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Gas analysis in internal combustion engines

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INTRODUCTION

The creation of internal combustion engines and the development of automotive vehicles constitutes a fundamental pillar for the transport of people and goods as we know it today.

Among the variety of engines developed and fuels available, petrol-fuelled 4-stroke combustion engines became dominant historically due to their operating flexibility and ease of control, and are now the most widely used engines in the field of mobility.

A large part of this success is due to the characteristics of the fuel used, which provides a good number of advantageous qualities with just one condition, its proportional mixing with air. As the intake air is a moving gaseous fluid, and the petrol is a liquid that must change state to initiate combustion, the direct measurement of the masses and the calculation of the proportion of the participating substances in each working cycle is, for practical purposes, impossible.

The exact dosing of the fuel mass at the stoichiometric ratio with the air drawn in by the cylinders ensures maximum performance of the engines with the minimum production of polluting substances, and this can be checked from the gases resulting from combustion.

The analysis of the exhaust gases allows the initial mixture ratio and the development of the combustion to be known. This is a powerful diagnostic tool for the resolution of faults and an essential checking process for the control of polluting emissions. The proportion and ratio of the exhaust gases under different operating conditions allow the malfunctioning of the fuel supply system, ignition, timing and other mechanical defects of the engine to be identified.

COMBUSTION ENGINE

The fuel: petrol

Petrol is a liquid made up of more than 100 different hydrocarbons, the majority having 4 to 12 carbon atom chains from the lightest fractions of the oil. Despite being useful as a solvent and thinner for many rubbery substances, its main application is as a fuel for combustion engines, due to the following properties:

- Calorific value: Between 42,900 and 43,280 KJ/Kg
- Latent heat of vaporisation: Between 315 and 376 kJ/kg
- Self-ignition temperature: Between 367 and 456 °C
- Octane rating: 95 - 98 - 100 RON (Research octane number)
- Density: 0.75 kg/l
- Stoichiometric ratio: 14.7/1

The petrol marketed as a fuel specific to combustion engines is modified at the refineries, and even locally depending on the temperature and humidity conditions of the storage and supply location, by means of specific additives added in small proportions. The main ones are antiknock agents, stabilisers and detergents.

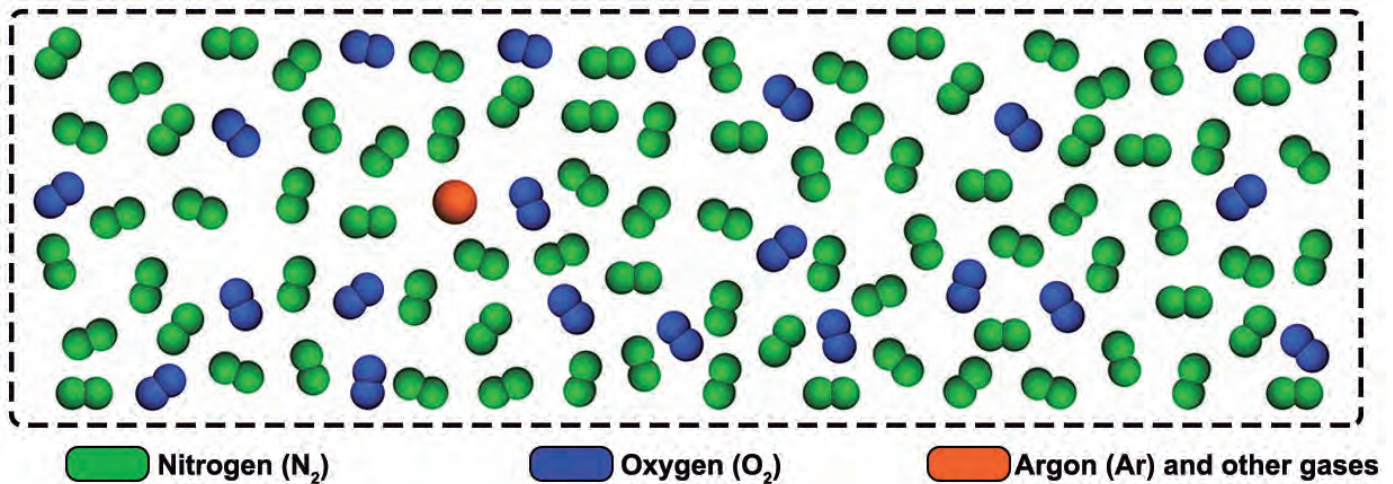
In addition to the additives already mentioned, other compounds are added for other purposes such as improving vaporisation and lubricity of the fuel or to dye the fuel by adopting different colours depending on the octane rating or the use for which it is intended (differential specific tariffs).

The oxidising agent

Oxygen from the atmospheric air is the crucial chemical element for producing the combustion reaction. As an oxidising agent, it makes the decomposition of the hydrocarbons possible, releasing energy in the form of light and heat inside the cylinders.

Only 20.95% in volume of the air that forms the Earth's atmosphere is oxygen, nitrogen accounts for 78% and the remainder is a mixture of various gases, mostly argon.

The final oxygen concentration in the aspirated air mass that enters the engine cylinders during each working cycle theoretically determines the maximum amount of fuel that can be oxidised.



Activation energy

Considering the large quantity of nitrogen present in the combustion chamber which does not take part in the oxidation reaction, and the combustion chamber as the receptacle that establishes its physical limits, the start of combustion only requires a minimal energy input, the activation energy of the reaction.

In four-stroke engines, the combustion activation moment must be synchronised with the power stroke and the piston stroke. For an air/fuel mixture at the correct ratio (14.7/1) under atmospheric pressure conditions and an initial temperature of 15°C, 0.2 mJ (millijoules) is needed to ignite the reactive mixture.

All the fuel will burn provided that a certain continuity and homogeneity is maintained in the distribution of the mixture, and there are no heat losses greater than that released by the combustion itself.

In combustion engines, the system that provides the energy to start combustion is the ignition system, which provides the necessary voltage step-up to allow the spark to jump across the spark plug electrodes in the combustion chamber, and also provides the required mechanical synchronisation.

IMPERFECT COMBUSTION

Combustion stoichiometry

This indicates the theoretical air/petrol ratio that produces complete oxidation of the fuel, thus obtaining maximum calorific output of the chemical reaction. 14.7 kg of air are required for complete oxidation of 1 kg of petrol.

In volume, which is the usual assimilation measure for liquids and gases, it is approximately 10,000 litres of air per 1 litre of petrol at at-

mospheric pressure (1000 mbar). Ignition and combustion is possible, however, in the margin between 8/1 and 18/1. Below this margin, a sufficient ignition temperature is not reached (the heat of vaporisation is greater than that obtained) and above, combustion propagation does not occur due to lack of continuity in the reactive material.

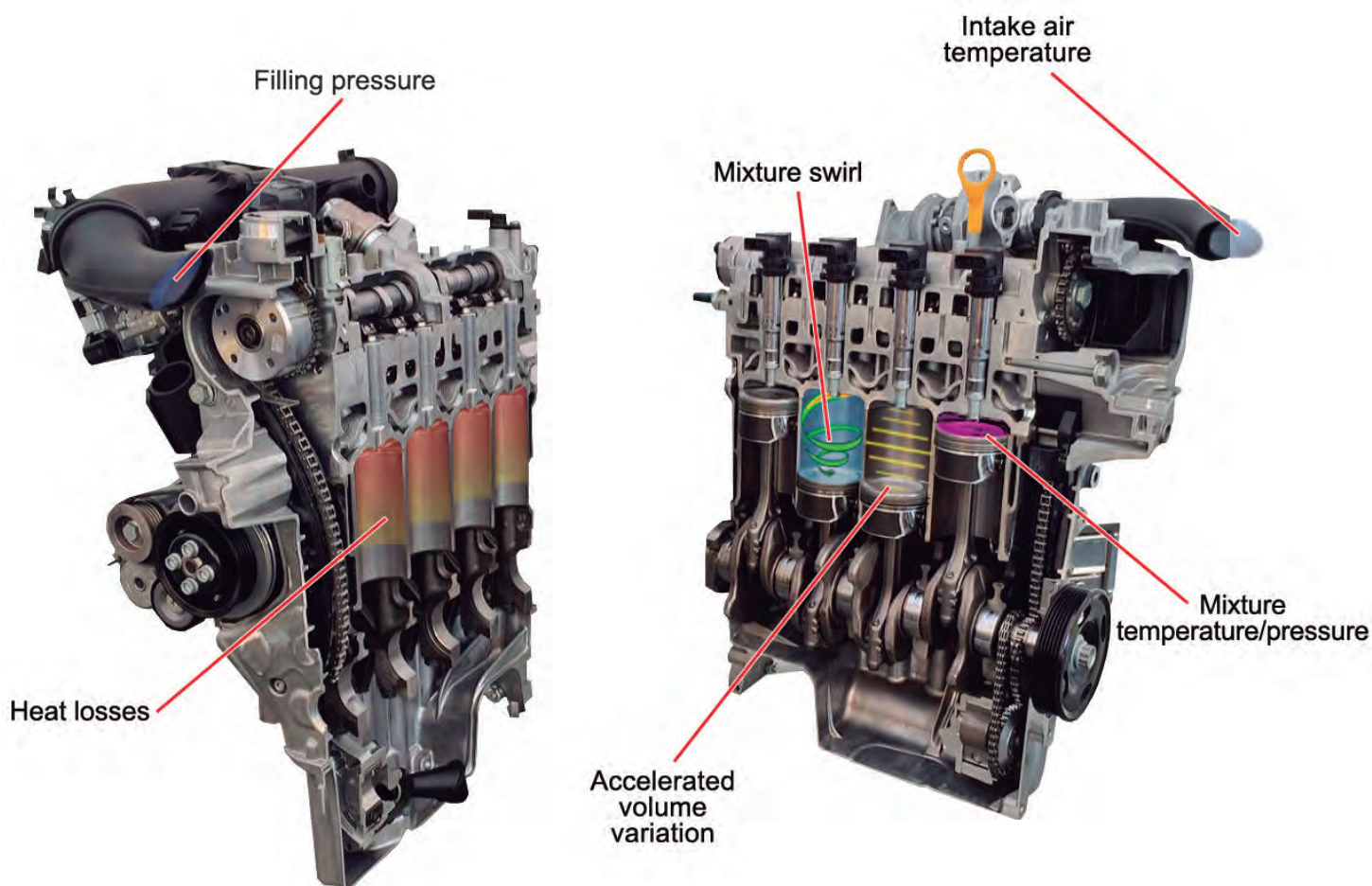
True combustion reaction

The actual development of the four-stroke cycle in combustion engines is very different to the original theoretical concept, particularly as regards the combustion time. In the practical cycle, the effectiveness of the energy conversion and the composition of the exhaust gases differ

substantially from the predicted values. This is due to a combination of deviation factors resulting from the intrinsic behaviour of the substances and the limitations arising from the mechanical construction of engines.

The oxidation reaction occurs under variable conditions, which are potentially not ideal, and with environmental interference, meaning that it is an imperfect reaction. The variable physical factors that have the greatest influence on combustion development are the following:

- Intake air temperature
- Initial pressure/temperature of the reactive mixture
- Swirl before and after combustion
- Heat losses
- Accelerated volume variation



The preparation of the mixture at an exact stoichiometric ratio is, for practical purposes, impossible, due to the numerous physical and dynamic factors the four-stroke cycle involves, the principle of intermittent fuel supply, the electro-hydraulic operation of current fuel injection systems and the use of compound substances.

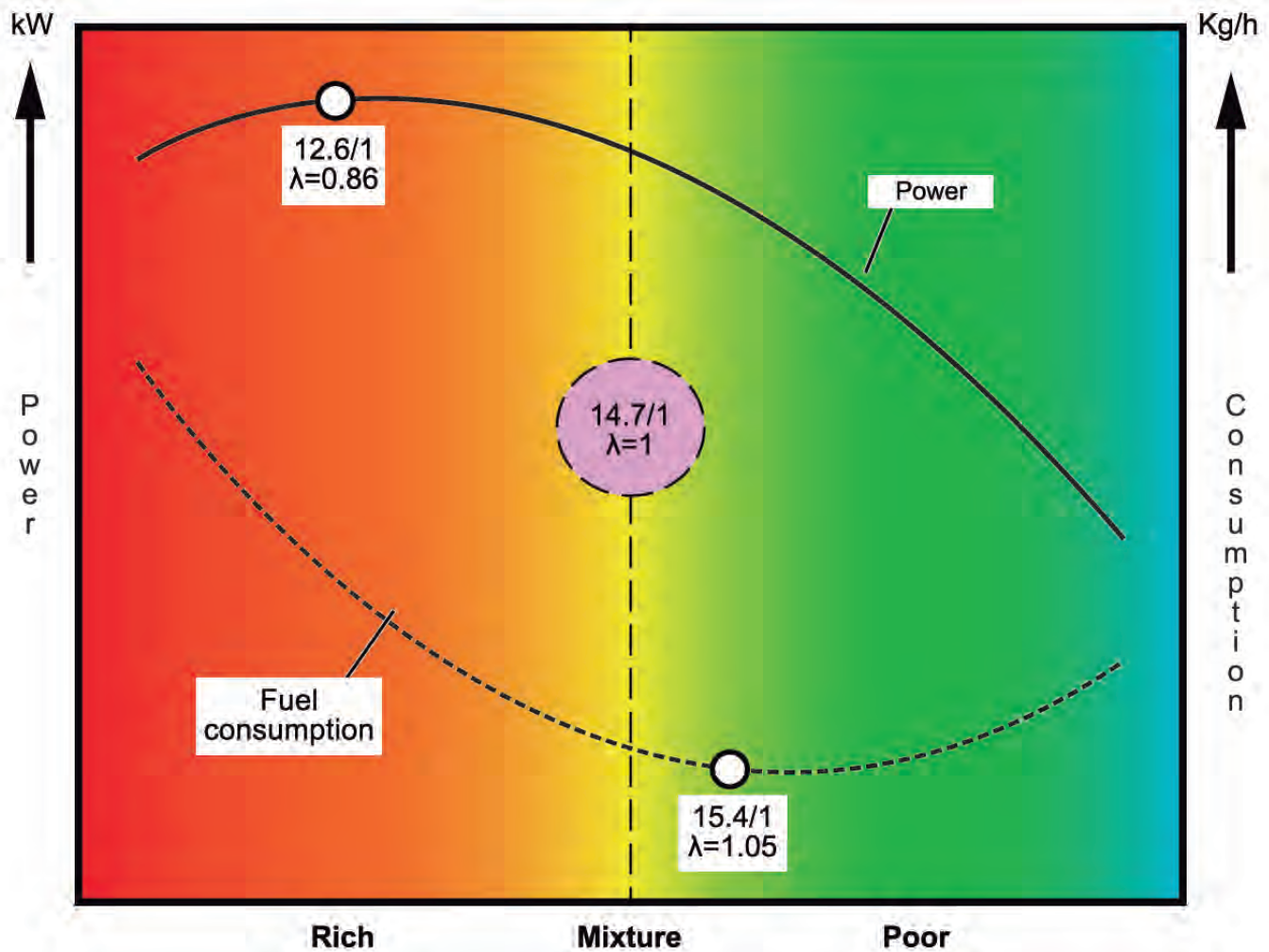
The main causes of this impossibility are the composition of the air (it does not always have the same density, humidity, temperature under different weather conditions), fuel composition (depends on the crude

oil refinement processes used), measurement and dosing of reagents. The real hydrocarbon mass supplied cannot be measured, therefore it is determined according to the theoretical density of the fuel, the flow rate of the injectors and their activation time. The response time of the injector together with the temperature and viscosity of the fuel are variable influencing factors that contribute to the deviation in the mixture ratio.

Non-stoichiometric mixture ratio

For the same engine under acceptable mechanical conditions, the nature and proportion of the substances resulting from the real combustion process mostly depend on the true ratio of the mixture, secondly on the physical conditions in which the reaction takes place and, lastly, on the real composition of the petrol.

To the aforementioned intrinsic variables, we must add the possibility of voluntarily working with a non-stoichiometric mixture. Under real operating conditions, the maximum mechanical performance of combustion engines is not obtained when working with the stoichiometric mixture, in the same way that the maximum fuel economy is not achieved with the provision of the reagents in an exact atomic ratio.



Maximum power is obtained with slightly rich mixtures. The excess fuel cools the mixture when changing from the liquid to gaseous state, reducing the tendency to detonation and slowing down the pressure increase during combustion. The useful working conditions increase and the maximum pressure in the combustion chamber is retarded thus facilitating its conversion into torque.

On the other hand, the best fuel economy is obtained with slightly lean mixtures. The excess oxygen mass guarantees complete oxida-

tion of the hydrocarbons even though the mixture is not 100% homogeneous. The reduction of the liquid mass leads to less heat absorption during compression and higher pressure values at the start of combustion.

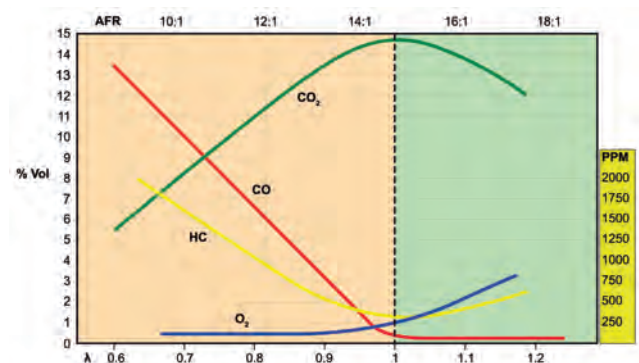
The regulation of the mixture to a rich ratio at specific moments during the car's work improves acceleration when there is maximum demand. On the other hand, supplying the fuel in slightly lean mode when idling or at low load reduces consumption and increases operating autonomy.

Exhaust gases

Due to imperfect combustion, deviation in the supply or voluntary non-stoichiometric control, the composition and ratio of the exhaust emissions in combustion engines differs slightly from the theoretical values under normal operating conditions, with the incorporation of new substances into the equation.

The combustion of slightly lean mixtures leads directly to the presence of O_2 in the exhaust as a non-participating surplus reagent. A very lean mixture prevents oxidation of the fuel near the combustion chamber walls so that the reaction does not start or it breaks down into smaller hydrocarbons.

The work with a rich mixture results in the partial oxidation of some fuel molecules, which produces CO instead of CO_2 and increases the proportion of hydrocarbons in the exhaust gases as a surplus reagent that, after changing state, does not find the necessary oxygen for its conversion.



Incomplete combustion

Particularly at idle (minimum load and filling pressure) or with insufficient effective compression ratios, the combustion of the hydrocarbons in combustion engines can be incomplete as the sufficient intensity is not reached to complete the oxidation reaction.

Starting from the correct reagent proportion and even with a moderate excess of O_2 , a sufficient energy level (temperature) must be reached during the reaction for the complete oxidation of the hydrocarbons. Under real conditions, this is not always achieved or maintained for

sufficient time for interaction with the medium. The heat absorption by the nitrogen mass and the walls of the combustion chamber are the key factors for this imperfection.

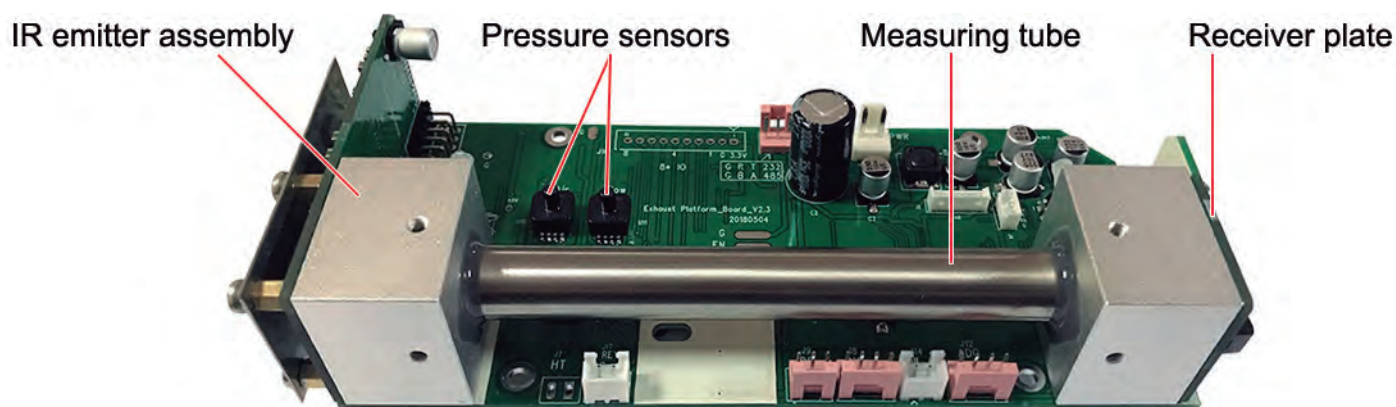
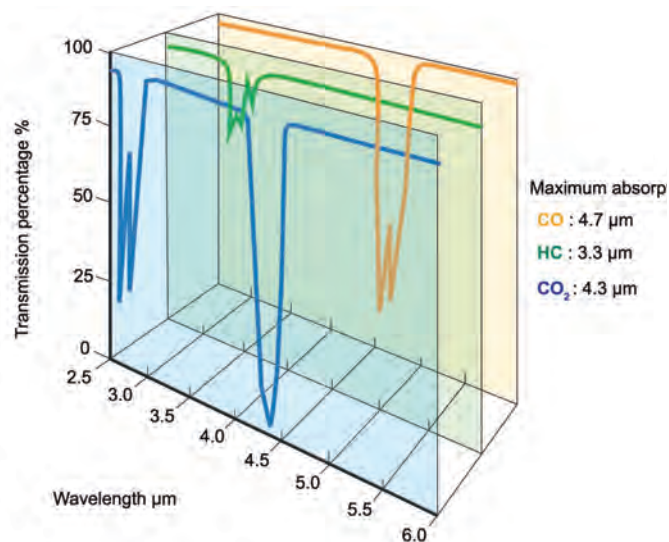
If, during combustion, the heat losses are greater than the energy released by the reaction, the process is interrupted without all the reagents being consumed. The proportion of hydrocarbons and O_2 in the exhaust gases increases for this reason.

4-GAS ANALYZER

The analysis of the CO_2 , CO and HCs is carried out in the workshop analysers by measuring the degree of infrared spectrum absorption. The absorption of light energy of the characteristic wavelength of these three compounds allows their concentration to be determined, in a space of defined and invariable volume that is crossed by a flow of gases stabilised at constant pressure.

For this, the gases from the exhaust pipe are drawn in by means of a pump and forced to cross the inside of a measuring tube in a controlled, continuous way. First, one or more filters are used to eliminate the solid particulates and a separator system to reduce the moisture as much as possible.

An infrared radiation source is placed at one end of the tube, normally a flat heater that is heated to $600^\circ C$. At the other end, specific wavelength filters for each of the gases and their respective radiation sensors are put in position. When the concentration inside the tube of the measured compound increases, it absorbs a greater quantity of radiation at the characteristic wavelength, thus the radiation received by the sensor is proportionally reduced.



In the oldest models, a rotating screen driven by a motor intermittently interrupts the flow of infrared radiation to force the cyclic measurement of the sensors with an approximate frequency of 3 Hz, more modern equipment uses software to carry out the same function.

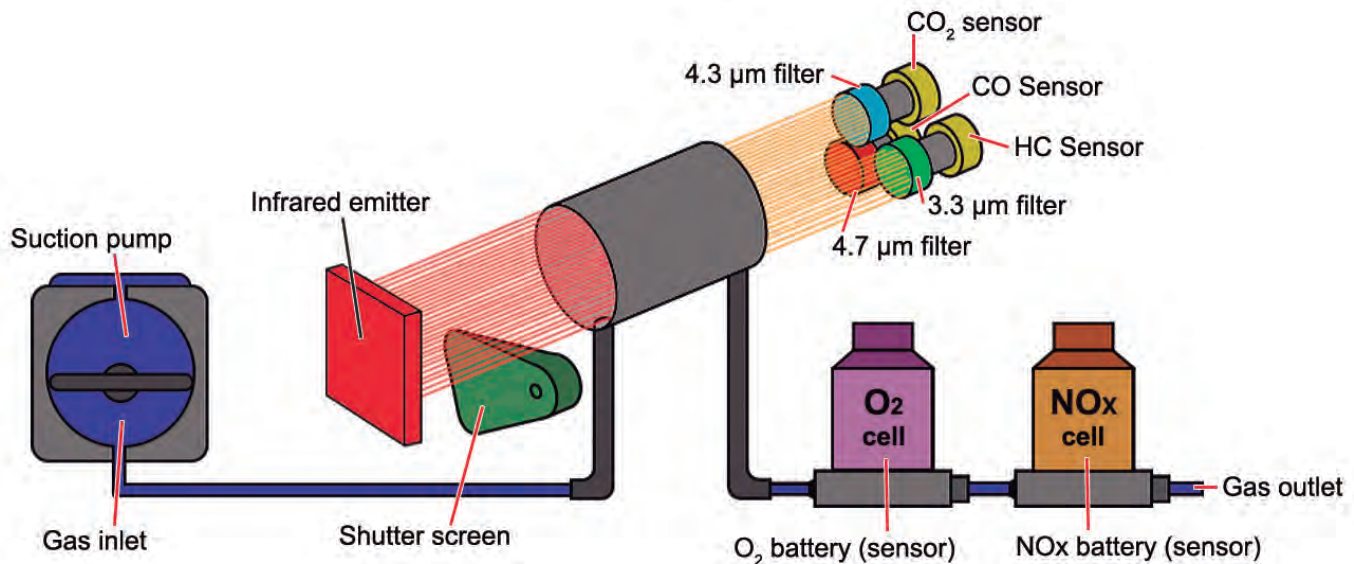
The hydrocarbon measurement results from direct absorption, principally for methane at 3.3 μm . The measured value is multiplied by x

in order to extrapolate it to the other hydrocarbons present in the fuel, depending on its initial composition (6 for petrol normally).

The proportion of O_2 , which does not absorb radiation at a specific wavelength, is determined by means of galvanic batteries. Inside them, the O_2 reacts with the specific base substance, forming an electrolyte which, on chemically reacting with two metal electrodes

of different composition, generates a voltage difference between them. The higher the concentration of the electrolyte, the higher the electrical current between both electrodes, giving rise to a variable electrical signal proportional to the gas concentration measured when the gas flow rate is constant.

The most modern analysers can measure nitrogen oxides in the same way; these are produced under high temperature and pressure conditions by the combination of O_2 and N_2 from the air.



The progressive decomposition of the base substance and the degradation of the electrodes leads to the wearing out of the O_2 and NO_x sensors. Thus they must be periodically replaced to maintain the measurement capacity and accuracy of both elements. Their reactivity in the presence of oxygen and nitrogen from the ambient air is the basis for calibration of both elements, and determines, to a certain extent, the useful life of both once installed in the analyser. For this same reason, they must be hermetically packaged and stored after manufacture and up until the moment they are installed.

The filters and separators must also be replaced or emptied periodically. Generally, their condition is verified by means of a pressure sensor connected to the measurement circuit that detects the obstruction when the internal pressure in the measuring area goes below a certain value. During operation, calibration and internal cleaning processes are carried out cyclically, which consist of the forced ventilation of the pneumatic circuit with purified atmospheric air to remove the hydrocarbons and moisture that has accumulated during the measurement.

The HCs and other substances from the ambient air used for cleaning and calibration are removed from the blast/ventilation air by means of an activated carbon filter that retains and stores them. In this way, the nearly invariable composition of the purified ambient air allows the calibration at zero of the various analyser sensors to be carried out.

In recent times, many manufacturers have developed gas measuring equipment that works in combination with personal computers. This combination allows, in addition to reducing the purchase costs of the measuring equipment, the development of specific tests for checking exhaust gas treatment systems and the execution of the official checking procedures.

In some cases, the graphic representation of the composition of the gases and their evolution facilitates the comprehension of the data and the analysis of the results. The delay in the measurement must be taken into consideration, so the option to store the data is very useful under the changing working conditions of the engine, intermittent faults, etc.

SAMPLE CHECK

Maximum and sufficient oxidation efficiency

The composition of the exhaust gases allows the mixture ratio to be known, which for $\lambda=1$ should allow the highest temperature to be reached inside the combustion chamber.

With a correct mixture, the mathematical proportionality between the exhaust gases will depend on the physical parameters that influence combustion, principally the homogeneity of the mixture together with the swirl, temperature and pressure during the reaction, which determine the oxidation efficiency.

It is deduced from the above that the minimum oxidation efficiency will occur, as a general rule, at idle, and increase with load and rpm up to a certain limit, which usually coincides with the drop of engine torque (cylinder filling defect increasing from a certain rpm).

Individual emission, combined composition and exhaust temperature

When the calculated lambda factor is acceptable (λ 0.98-1.02) and the oxidation efficiency is insufficient, we must determine if the measured substances correspond in equal parts to the different engine cylinders, or analyse the results considering the separate reaction and individual contribution of complete oxidation product (CO_2), partial oxidation product (CO) and non-participating reagents (HCs and O_2) for each engine cylinder.

The maximum production of CO_2 can only be achieved with sufficient oxidation efficiency in all cylinders, so a combustion defect in one or more cylinders is easily recognisable due to the clearly insufficient production of CO_2 in the exhaust gases, together with abnormally high O_2 , HC and CO values.

At first sight, if the proportion of CO_2 in the dry sample does not reach 85% of the maximum CO_2 of the fuel (12.75%) with the correct λ factor,

we must suspect that there is a combustion defect in one of the cylinders. If, on adding half the measured CO to the CO_2 , the final oxidation value still does not reach 90% of the maximum CO_2 of the fuel (13.5%) necessary for considering the oxidation efficiency acceptable in a conventional petrol engine, whatever its fuel supply system, it would indicate that the combustion reaction in one of the cylinders is not occurring or is not correct.

As a general rule, the exhaust pipes from all the engine cylinders, or at least those from the same bank, join together to form a common pipe, creating a perfectly homogeneous mixture of the exhaust gases from the different cylinders. The gas sample for the analysis is taken, except in some cases, from the only accessible opening, which is the end of the exhaust train.

Dilution of the gas sample

Having reached this point, for an effective diagnostic, certain factors relating to the mechanics of combustion engines, the dynamics of the

gaseous fluids and the acoustics of the exhaust train must be taken into consideration.

Dilution of the exhaust gas sample

The overlap in the work of the exhaust - intake valves and the resonant behaviour of the exhaust line can have an influence on the sample composition of the 4 gases, which moves the calculated λ factor towards lean.

The sample of the 4 gases is diluted due to the presence of O_2 which has never been present during the reaction in the combustion chamber. The effect on the calculation of the λ factor is twofold since it increases the proportion of O_2 in the sample at the same time as it reduces the concentration of CO_2 and CO by dilution. It can be principally due to 3 factors:

- Late exhaust valve closing (LEVC) together with early intake valve opening (EIVO) or valve crossing.
- Entry of parasitic air into the exhaust
- Reverse pulse at the measurement point

When the combustion efficiency is insufficient with low hydrocarbons and the measured lambda factor is clearly lean, it is advisable to rule out the possibility of dilution of the sample by partially obstructing the exhaust gas outlet pipe to prevent back flows and generate a slight overpressure in the entire exhaust line, thus preventing the entry of air from the outside.

The composition of a non-contaminated sample is recognised as it maintains its proportionality irrespective of the pressure in the exhaust line.

Accuracy of the data and corrected CO

The presence of parasitic air in the analysed gas composition alters the proportion between the combustion products, thus invalidating the measurement and the calculations derived from it. The inaccuracy of

the measured data rules out any possibility of analysis or diagnostic.

The coherence of the values together must be verified as a step prior to the acceptance of the individual values of each substance.

Corrected CO

In addition to the error in the calculation of the λ factor, the reduction of the measured CO (proportion with respect to the total) is very important at an individual level due to its extreme toxicity and the danger it poses on accumulating in enclosed or poorly ventilated spaces. The corrected

CO gives the equivalent CO concentration for a sample without parasitic air, and its difference from the measured CO is an indication of the reduction of the sampled CO_2 and HC values and of the inaccuracy of the calculated λ factor.

CORRECTION OF THE MIXTURE BASED ON THE EXHAUST GASES

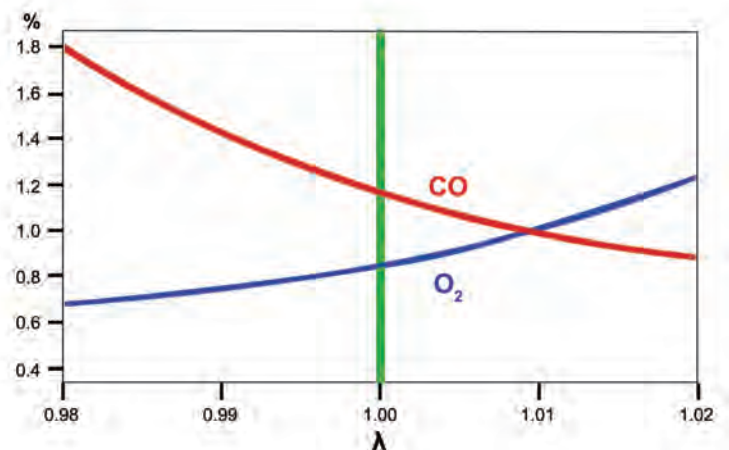
Combustion efficiency and polluting gases

The most efficient combustion is, at the same time, the most environmentally friendly, as obtaining the most energy from the fuel possible reduces consumption. However, it is not the least polluting.

As we have previously seen, the regulation of the air/fuel mixture at the stoichiometric ratio is essential when working with a homogeneous mixture for maximum temperature and oxidation efficiency of the chemical reaction. This provides a combination of maximum mechanical performance with the minimum proportion of incomplete combustion products (CO) and non-participating substances (HCs and O_2).

The oxidation efficiency in petrol engines is variable and practically never absolute, it is a maximum under very specific operating conditions which during the real work of engines is a very small part of their service time.

Depending on the compression ratio, the filling of the cylinders, the working temperature, the fuel supply system and many other variables, the average oxidation efficiency of petrol engines in the modern era varies between 90 and 97%. It is deduced from the remaining 3-10%,

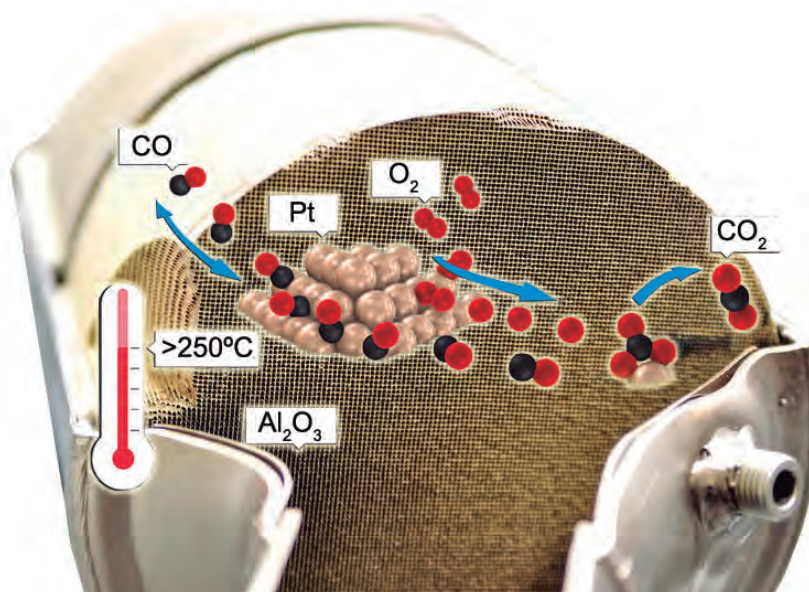


an indicator of the oxidation defect, that the emission of partially oxidised substances and vaporised fuel during the operation of the petrol combustion engine is continuously occurring even at $\lambda=1$.

Exhaust gas catalytic converter

Its operating principle consists of creating the ideal conditions for the complete oxidation of the CO and HCs, which occurs in an accelerated way due to the interaction with a non-reactive element, the catalytic converter. To achieve the oxidation of both substances, the necessary activation energy is required (sufficient temperature), the correct reaction distance (proximity of the reagents) and sufficient oxidising agent (O_2).

The oxidation catalyst is made up of a stainless steel box with a ceramic monolith inside. The ceramic body has a network of cells whose surfaces are coated with a layer of aluminium oxide vaporized with platinum and palladium. When the exhaust gas crosses the cells, they heat up the catalytic converter, starting the conversion of pollutants into inert substances. Noble metals oxidise exhaust gases, lowering the concentration of carbon monoxide and of unburnt hydrocarbons.



Oxygen sensor

This is an electrochemical sensor specifically developed for detecting the deviation of the air/fuel mixture from the ideal or stoichiometric ratio. Its work is based on the electrical potential difference generated by the different oxygen concentrations of the atmospheric air and the exhaust gases when the diatomic oxygen is decomposed into ions. The oxygen sensor is made up of a sheet of zirconium dioxide substrate on which 2 platinum alloy electrodes are placed which function as electrodes, all of which is encapsulated in a metal support screwed to the vehicle's exhaust pipe.

The sensor's external electrode is in contact with the engine's exhaust gases, the oxygen content of which depends on the mixture ratio when the combustion efficiency is sufficient. And the opposing electrode is referenced to the constant oxygen value present in the atmospheric air through a ventilation channel.

On exceeding 300°C, the yttrium-doped zirconium dioxide becomes permeable to the atomic oxygen thus allowing the flow of ions through it. For its part, the platinum of the electrodes becomes very reactive thus boosting its natural capacity to attract certain chemical elements and its catalytic behaviour. To raise and maintain the temperature of the oxygen sensor at optimal working values, an electrically powered heating element is placed inside it.



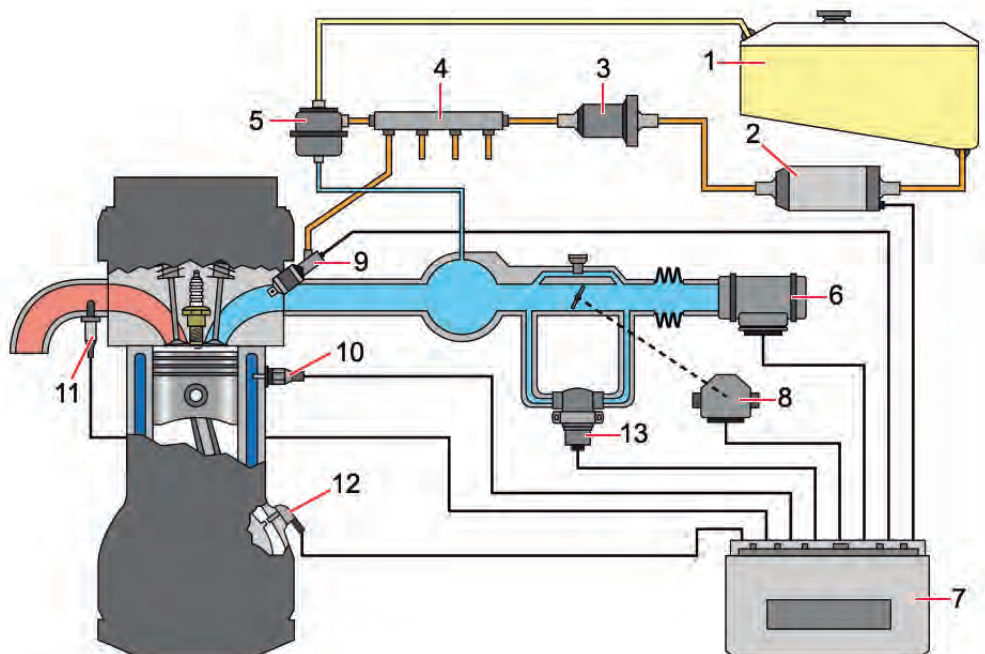
Adaptation of the mixture

The fuel in indirect injection systems is supplied by regulating the opening time of the injectors necessary for supplying the fuel mass at an approximately stoichiometric ratio with the air that fills the cylinders in each working cycle.

The fuel supplied to the injectors is regulated mechanically at a fixed pressure or constant differential from the internal pressure of the intake manifold in some systems. The control unit activates the injectors with an electrical frequency signal proportional to the engine speed and of variable duration, in order to regulate the fuel mass supplied in each cycle.

The engine service conditions and the dynamics related to the vehicle and traffic determine the effective injection time and the possibility of adapting the mixture to achieve the maximum performance of the catalytic converter. The adaptive correction of injection time depending on the composition of the gases captured by the oxygen sensor is only possible in sufficiently regular working conditions that allow a closed continuous control loop to be established in consecutive cycles.

- 1.- Fuel tank
- 2.- Electric fuel pump
- 3.- Fuel filter
- 4.- Injection rail
- 5.- Pressure regulator
- 6.- Air flow meter
- 7.- Control unit
- 8.- Throttle sensor
- 9.- Electromagnetic injector
- 10.- Temperature sensor
- 11.- Oxygen sensor
- 12.- Rpm sensor
- 13.- Additional air valve



PRACTICAL ANALYSIS

Prior requirements

The regulation of the mixture under the real working conditions of the vehicle responds to the power demand from the driver and the dynamic traffic conditions, factors that are difficult to reproduce during the analysis of the gases in the workshop. Enrichment during acceleration/full load or the full cut-off of the fuel supply during the overrun phase are logical functions that are activated under very specific conditions and modify the injection time in a limited way. Carburettor systems do not have these functions or do them mechanically.

Under static and minimum resistant torque conditions, the demand and delivery of engine performance is quickly balanced when the engine

rpm is stable or changes very gradually. So the injection time and the composition of the exhaust gases principally depends on the signals from the sensors and mechanical variables that can have an influence on the composition of the mixture or the development of combustion.

To facilitate diagnosis of faults and their possible repair, the analysis of the exhaust gases must be carried out under predetermined conditions that allow the comparison of the measured values with the reference figures and the checking of the control factor of the mixture (λ).



The basic requirements for the analysis of the exhaust gases are the following:

- Sufficient engine lubricant but not excessive.
- Engine cooling system working and engine at service temperature.
- Transmission in neutral or parking position.
- Electrical loads switched off.
- Battery charging voltage stable with the engine running.
- Air filter in good condition.
- Sufficient quantity of fuel in the tank and fuel specification in accordance with the manufacturer's indications.
- Fuel tank cap and engine oil filler cap fitted.
- Ignition system in good condition and ignition point correct.
- Engine vapour recirculation system in good condition (visual check).
- Sufficient ventilation in the working area or fume extraction in operation.
- Exhaust gas analyser in good condition. Measurement of background O₂ between 20.3 and 21.2% depending on atmospheric humidity, altitude and pressure. Gas sampling pipe free of obstructions, water or residue accumulation.

Reference values and manual adjustment of the mixture

As seen previously, the proportion of the different gases that form the exhaust emissions depend on the nature of the mixture, the development of combustion and their possible conversion or not by the catalytic converter.

The acceptable values for each one of the substances depend on the evolutionary level of the engines and combustion efficiency, which increases slightly with operating speed and filling of the cylinders. The following combinations are considered acceptable as a reference:

	Carburation	Injection (without λ control)	Injection before the catalytic converter	Injection after the catalytic converter
CO	< 1% and 2% >	$1 \pm 0.5 \%$	< 0.4 % and 0.8% >	< 0.2%
CO ₂	> 11%	> 12%	> 13%	> 13.5%
HC	< 400 ppm	< 300 ppm	< 250 ppm	< 100 ppm
O ₂	< 3.5%	< 2.5%	< 1.5%	< 0.2%
λ			< 0.99 and 1.02 >	< 0.99 and 1.02 >
rpm			Idling	2000 rpm

The effective compression ratio of the engine is the determining factor in this aspect. The higher the compression, the higher the combustion temperature and the oxidation efficiency.

Insufficient ignition advance reduces the combustion temperature and the oxidation efficiency, which also hampers the mechanical performance. Therefore, the hydrocarbons and the CO increase to the detriment of the CO₂.

The verification of the λ factor between 0.98-1.02 must be carried out on vehicles with catalytic converters, to ensure it performs adequately.

Manual adjustment of the mixture

The proportion of CO and the idling speed in carburettor fed vehicles is adjustable and must be adjusted in accordance with the data specified by the manufacturer, which in many cases does not coincide with the ideal λ factor. If you do not have the specific data, it is recommendable to adjust it by reducing the CO as much as possible, provided that it increases CO₂ which indicates improved oxidation efficiency. It usually coincides with an increase in the engine rpm.

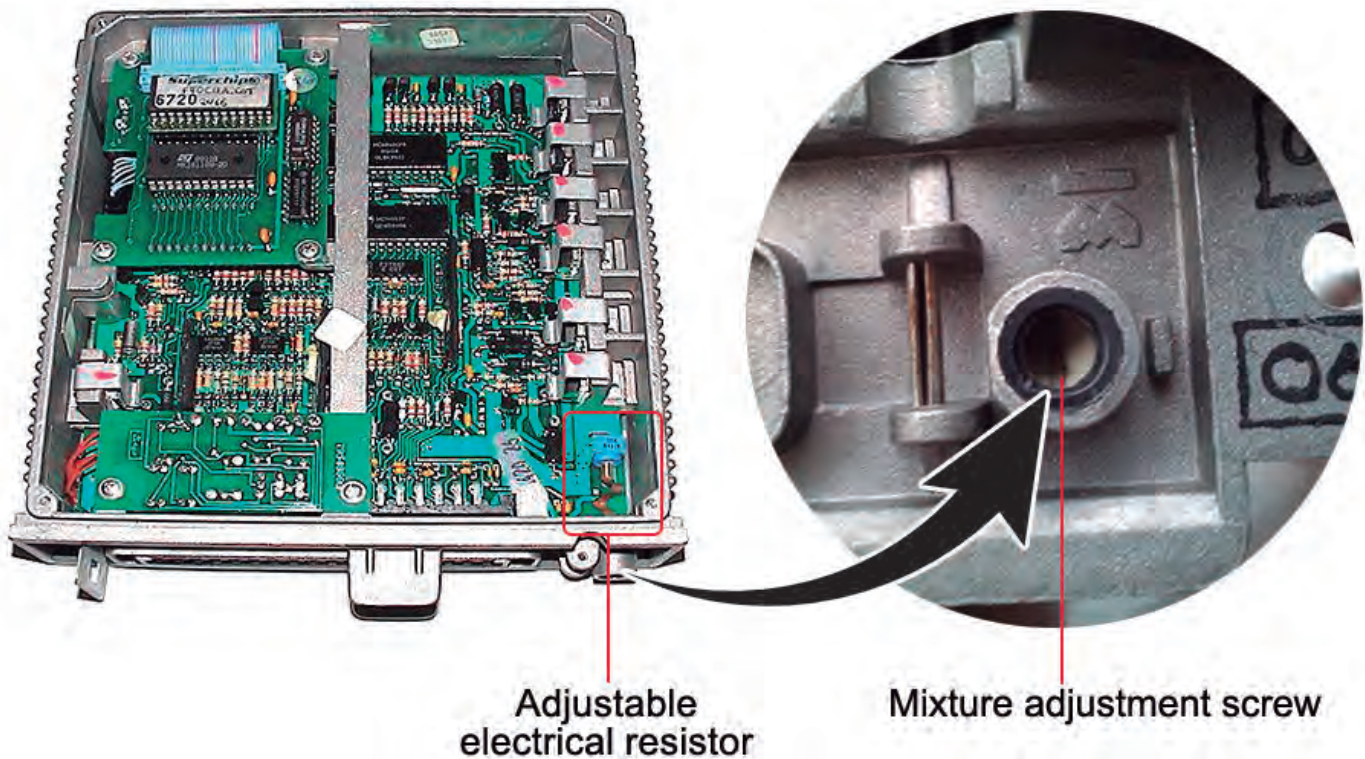
Under these conditions, leaner mixtures will produce a lower proportion of CO but lower mechanical performance as well, so the throttle position must be adjusted to a more open position to maintain the minimum stable speed. An excessively open rest position of the throttle allows the early enrichment of the mixture through the main nozzle in the transitory phase coming out of idling and during the overrun, raising fuel consumption and the absolute mass of CO produced by the engine when driving.

The working load and performance of the catalytic converter must also be checked to ensure its physical integrity and longevity.

If you have the corrected CO value and it is higher than the measured CO, the dilution of the mixture must be corrected before proceeding to check the λ factor. If it is not available, confirm the sufficient accuracy of the sample with CO₂ + CO higher than 14. Otherwise, the calculated λ value does not have the necessary accuracy to be a reliable indicator of the nature of the air/fuel mixture.

In engines fitted with first-generation injection systems, with or without an oxygen sensor, and in some cases catalytic converters, the manual adjustment of the mixture and sometimes the idle speed may be necessary to make up for the lack of a barometric sensor in many cases and to compensate for the lack of accuracy or wear of sensors and actuators.

The service adjustment to the approximate stoichiometric value of the mixture (basic injection time) ensures the best consumption/performance relationship during open-loop operation and facilitates the correction to optimal values in the least number of control/time cycles possible when there is an oxygen sensor. The initial adjustment procedure must in all cases be carried out according to the manufacturer's instructions and may require the disconnection of certain sensors/actuators or air lines.



Checking sequence

The initial check of the mixture control must be carried out with the engine at a stabilised intermediate working speed for 30 seconds to achieve an initial reference under favourable combustion conditions, with closed-loop lambda control and sufficient catalytic converter temperature, if there is one.

As an initial criterion, a control factor for the mixture between 14/1 and 15.4/1 should be adopted which means approximately 5% less or excess oxygen with respect to the stoichiometric ratio necessary for achieving complete combustion of the fuel.

If the λ factor of the exhaust gases under these conditions is not minimally acceptable (0.95-1.05), or if it is acceptable and the measured oxygen is greater than 3.5%, then proceed in the following order:

- Verify the accuracy of the sample and its possible dilution.
- Rule out any possibility of the direct entry of parasitic air to the intake system.
- Check that the engine temperature sensor is measuring correctly.
- Check that the fuel supply pressure is in line with the manufacturer's specifications.
- Verify the ignition system (colouration, wear and separation of the spark plug electrodes), as well as the ignition point in the adjustable systems.
- In injection engines with or without an oxygen sensor, adjust the mixture according to the manufacturer's specifications, if it is adjustable, and repeat the measurement.
- Disconnect the oxygen sensor if there is one and check whether the composition of the gases improves. If so, check the coherence of the signal supplied by the oxygen sensor by making the mixture richer or leaner manually. If the sensor responds correctly, continue in order.
- In carburettor fed engines, check the adjustment of the mixture at idle, the correct closing of the throttle of the second body, if there is one, the closing of the float and the correct fuel level in the bowl.
- At the inlet to the engine's intake, remove and seal the pneumatic connections of the vapour recirculation systems for the engine block and fuel tank, the vacuum connection for the brake servo and any other that does not interfere in the control of the fuel supply, the mixture control (MAP) or the ignition (distributor with pneumatic advance).
- Check that there is sufficient compression in all the engine cylinders during starting, with the throttle open. If there is an imbalance between the cylinders greater than 15%, check for cylinder leaks, correct valve adjustment/lift and condition of the valve springs.
- Analyse the balance between the exhaust temperatures of the different cylinders. If there is a significant difference ($\pm 50^\circ\text{C}$) carry out a flow comparison and injector atomisation test.

When the lambda factor of the exhaust gases and the proportion of O_2 at mid-range are acceptable, we must then measure the gases at idle under unfavourable filling, swirl and oxidation conditions.

If the new measurement gives incorrect values or the control factor differs with respect to the previous one, carry out the following checks in addition to the above:

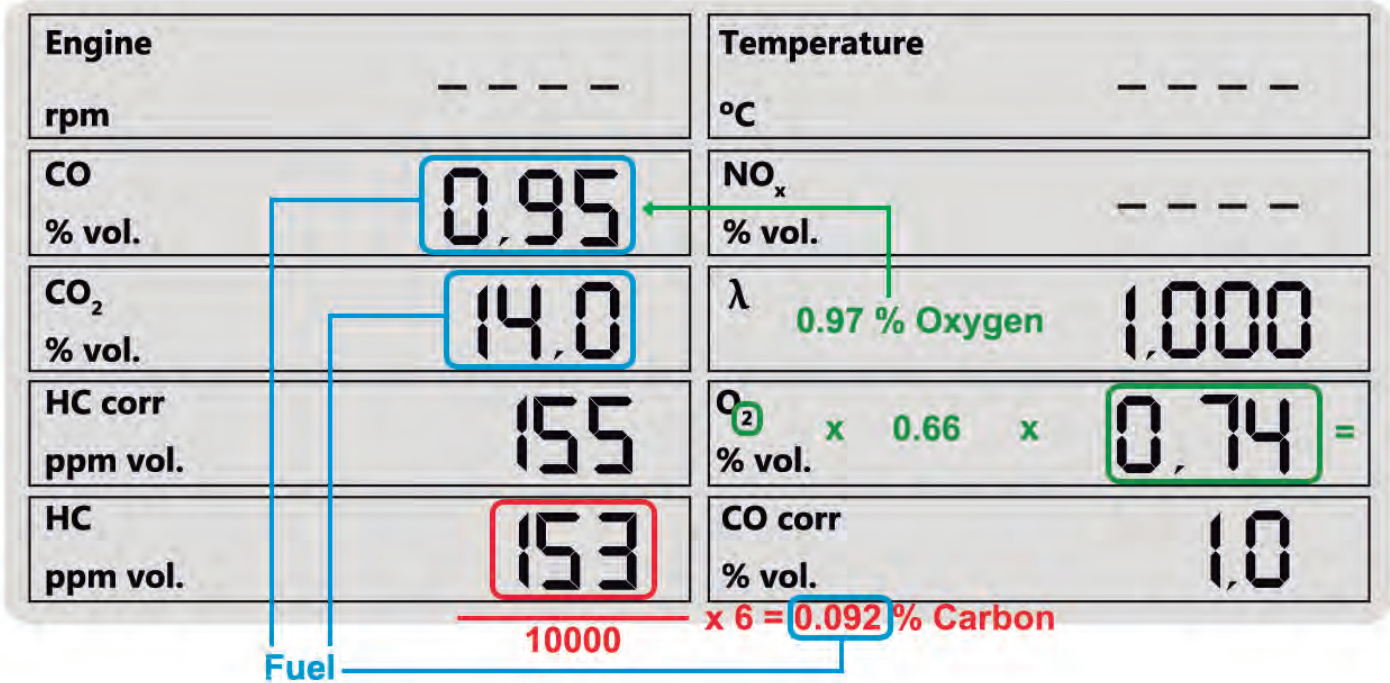
- If there is an oxygen sensor, verify that the heating functions correctly.
- Ensure there are no inlets for parasitic air, particularly through the injector seals, the seal of the intake manifold with the cylinder head and the throttle body with the manifold.
- Compare the true working temperature of the engine with the theoretically correct temperature.
- Measure the intake manifold pressure and, if necessary, verify that the engine timing system is set correctly and for possible clearances.

- Check there is no ventilation or excessive gas flow from the engine block, or possible air inlet through the filler cap or the oil dipstick and operation of the flow control or retention devices.
- Check that the injectors are sufficiently leak-tight under pressure.
- Analyse the condition of the engine oil (dilution by fuel) and the viscosity specification in accordance with the data provided by the manufacturer.
- Check that the back pressure of the exhaust train is sufficient but not excessive.
- First remove the intake manifolds and then the exhaust manifolds to inspect the possible accumulation of solids in the filling/exhaust ports of the cylinders and the valves.

Interpretation of the results

The great diversity in current combustion engines and their respective particular technical features means there is a wide range of operating possibilities, precision in the mixture control and combustion efficiency. The individual values of the different exhaust gases are not sufficient for the diagnostic when there is a small deviation; the proportions be-

tween some of them and their possible variation when the load or rpm is increased are more useful indicators. To identify the possible anomalies and to repair them, the comparison of the results against the applicable reference values in each specific case requires care and the cross-relationship between them.



On many occasions, slightly modifying the mixture manually, or simply increasing the engine's working load by switching on the largest number of electrical loads possible, allows the improvement in the exhaust gases to be detected which reveals the cause of the problem and facilitates the solution.

For greater clarity and ease in the interpretation of the results of the analysis, it is recommended to take the gas sample before the catalytic converter, whenever possible. Otherwise, its work and conversion capacity must be taken into consideration, which is always limited and conditioned by the proportion of CO/O₂ and sufficient temperature necessary.

The pronounced disproportion of the mixture or defective combustion in a single cylinder in engines equipped with an oxygen sensor will result in the erroneous control of the others during closed-loop work.

If the proportion of measured CO₂ is less than $[(14 / \text{number of cylinders}) \times (\text{number of cylinders} - 0.5)]$, or the O₂ greater than 2.5% before the catalytic converter (1.5% after), carry out the initial check of the gases with the oxygen sensor disconnected.

Checking the gases with the oxygen sensor disconnected makes it possible to determine the nature of the air/fuel mixture without correction,

whether the sensors are informing the injection control unit in a minimally coherent way or whether there is a significant mechanical defect.

The following logical considerations must be taken into account for the diagnostic:

- When working with nearly stoichiometric mixtures, the variation between the CO and O₂ of the exhaust gases is always inverse and the proportion of hydrocarbons varies very little. The evident increase of the HCs occurs when the useful richness limit of the mixture is exceeded (CO > 4%).
- The high CO, HCs and O₂ combination indicates the failure of ignition of part of the mixture due to it being too rich, and it produces excessive heating of the catalytic converter under real working and variable load conditions.
- The failure of ignition of the mixture when exceeding the usable lean limit is recognised by the high HC and O₂ combination together with very low or no CO. The reduction of CO₂ is accompanied by an excess of measured O₂.
- Low-efficiency combustion inside the cylinders is recognised by the high HC and O₂ combination with moderate CO and low CO₂.

Engine	— — — —	Temperature	— — — —
rpm		°C	
CO	1.03	NO_x	— — — —
% vol.		% vol.	
CO₂	12.6	λ	1.021
% vol.			
HC corr	974	O₂	1.82
ppm vol.		% vol.	
HC	885	CO corr	1.1
ppm vol.		% vol.	

- Low CO₂, CO and O₂ in combination with high HCs can only be due to an initial disproportion of O₂-N₂, as a consequence of insufficient emptying/filling of the cylinders due to excessive exhaust back pressure or operating with incorrect timing. It can be normal from mid-range in engines equipped with EGR, but it is not acceptable at idle. The CO₂ and N₂ recirculated to the engine's intake mathematically reduce the measurement value of the gases. The lambda factor of the mixture may be correct, given that its calculation is based on the carbon-oxygen proportion in the exhaust gases. As N₂ is approxi-

mately an absolute 74% of the recirculated gases, its proportion in the gas sample increases and that of the CO₂ reduces with respect to the total. The increase of the non-reactive material (N₂+CO₂) in the combustion chamber with respect to the reactive material (O₂ and HCs) isolates the elements making their reaction more difficult. The hydrocarbons that do not start the chemical reaction compensate for the proportional reduction of the exhaust gases that dilute the sample due to the increase of N₂.

Evolution of the measured CO₂

Combustion imperfection is more pronounced at low speed. The cooling time of the combustion chamber and of the exhaust is greater, the longer the time between the explosions. Therefore, the temperature of the reaction under static working conditions (almost constant load) and the temperature of the exhaust increase with the engine speed, which favours oxidation both inside and outside the cylinders.

- As a general rule, the CO₂ will increase slightly to operating mid-range, thus reducing the proportion of O₂ and CO.
- When, as the engine speed increases, the mixture ratio is maintained at an acceptable value and the CO₂ reduces before the catalytic converter, the most probable cause is deficient sealing of the valves (exhaust/intake in that order) or atomisation problems of the injectors.

- When the mixture ratio is maintained and the CO₂ increases before the catalytic converter by more than 0.5%, when the speed of the engine increases to mid-range, the most probable cause is insufficient compression or swirl of the mixture at low speed.

The post-combustion work of the catalytic converter masks the three above assertions.

Checking the catalytic converter

The CO₂ measured after the catalytic converter must always be greater, the amounts of CO/O₂ lower and the lambda factor of the gases should remain constant.

The conversion of the hydrocarbons should also be significant, although it is rarely absolute, and is more effective the higher the working temperature.

As a general rule, the maximum conversion capacity of the catalytic

converter is 1-1.5% of the CO present in the exhaust gases provided that the amount of oxygen available is sufficient or slightly high without being excessive, a rule that ensures the λ value between 1-1.02.

The reduction capacity is at its maximum when the average mixture is exactly stoichiometric and this can result in the complete exhaustion of the O₂ present in the exhaust gases, which should coincide with the complete conversion of the CO.

Engine	-----	Temperature	-----
rpm		°C	
CO	0.95	NO _x	-----
% vol.		% vol.	
CO ₂	14.0	λ	1.000
% vol.			
HC corr	155	O ₂	0.74
ppm vol.		% vol.	
HC	153	CO corr	1.0
ppm vol.		% vol.	

Engine	-----	Temperature	-----
rpm		°C	
CO	0.01	NO _x	-----
% vol.		% vol.	
CO ₂	15.0	λ	1.000
% vol.			
HC corr	22	O ₂	0.03
ppm vol.		% vol.	
HC	22	CO corr	0.0
ppm vol.		% vol.	

The efficiency of the catalytic converter can be calculated when the above CO and the lambda factor of the gases are acceptable ($CO < 1\%$ and $\lambda 0.98-1.02$) according to the following formula, and it should exceed 90% in static conditions to ensure sufficient conversion of the polluting substances when driving.

If the sample cannot be taken in a direct physical way, the value of the CO before the catalytic converter can be obtained at the final exhaust outlet with the engine at service temperature and the catalytic converter

“cold”. For this, let the vehicle rest for a period of 5 to 10 minutes after reaching service temperature (open thermostat and the electric fan running at least once). The temperature of the catalytic converter should drop below 150°C in this time.

Start the engine and, without delay, measure the gases at stabilised mid-range (2500-3000 rpm) as soon as the acceptable lambda factor allows it.

$$\frac{CO \text{ inlet} - CO \text{ outlet}}{CO \text{ inlet}} \times 100 = \text{Efficiency of the catalytic converter}$$

The conversion performance of the catalytic converter depends on its sufficient temperature, therefore for taking the post-catalytic converter CO value, it is recommended to wait with the engine running until the electric fan comes on and carries out the conditioning before the measurement. Maintain the engine at medium/high speed for 60 seconds before taking the data again.

Under static test conditions, when the mixture control factor is correct and is maintained stable throughout the engine rpm range, the values of the exhaust gases after the catalytic converter must also remain

steady. This indicates that the active surface of the catalytic converter is sufficient for the volume of gases produced by the engine, which ensures its effectiveness under real working conditions.

If the values of CO and O_2 increase as the engine rpm increases, the capacity of the catalytic converter is insufficient.

The catalytic reaction can be checked indirectly as well, by measuring the difference in temperature between the inlet and outlet of the catalytic converter.



The oxidation reaction of the CO and HCs is endothermic, so the gases are heated as they pass through the catalytic converter. The outlet-inlet temperature difference of the catalytic converter must be between $50-70^{\circ}\text{C}$, provided that the mixture ratio is acceptable, the quantity of CO at the catalytic converter inlet is greater than 0.4% and the CO_2 greater than 13%.

These conditions can be checked as described previously for the measurement of the pre-catalytic converter CO and the measurement of the temperatures must be carried out with the engine at stabilised mid-range rpm and the inlet temperature greater than 250°C (activation temperature of the catalytic converter).

TECHNICAL NOTES

This section covers the most common malfunctions related to the treatment of exhaust gases. Depending on the manufacturer and the different models, the number of faults occurring over the years may vary.

These faults are selected from the online platform: www.einavts.com. This platform has a series of sections that specify: make, model, line, system affected, and subsystem, which can be selected independently depending on the desired search.

MERCEDES-BENZ

S CLASS (W220) S 600 (220.878, 220.178) (M 137.970), S CLASS (W220) S 63 AMG (M 137.980), S CLASS (W220) S 65 AMG (220.179) (M 275.980), S CLASS Coupé (C215) CL 600 (215.378) (M 137.970), S CLASS Coupé (C215) CL 63 AMG (M 137.980), S CLASS Coupé (C215) CL 65 AMG (215.379) (M 275.980), SL (R230) 600 (230.477) (M 275.954), SL (R230) 600 (230.476) (M 275.951), SL (R230) 65 AMG (230.479) (M 275.981), S CLASS (W221) S 600 (221.176) (M 275.953), S CLASS (W221) S 65 AMG (221.179) (M 275.982), S CLASS Coupé (C216) CL 65 AMG (216.379) (M 275.982)	
Symptom	<p>P0300 - Ignition failure detected in one or more cylinders</p> <p>P0301 - Cylinder 1. False explosion detected.</p> <p>P0302 - Cylinder 2. False explosion detected.</p> <p>P0303 - Cylinder 3. False explosion detected.</p> <p>P0304 - Cylinder 4. False explosion detected.</p> <p>P0305 - Cylinder 5. False explosion detected.</p> <p>P0306 - Cylinder 6. False explosion detected.</p> <p>P0307 - Ignition failure cylinder 7 Left bank.</p> <p>P0308 - Ignition failure cylinder 8 Left bank.</p> <p>P0309 - Ignition failure cylinder 9 Left bank.</p> <p>P0310 - Ignition failure cylinder 10 Left bank.</p> <p>P0311 - Ignition failure cylinder 11 Left bank.</p> <p>P0312 - Ignition failure cylinder 12 Left bank.</p> <p>Malfunction indicator lamp (MIL) on.</p> <p>NOTE: This newsletter only affects those vehicles equipped with a specific type of engine.</p>
Cause	<p>Possible causes:</p> <ul style="list-style-type: none"> • Lambda regulation. • Cylinder deactivation switching valve. • Defect in the ignition unit.
Solution	<p>Repair procedure:</p> <ul style="list-style-type: none"> • Check the condition of the oxygen sensor. • Read the lambda control value parameters with the diagnostic tool. • Check the leak-tightness of the exhaust train or the catalytic converter. • Check the cylinder deactivation function with the diagnostic tool. • Replace the engine control unit with a modified version.

OPEL

ASTRA (Z 14 XEP) (Z 12 XEP), CORSA (Z 14 XEP) (Z 12 XEP), COMBO (Z 14 XEP), MERIVA (Z 14 XEP), TIGRA (Z 14 XEP)
AGILA (Z 12 XEP), HOLDEN BARINA (Z 14 XEP)

Symptom	<p>P0130 - Oxygen sensor 1, block 1. Faulty circuit. P0131 - Oxygen sensor 1, block 1. Low voltage. P0132 - Oxygen sensor 1, block 1. High voltage. P0134 - Oxygen sensor 1, block 1. No activity detected. P1138 - Sensor 2 heated, block 1. Defective signal. P2187 - Mixture too lean on idle, block 1. P2191 - Mixture too lean at a higher engine load, block 1. Malfunction indicator lamp (MIL) on. Failure codes reported by the engine control unit. The following symptoms are observed in the workshop:</p> <ul style="list-style-type: none"> • High fuel consumption. • The engine sporadically jerks.
Cause	<p>Internal defect of the oil pressure sensor. The sensor is internally cracked and the oil, by capillary effect, runs along the electrical installation until it reaches the engine control unit, causing the symptoms and fault codes mentioned in the symptom field of this technical note.</p>
Solution	<p>Repair procedure:</p> <ul style="list-style-type: none"> • Disconnect the oil pressure sensor connector (S87). • Check for the presence of oil in the connector. • Replace the oil pressure sensor if there is oil in the connector. • Clean the connector. • Disconnect the XC1 connector from the engine control unit. • Check the engine oil pressure. • Clean the XC1 connector and the engine control unit contacts. • Delete the fault codes reported by the engine control unit with the diagnostic tool. • Carry out a second reading of the fault codes on the engine control unit with the diagnostic tool and confirm that the fault codes mentioned in the symptom field of this technical note are NOT displayed. • Conduct a test on the road.



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Active safety



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