A 07.02.97

JP9041950 A 10.02.97 **345**
Priority: JP950190845 26.07.95
Applicant: TOYOTA MOTOR CORP
Inventor: OHASHI MICHIHIRO; HANABUSA TORU
Title: CATALYST DETERIORATION DETERMINATION DEVICE FOR INTERNAL
Family: JP9041950 A 10.02.97

JP9041952 A 10.02.97 **141**
Priority: JP950215494 02.08.95
Applicant: HONDA MOTOR CO LTD
Inventor: HARA FUMIO; KUBO HIROSHI; SENURA ATSUSHI
Title: DETERIORATION DETECTOR FOR CATALYST OF INTERNAL COMBUSTION
Family: JP9041952 A 10.02.97

JP9041953 A 10.02.97 **141**
Priority: JP950215495 02.08.95
Applicant: HONDA MOTOR CO LTD
Inventor: HARA FUMIO; KUBO HIROSHI; SENURA ATSUSHI
Title: DETERIORATION DETECTOR FOR CATALYST OF INTERNAL COMBUSTION
Family: JP9041953 A 10.02.97

JP9041954 A 10.02.97 **141**
Priority: JP950215496 02.08.95
Applicant: HONDA MOTOR CO LTD
Inventor: HARA FUMIO; KUBO HIROSHI; SENURA ATSUSHI
Title: DETERIORATION DETECTOR FOR CATALYST OF INTERNAL COMBUSTION
Family: JP9041954 A 10.02.97

JP9088560 A 31.03.97 **339**
Priority: JP950249179 27.09.95
Applicant: NISSAN MOTOR
Inventor: MITSUMOTO HISASHI
Title: DIAGNOSTIC DEVICE FOR ENGINE
Family: JP9088560 A 31.03.97

JP9096237 A 08.04.97 **186**
Priority: JP950277228 30.09.95
Applicant: SUZUKI MOTOR CO
Inventor: TOYODA KATSUHIKO
Title: CATALYTIC DETERIORATION DIAGNOSTIC DEVICE FOR INTERNAL
Family: JP9096237 A 08.04.97

RU2059080 C 27.04.96 **230**
Priority: RU940040644 03.11.94
Applicant: AKTSIONERNOE OBSHCHESTVO ELKAR (RU)
Inventor: GIRYAVETS ALEKSANDR K (RU); NADZHAROV SAMSON G (RU); MURAVLEV VIKTOR (RU)
Title: METHOD OF ON-BOARD DIAGNOSING OF CATALYTIC CONVERTER OF EXHAUST GASES OF VEHICLE INTERNAL COMBUSTION ENGINE
Family: RU2059080 C 27.04.96

SU1741880 A 23.06.92 **349**
Priority: SU894788203 26.12.89
Applicant: OD POLT INSTITUT (SU)
Inventor: VAGANOV ALEKSANDR I (SU); DOROKHOV IGOR N (SU); TODORTSEV YURIJ K (SU); GOLUBOV SERGEJ P (SU); BALASANYAN GENNADIJ A (SU)
Title: METHOD OF CHECKING CONDITIONS OF REACTOR WITH FIXED CATALYST BED
Family: SU1741880 A 23.06.92

US3667914 A 06.06.72 **335**
Priority: US700086549 03.11.70
Applicant: MONSANTO CO
Inventor: PENQUITE CHARLES R; BARKER GEORGE E

Title: System for detecting deterioration of catalyst in catalytic converter
Family: US5060473 A 29.10.91
JP2027109 A 29.01.90

US5060474 A 29.10.91 **256**
Priority: JP890191523 26.07.89
Applicant: NISSAN MOTOR (JP)
Inventor: ARAMAKI TAKASHI (JP)
Title: Exhaust emission control failure detection system for internal combustion engine
Family: US5060474 A 29.10.91

US5088281 A 18.02.92 **86; 87**
Priority: JP890023962 03.02.89; JP880179155 20.07.88; JP880180336 21.07.88
Applicant: TOYOTA MOTOR CO LTD
Inventor: IZUTANI TAKAHIDE (JP); KAYANUMA NOBUAKI (JP); FURUHASHI MICHIO (JP); SONODA YUKIHIRO (JP); SAWAMOTO HIROYUKI (JP); HOSHI KOUICHI (JP); OSAWA KOUICHI (JP); BESSHO HIRONORI (JP)
Title: Method and apparatus for determining deterioration of three-way catalysts in double air-fuel ratio sensor system
Family: US5088281 A 18.02.92
JP2030915 A 01.02.90
JP2033408 A 02.02.90
JP2207159 A 16.08.90

US5089236 A 18.02.92 **21**
Priority: US900467165 19.01.90
Applicant: CUMMMINS ENGINE COMPANY INC (US)
Inventor: CLERC JAMES C (US)
Title: Variable geometry catalytic converter
Family: US5089236 A 18.02.92

US5097700 A 24.03.92 **122**
Priority: JP900046579 27.02.90
Applicant: NIPPON DENSO CO (JP)
Inventor: NAKANE HIROAKI (JP)
Title: Apparatus for judging catalyst of catalytic converter in internal combustion engine
Family: US5097700 A 24.03.92
JP3249357 A 07.11.91

US5099647 A 31.03.92 **67**
Priority: US910722797 28.06.91
Applicant: FORD MOTOR CO (US)
Inventor: HAMBURG DOUGLAS R (US)
Title: Combined engine air/fuel control and catalyst monitoring
Family: US5099647 A 31.03.92
GB2257546 A 13.01.93
DE4219898 A 14.01.93
DE4219898 C 11.08.94
GB2257546 B 08.02.95

US5119628 A 09.06.92 **199; 200; 201**
Priority: JP900181074 09.07.90
Applicant: NISSAN MOTOR (JP)
Inventor: UEMA HIDEKI (JP); MITSUHASHI KOHEI (JP); UCHIDA MASAAKI (JP); NAKAJIMA YUKI (JP)
Title: CATALYST DETERIORATION DIAGNOSING APPARATUS FOR AIR/FUEL RATIO CONTROL SYSTEM
Family: DE4122702 A 23.01.92
US5119628 A 09.06.92
DE4122702 C 18.11.93

US5134847 A 04.08.92 **88**
Priority: JP900087726 02.04.90
Applicant: TOYOTA MOTOR CO LTD
Inventor: OGAWA TAKASHI (JP); FUNATO KAZUHIKO (JP)
Title: Double air-fuel ratio sensor system in internal combustion engine
Family: US5134847 A 04.08.92

US5154055 A 13.10.92 **117**
Priority: JP900013219 22.01.90; JP900281290 18.10.90
Applicant: NIPPON DENSO CO (JP)
Inventor: NAKANE HIROAKI (JP); NAKABAYASHI KATSUHIKO (JP); KURITA NORIAKI (JP)
Title: Apparatus for detecting purification factor of catalyst
Family: DE4101616 A 14.08.91
US5154055 A 13.10.92

US5157919 A 27.10.92 **67**
Priority: US910733932 22.07.91

US5207057 A 04.05.93 **114**
Priority: JP910111852 16.05.91
Applicant: TOYOTA MOTOR CO LTD
Inventor: KAYANUMA NOBUAKI (JP)
Title: Air-fuel ratio control device for an engine
Family: US5207057 A 04.05.93

US5220788 A 22.06.93 **120**
Priority: JP910215935 31.07.91; JP900223465 24.08.90
Applicant: NIPPON DENSO CO (JP)
Inventor: KURITA NORIAKI (JP); NAKABAYASHI KATSUHIKO
Title: Apparatus for detecting purification factor of catalyst in catalytic converter of internal combustion engine
Family: EP0475177 A 18.03.92
US5220788 A 22.06.93
EP0475177 A 21.04.93
EP0475177 B 23.10.96
DE69122822E E 28.11.96

US5228287 A 20.07.93 **165**
Priority: JP910158354 28.06.91
Applicant: MAZDA MOTOR (JP)
Inventor: KURONISHI KIYOSHI (JP); KOMATSU KAZUNARI (JP); NOGUCHI NAOYUKI (JP); NISHIMURA HIROFUMI (JP)
Title: Exhaust system for internal combustion engine
Family: US5228287 A 20.07.93

US5228335 A 20.07.93 **39; 218; 219**
Priority: US910660654 25.02.91
Applicant: US ENVIRONMENT (US)
Inventor: CLEMMENS WILLIAM B (US); KOUPAL JOHN W (US); SABOURIN MICHAEL A (US)
Title: Method and apparatus for detection of catalyst failure on-board a motor vehicle using a dual oxygen sensor and an algorithm
Family: US5228335 A 20.07.93

US5233829 A 10.08.93 **165; 167; 168**
Priority: JP910207473 23.07.91
Applicant: MAZDA MOTOR (JP)
Inventor: KOMATSU KAZUNARI (JP)
Title: Exhaust system for internal combustion engine
Family: US5233829 A 10.08.93

US5237818 A 24.08.93 **147; 148; 150**
Priority: JP910057106 20.03.91
Applicant: HITACHI LTD (JP)
Inventor: ISHII TOSHIO (JP); KANEYASU MASAYOSHI (US); ASANO SEIJI (JP)
Title: Conversion efficiency measuring apparatus of catalyst used for exhaust gas purification of internal combustion engine and the method of the same
Family: DE4209136 A 01.10.92
US5237818 A 24.08.93

US5265416 A 30.11.93 **71; 72**
Priority: US920935808 27.08.92
Applicant: FORD MOTOR CO (US)
Inventor: HAMBURG DOUGLAS R (US); DOBBINS KELVIN L (US)
Title: On-board catalytic converter efficiency monitoring
Family: US5265416 A 30.11.93
CA2104573 A 28.02.94
CA2104573 C 03.10.95

US5265417 A 30.11.93 **314; 315; 323**
Priority: US930001599 07.01.93
Applicant: FORD MOTOR CO (US)
Inventor: VISSER JACOBUS H (US); SOLTIS RICHARD E (US); LOGOTHETIS ELEFTHERIOS M (US); HAMBURG DOUGLAS R (US); COOK JEFFREY A (US); ZANINI-FISHER MARGHERITA (US)
Title: Method and apparatus for determining the hydrocarbon conversion efficiency of a catalytic converter
Family: US5265417 A 30.11.93
GB2274169 A 13.07.94
DE4342035 A 14.07.94

US5272872 A 28.12.93 **72**
Priority: US920981736 25.11.92
Applicant: FORD MOTOR CO (US)
Inventor: GRUTTER PETER J (US); STOCK GERALD G (US)

MATSUNAGA TAKAO (JP); SHINMOTO KAZUHIRO (JP); TERADA KOICHI (JP); YAMAMOTO YOSHIMI (JP)
Title: Failure detection system for air-fuel ratio control system
Family: US5337555 A 16.08.94

US5337556 A 16.08.94 **213; 214**
Priority: JP920074214 30.03.92
Applicant: FUJI HEAVY IND LTD (JP)
Inventor: AIHARA MASAAKI (JP)
Title: Detecting device and method for engine catalyst deterioration
Family: US5337556 A 16.08.94

US5337558 A 16.08.94 **163**
Priority: JP920058251 16.03.92
Applicant: MAZDA MOTOR (JP)
Inventor: KOMATSU KAZUNARI (JP)
Title: Engine exhaust purification system
Family: US5337558 A 16.08.94

US5339628 A 23.08.94 **242**
Priority: DE904027207 28.08.90
Applicant: EMITEC EMISSIONSTECHNIK
Inventor: MAUS W. (DE); SWARS H. (DE); BRÜCK ROLF (DE)
Title: Method for monitoring the catalytic activity of a catalytic converter in the exhaust gas system of an internal combustion engine
Family: DE4027207 A 05.03.92
WO9203642 A 05.03.92
EP0545974 A 16.06.93
BR9106797 A 06.07.93
BR9106810 A 06.07.93
CZ9300220 A 11.08.93
CZ9300221 A 11.08.93
JP5508900T T 09.12.93
EP0545974 B 26.01.94
EP0545976 B 26.01.94
DE59100960G G 10.03.94
DE59100961G G 10.03.94
JP6501532T T 17.02.94
ES2048017T T 01.03.94
ES2048597T T 16.03.94
US5339628 A 23.08.94
US5428956 A 04.07.95
RU2076930 C 10.04.97

US5341642 A 30.08.94 **146; 150; 151**
Priority: JP910338220 20.12.91
Applicant: HITACHI LTD (JP)
Inventor: KURIHARA NOBUO (JP); ISHII TOSHIO (JP); MUKAIHIRA TAKASHI (JP); KAWANO KAZUYA (JP); TAKAKU YUTAKA (JP)
Title: System for diagnosing engine exhaust gas purifying device and system for diagnosing sensor
Family: DE4243339 A 24.06.93
US5341642 A 30.08.94

US5351484 A 04.10.94 **73**
Priority: US930167301 16.12.93
Applicant: FORD MOTOR CO (US)
Inventor: WADE WALLACE R (US)
Title: Light-off catalyst monitor
Family: US5351484 A 04.10.94
EP0659988 A 28.06.95

US5353592 A 11.10.94 **73**
Priority: US930157548 26.11.93
Applicant: FORD MOTOR CO (US)
Inventor: ZIMLICH GLENN A (US); ORZEL DANIEL V (US); TRUONG TRI T (US)
Title: Engine air/fuel control with monitoring
Family: US5353592 A 11.10.94

US5357750 A 25.10.94 **177**
Priority: US930001225 06.01.93; JP900096935 12.04.90; US910684077 12.04.91
Applicant: NGK SPARK PLUG CO (JP)
Inventor: ITO YASUO (JP); HAYAKAWA NOBUHIRO (JP); YAMADA TESSHO (JP)
Title: Method for detecting deterioration of catalyst and measuring conversion efficiency thereof with an air/fuel ratio sensor
Family: US5357750 A 25.10.94

US5357753 A 25.10.94 **80; 81; 165**
Priority: US930167303 16.12.93
Applicant: FORD MOTOR CO (US)
Inventor: WADE WALLACE R (US)
Title: Catalyst monitor for a Y pipe

TSUYOSHI (JP); NAKAYAMA TAKAYOSHI (JP)
Title: Air-fuel ratio control system for internal combustion engines, having catalytic converter deterioration-detecting function
Family: US5386695 A 07.02.95

US5388403 A 14.02.95 **15**
Priority: JP930052426 12.03.93
Applicant: TOYOTA MOTOR CO LTD
Inventor: NAGAMI TETSUO (JP); HIRAYAMA HIROSHI (JP)
Title: Exhaust gas purification device for an engine
Family: US5388403 A 14.02.95

US5390490 A 21.02.95 77
Priority: US930145549 04.11.93
Applicant: FORD MOTOR CO (US)
Inventor: BROOKS TIMOTHY J (US)
Title: Method and apparatus for measuring the efficacy of a catalytic converter
Family: US5390490 A 21.02.95
EP0652357 A 10.05.95
JP7180538 A 18.07.95
EP0652357 B 17.09.97

US5394691 A 07.03.95 **143**
Priority: JP930063103 26.02.93
Applicant: HONDA MOTOR CO LTD (JP)
Inventor: SEKI YASUNARI (JP)
Title: Air-fuel ratio control system for internal combustion engines having a plurality of cylinder groups
Family: EP0614004 A 07.09.94
US5394691 A 07.03.95

US5396766 A 14.03.95 **139; 140**
Priority: JP920225285 31.07.92
Applicant: HONDA MOTOR CO LTD (JP)
Inventor: SATO TOSHIHIKO (JP); IWATA YOICHI (JP); ITO HIROSHI (JP); TAKIZAWA TSUYOSHI (JP); NAKAYAMA TAKAYOSHI (JP)
Title: Abnormality-detecting device for internal combustion engines
Family: US5396766 A 14.03.95

US5400592 A 28.03.95 **151; 154**
Priority: JP930024163 12.02.93
Applicant: HITACHI LTD (JP)
Inventor: MUKAIHIRA TAKASHI (JP); ISHII TOSHIO (JP); TAKAKU YUTAKA (JP); NUMATA AKIHITO (JP)
Title: Diagnostic apparatus for catalytic converter of an internal combustion engine
Family: DE4404449 A 15.09.94
US5400592 A 28.03.95

US5404718 A 11.04.95 77
Priority: US930127152 27.09.93
Applicant: FORD MOTOR CO (US)
Inventor: ORZEL DANIEL V (US); TRUONG TRI T (US); FARMER DAVID G (US)
Title: Engine control system
Family: US5404718 A 11.04.95

US5412941 A 09.05.95 **100**
Priority: JP920064883 23.03.92
Applicant: TOYOTA MOTOR CO LTD
Inventor: SUZUKI KATSUHIRO (JP); HAYASHI KATSUHIKO (JP); ITOH AKIRA (JP)
Title: Device for determining deterioration of a catalytic converter for an engine
Family: US5412941 A 09.05.95

US5412942 A 09.05.95 **123; 124**
Priority: JP920228564 27.08.92; JP930046777 08.03.93; JP930088547 15.04.93
Applicant: NIPPON DENSO CO (JP)
Inventor: MUKAI YASUO (JP); TAKASU YASUHITO (JP); NAKAYAMA MASAAKI (JP)
Title: Catalytic converter deterioration detecting system for engine
Family: US5412942 A 09.05.95

US5414995 A 16.05.95 **162; 163**
Priority: US940195671 16.02.94; JP910330421 13.12.91; JP910330429 13.12.91; US920988274 14.12.92
Applicant: MAZDA MOTOR (JP)
Inventor: TOKUDA SHOJI (JP); MATSUNAGA TAKAO (JP); SHINMOTO KAZUHIRO (JP); TERADA KOICHI (JP); YAMAMOTO YOSHIMI (JP)

performance of automotive catalysts
Family: US5431012 A 11.07.95
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EP0769096 A 23.04.97

US5431043 A 11.07.95 **326**
Priority: US940236837 02.05.94
Applicant: GENERAL MOTORS CORP
Inventor: GUGEL JONATHAN K (US); VANDENBUSH ROBERT W (US); GHANAM PAUL F (US)
Title: Catalyst activity test
Family: US5431043 A 11.07.95

US5437154 A 01.08.95 **140**
Priority: JP930085324 19.03.93
Applicant: HONDA MOTOR CO LTD (JP)
Inventor: SATO TOSHIHIKO (JP); TAKIZAWA TSUYOSHI (JP); IWATA YOICHI (JP); ITO HIROSHI (JP); NAKAYAMA TAKAYOSHI (JP)
Title: Misfire-detecting system for internal combustion engines
Family: US5437154 A 01.08.95

US5444974 A 29.08.95 **301**
Priority: US930088029 09.07.93
Applicant: GENERAL MOTORS CORP
Inventor: BECK DONALD D (US); DORASWAMY JAYANTHI (US); LECEA OSCAR A (US)
Title: On-board automotive exhaust catalyst monitoring with a calorimetric sensor
Family: US5444974 A 29.08.95

US5447696 A 05.09.95 **286; 287; 289**
Priority: JP930159081 29.06.93; JP930178088 19.07.93; JP930207417 23.08.93
Applicant: TOYOTA MOTOR CO LTD
Inventor: HARADA KENICHI (JP)
Title: Electrically heated catalytic converter system for an engine
Family: US5447696 A 05.09.95

US5448886 A 12.09.95 **183; 184**
Priority: JP920319379 04.11.92
Applicant: SUZUKI MOTOR CO (JP)
Inventor: TOYODA KATSUHIKO (JP)
Title: Catalyst deterioration-determining device for an internal combustion engine
Family: US5448886 A 12.09.95

US5472580 A 05.12.95 **315; 316; 327**
Priority: US940257777 09.06.94
Applicant: GENERAL MOTORS CORP
Inventor: KENNARD III FREDERICK L (US); VALDES CARLOS A (US); LANKHEET EARL W
Title: Catalytic converter diagnostic sensor
Family: US5472580 A 05.12.95

US5487269 A 30.01.96 **169**
Priority: WO92EP02303 06.10.92; FR910013237 28.10.91
Applicant: SIEMENS AUTOMOTIVE SA
Inventor: ATANASYAN ALAIN A (FR); TARROUX FRANCIS (FR)
Title: Method for monitoring the efficiency of a catalytic converter for treating exhaust gases from an internal combustion engine
Family: WO9309335 A 13.05.93
FR2682993 A 30.04.93
EP0611415 A 24.08.94
JP7500398T T 12.01.95
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DE69204298E E 28.09.95
ES2076038T T 16.10.95
US5487269 A 30.01.96

US5499500 A 19.03.96 **78**
Priority: US940358509 19.12.94
Applicant: FORD MOTOR CO (US)
Inventor: HAMBURG DOUGLAS R (US); LOGOTHETIS EL. (US)
Title: Engine air/fuel control system with catalytic converter and exhaust gas oxygen sensor monitoring
Family: US5499500 A 19.03.96

US5509267 A 23.04.96 **209; 212**
Priority: US940337703 14.11.94
Applicant: GENERAL MOTORS CORP
Inventor: THEIS JOSEPH R (US)
Title: Automotive vehicle catalyst diagnostic
Family: US5509267 A 23.04.96

US5522219 A 04.06.96 **78; 79**

Family: JP7225203 A 22.08.95
US5591905 A 07.01.97

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Priority: US940318599 05.10.94; JP920177229 03.07.92; JP930253890 12.10.93; US930084730 01.07.93
Applicant: NIPPON DENSO CO (JP)
Inventor: YAMASHITA YUKIHIRO (JP); IKUTA KENJI (US); ISOMURA SHIGENORI (JP)
Title: Method and apparatus for detecting saturation gas amount absorbed by catalytic converter
Family: DE4322341 A 05.01.94

US5626014 A 06.05.97 273; 275
Priority: US950497562 30.06.95
Applicant: FORD MOTOR CO (US)
Inventor: HEPBURN JEFFREY S (US); MEITZLER ALLEN H (US)
Title: Catalyst monitor based on a thermal power model
Family: US5626014 A 06.05.97

US5627757 A 06.05.97 220
Priority: US950520038 28.08.95; IT92TO00760 14.09.92; US930119503 10.09.93
Applicant: FIAT AUTO SPA (IT)
Inventor: COMIGNAGHI EMILIO (IT); PEROTTO ALDO (IT)
Title: System for monitoring the efficiency of a catalyst, in particular for motor vehicles
Family: EP0588123 A 23.03.94
EP0588123 B 28.02.96
DE69301648E E 04.04.96
IT1257100 B 05.01.96
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US5630315 A 20.05.97 301; 302; 303
Priority: US950556292 06.10.95
Applicant: GENERAL MOTORS CORP
Inventor: THEIS JOSEPH R (US)
Title: Catalyst diagnostic system and method
Family: US5630315 A 20.05.97

US5636514 A 10.06.97 141
Priority: JP940308229 17.11.94; JP940309860 18.11.94
Applicant: HONDA MOTOR CO LTD (JP)
Inventor: SEKI YASUNARI (JP)
Title: Catalyst deterioration-determining system for internal combustion engines
Family: JP8144744 A 04.06.96
US5636514 A 10.06.97

US5640846 A 24.06.97 196
Priority: US950420736 11.04.95; JP920274337 13.10.92; JP920277444 15.10.92; JP920283182 21.10.92; US940308510 21.09.94; US930133983 08.10.93
Applicant: MITSUBISHI ELECTRIC CORP
Inventor: OHUCHI HIROFUMI (JP); FUJIMOTO SHINYA (JP)
Title: Dual-sensor type air-fuel ratio control system for internal combustion engine and catalytic converter diagnosis apparatus for the same
Family: US5363647 A 15.11.94

US5644912 A 08.07.97 198; 205
Priority: US950503256 17.07.95; JP920228107 27.08.92; US930104569 11.08.93
Applicant: NISSAN MOTOR (JP)
Inventor: KAWAMURA KATSUHIKO
Title: System for diagnosing deterioration of catalyst in exhaust system of internal combustion engine
Family: US5644912 A 08.07.97

US5649420 A 22.07.97 153; 356
Priority: US960663942 14.06.96; JP930099765 26.04.93; US940233398 26.04.94
Applicant: HITACHI LTD (JP)
Inventor: MUKAIHIRA TAKASHI (JP); ISHII TOSHIO (JP); MIURA KIYOSHI (JP); KAWANO KAZUYA (JP)
Title: System for diagnosing deterioration of catalyst
Family: EP0626507 A 30.11.94
US5526643 A 18.06.96
US5649420 A 22.07.97

US5678402 A 21.10.97 142
Priority: JP940076649 23.03.94;

DE59100961G G 10.03.94
JP6501532T T 17.02.94
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US5339628 A 23.08.94
US5428956 A 04.07.95
RU2076930 C 10.04.97

WO9303357 A 18.02.93 **70**
Priority: US910741378 07.08.91
Applicant: FORD MOTOR CANADA (CA); FORD WERKE AG (DE); FORD FRANCE (FR); FORD MOTOR CO (GB); FORD MOTOR CO (US)
Inventor: HAMBURG DOUGLAS RAY (US); LOGOTHETIS EL. (US); VISSER JACOBUS HENDRIK (US); SOLTIS RICHARD EDWARD (US)
Title: AN EXHAUST GAS OXYGEN SENSOR.
Family: WO9303357 A 18.02.93
US5268086 A 07.12.93
EP0599875 A 08.06.94

WO9303358 A 18.02.93 **69; 70**
Priority: US910741881 07.08.91
Applicant: FORD MOTOR CO (US); FORD MOTOR CANADA (CA); FORD WERKE AG (DE); FORD FRANCE (FR); FORD MOTOR CO (GB)
Inventor: KOTWICKI ALLAN J. (US); HAMBURG DOUGLAS RAY
Title: CATALYST MONITORING USING EGO SENSORS.
Family: WO9303358 A 18.02.93
EP0598785 A 01.06.94
US5363091 A 08.11.94
US5365216 A 15.11.94
JP6509644T T 27.10.94

WO9309335 A 13.05.93 **169; 170; 171; 173**
Priority: FR910013237 28.10.91
Applicant: SIEMENS AUTOMOTIVE SA
Inventor: ATANASYAN ALAIN ANTRANIK (FR); TARROUX FRANCIS (FR)
Title: METHOD FOR MONITORING THE EFFICIENCY OF A CATALYTIC CONVERTER FOR TREATING EXHAUST GASES FROM AN INTERNAL COMBUSTION ENGINE.
Family: WO9309335 A 13.05.93
FR2682993 A 30.04.93
EP0611415 A 24.08.94
JP7500398T T 12.01.95
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DE69204298E E 28.09.95
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WO9314305 A 22.07.93 **246; 247**
Priority: DE924201136 17.01.92
Applicant: EMITEC EMISSIONSTECHNIK (DE); PORSCHE AG (DE)
Inventor: MAUS W. (DE); BRÜCK ROLF (DE); SWARS H. (DE); PELTERS STEPHAN (DE)
Title: VERFAHREN ZUR ÜBERWACHUNG EINER KATALYTISCHE ABGASREINIGUNGSANLAGE
Family: DE4201136 A 22.07.93
WO9314305 A 22.07.93

WO9404800 A 03.03.94 **249**
Priority: DE924227207 17.08.92; DE934319924 16.06.93
Applicant: EMITEC EMISSIONSTECHNIK (DE); MAUS W. (DE); SWARS H. (DE); BRÜCK ROLF (DE)
Inventor: MAUS W. (DE); SWARS H. (DE); BRÜCK ROLF (DE)
Title: VERFAHREN ZUR ÜBERWACHUNG DER FUNKTION EINES KATALYTISCHEN KONVERTERS.
Family: DE4227207 A 24.02.94
EP0655104 A 31.05.95
JP7509551T T 19.10.95
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WO9409266 A 28.04.94 **341**
Priority: DE924235225 13.10.92
Applicant: IRIS GMBH INFRARED & INTELLIGE (DE)
Inventor: BITTNER HARALD (DE); SCHUBERT BERND (DE); TRULL THOMAS (DE); BÖNICK RAINER (DE)
Title: SENSORANORDNUNG UND

EP0760055 A 05.03.97
JP9505382T T 27.05.97

WO9636863 A 21.11.96 289
Priority: JP950119877 18.05.95
Applicant: TOYOTA MOTOR CO LTD; TOYODA CHUO KENKYUSHO
Inventor: TANAHASHI TOSHIO (JP); SANADA MASAKATSU (JP); DOMYO HIROYUKI (JP); HIRAYAMA HIROSHI (JP); SOBUE KAZUAKI (JP); HIGASHI TSUNEO (JP); YOKOTA KOJI (JP); SOBUKAWA HIDEO (JP); SUZUKI TADASHI (JP); MATSUNAGA SHINICHI
Title: DURABILITY TEST METHOD FOR EXHAUST GAS PURIFICATION DEVICE
Family: WO9636863 A 21.11.96
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WO9641071 A 19.12.96 226
Priority: SE950002066 07.06.95
Applicant: VOLVO AB (SE
Inventor: ERIKSSON SOEREN (SE); HEDSTRÖM RONALD (SE); HJORTSBERG OVE (SE); LAURELL MATS (SE)
Title: ARRANGEMENT AND METHOD FOR DETERMINING THE OXYGEN BUFFER CAPACITY IN A CATALYTIC CONVERTER
Family: WO9641071 A 19.12.96
SE9502066 A 08.12.96
SE505235 C 21.07.97

WO9713058 A 10.04.97 345
Priority: JP950278350 02.10.95
Applicant: KOMATSU MFG CO LTD (JP); WAKAMOTO KOUTAROU
Inventor: WAKAMOTO KOUTAROU
Title: APPARATUS AND METHOD FOR DETECTING DETERIORATION OF NO_x CATALYST IN DIESEL ENGINE
Family: WO9713058 A 10.04.97
JP9096215 A 08.04.97
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Priority: DE951038787 18.10.95
Applicant: BOSCH GMBH ROBERT (DE)
Inventor: OTT KARL (DE); DENZ H. (DE); WILD ERNST (DE)
Title: VERFAHREN UND VORRICHTUNG ZUM ERFASSEN UND DOKUMENTIEREN VON KATALYSATORSCHÄDEN
Family: WO9715468 A 01.05.97
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Priority: SE950003762 25.10.95
Applicant: FORSKARPATENT I LINKÖPING AB (SE)
Inventor: BARANZAI AMIR (SE); LUNDSTRÖM EMAR (SE); LLOYD SPETZ ANITA (SE)
Title: TESTING OF CATALYST IN THE EXHAUST SYSTEM OF AN INTERNAL COMBUSTION ENGINE
Family: WO9715751 A 01.05.97
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