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Analysis of behavior of CO_2 emissions, CO and the lambda factor of a vehicle with a conventional injection system with catalyst and without catalyst

Análisis del comportamiento de las emisiones de CO_2, CO y del factor lambda de un vehículo con sistema de inyección convencional con catalizador y sin catalizador

Edgar Vicente Rojas Reinoso[1,*], Vicente Javier Romero Hidalgo[2], Johnny Marcelo Pancha Ramos[2]

Abstract

The analysis of the behavior of the CO and CO2 emissions is used to determine the performance of the engine work cycle, and in addition to verify the graph of the lambda factor, for which a study of the importance of a catalyst is carried out because sometimes the owners of the vehicles decide to eliminate the catalytic converter from the outlet lines of the engine burnt gases, and circulate along the roads of Ecuador ignoring the impact on the health of citizens and direct pollution towards the environment. With the analysis of the operation and characteristics of the pollutant emissions of an Otto cycle internal combustion engine, control models are generated for the projection of the amount of pollutant gases that are emitted when eliminating the catalytic converter and thereby establishing the levels of emission generated by a vehicle without a catalyst, despite the fact that the engine is in optimal operating conditions at different running speeds.

Keywords: catalyst, environmental mitigation, Otto cycle, Pollution.

Resumen

El análisis del comportamiento de emisiones de CO, CO_2 sirve para determinar el comportamiento del ciclo de trabajo del motor, además de la verificación de la gráfica del factor lambda, para lo cual se realiza el estudio de la importancia de un catalizador porque en algunas ocasiones los propietarios de los vehículos deciden eliminar el convertidor catalítico de la línea de salida de los gases combustionados del motor y así circulan por las vías del Ecuador desconociendo la afectación hacia la salud de los ciudadanos y la contaminación directa hacia el medioambiente. Con el análisis del funcionamiento y características de las emisiones contaminantes de un motor de combustión interna ciclo Otto se generan modelos de control para la proyección de la cantidad de gases contaminantes que se emiten al eliminar el convertidor catalítico y de tal forma establecer los niveles de emisiones que un vehículo sin catalizador genera, a pesar de que el motor se encuentre en óptimas condiciones de funcionamiento en diferentes regímenes de giro.

Palabras clave: catalizador, ciclo Otto, gases de combustión, mitigación ambiental.

[1,*]Researcher, Automotive engineering, Universidad Politécnica Salesiana, Ecuador.
Corresponding author ✉: erojas@ups.edu.ec. http://orcid.org/0000-0001-5658-3055
[2]Researcher, Automotive engineering, Escuela Superior Politecnica de Chimborazo, Ecuador.
http://orcid.org/0000-0003-2317-7071, http://orcid.org/0000-0001-7320-2154

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1. Introduction

At present, the polluting emissions of a vehicle are under constant analysis and study, in the search for more efficient engines and with low level of such emissions. For several years, vehicles have been considered an important source of polluting emissions to the environment due to the use of internal combustion engines. During the operation cycle of the engine and accomplishing an ideal combustion, molecular nitrogen (N_2), water (H_2O) and carbon dioxide (CO_2) would be obtained. Nevertheless, as a result of the operating cycles of a thermal engine the combustion is not perfect, thus generating additional elements such as volatile organic compounds (VOC), carbon monoxide (CO), sulphur oxides, black smokes, lead compound and nitrous oxides (NO and NO_2) [1]. Among some of the strategies to reduce the level of polluting gases it can be mentioned the use of catalytic converters at the outlet of the burnt gases of the engine, through chemical reactions and influenced by conditions such as the temperature, pressure and the application of materials that interact with the exhaust gases [2]. The use and application of these catalytic converters have been developed by means of studies conducted by each of the manufacturers, in order for their vehicles to be more environmental friendly; thus, it is necessary to keep them installed.

The importance of the study has been defined through the analysis of the polluting gases when the catalytic converter is eliminated; it is considered the initial values of the exhaust gases with the converter installed and the values obtained after it is eliminated, to define a mathematical model to forecast the importance of not suspending or uninstalling a catalytic converter from the exhaust line.

1.1. Polluting emissions

The polluting gases that originate in the vehicles act as irritants in the airways, harm the tissues altering their permeability, making them more vulnerable to develop illnesses, and that it possibly may appear viral and bacterial infection.

The nitrogen monoxide (NO) is formed due to the reaction of nitrogen and oxygen, at high temperatures in the combustion chamber. The nitrogen dioxide (NO_2) is a reddish and irritant gas, which when inhaled adheres to the nasal mucosa forming nitric acid. The generation of this acid causes an immediate reaction: the irritation of the airways jointly with an eye discomfort; the lungs are affected causing respiratory problems and bronchopulmonary reactions.

The carbon monoxide (CO) is generated by the incomplete combustion of the fuel due to the presence of low levels of oxygen; it should be considered that the carbon monoxide increases with the variation of the air-fuel ratio during the mixing. The unburned hydrocarbons (UH) produce irritation in the eyes and directly affect the mucous in the respiratory tract, besides, they can cause a narcotic effect and are carcinogenic compounds. The hydrocarbons cause the presence of acid rains, and jointly with the ultraviolet rays produce the photochemical smoke [3].

1.1.1. Catalytic converter

A solution of precious metals, used with different alloys (Al_2O_3) is integrated to the catalytic converter, which is installed at the outlet of the exhaust gases [4].

Other elements that complement the structure of a catalytic converter are the platinum (Pt), rhodium (Rh) and the palladium (Pd); these catalytic materials integrate various types of catalysts; for exampleexample, the use of the platinum and palladium form the two-ways catalytic converter, also known as oxidation catalyst, while these elements together with the rhodium are used in the three-ways catalysts or reduction and oxidation catalysts [4].

Hereunder, the reduction chemical processes in a catalytic converter are shown.

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \tag{1}$$

$$C_aH_b + \left(a + \frac{b}{4}\right) O_2 \rightarrow xCO_2 + \frac{b}{2}H_2O \tag{2}$$

$$C_3H_6 + \frac{9}{2}O_2 \rightarrow 3CO_2 + 3H_2O \tag{3}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{4}$$

The reactions generated in an oxidation catalytic converter are:

$$NO + CO \rightarrow CO_2 + \frac{1}{2}N_2 \tag{5}$$

$$C_3H_6 + \frac{9}{2}O_2 \rightarrow 3CO_2 + 3H_2O \tag{6}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{7}$$

For a better performance of the catalysts it is necessary that the air-gasoline mixture is dosed to the engine; in other words, that it possesses a proportionate composition of one kilogram of gasoline per 14.7 kilograms of air. The element that registers the composition of the mixture is a monitoring device called lambda probe [5]. This device verifies and allows that a control unit carries out continuous adjustments on the air and fuel mixture, taking as reference the percentage of oxygen that exists in the burnt gases that exit through the exhaust pipe, to inform the unit that manages the injection of the engine about the amount of fuel; this characteristic is called as lambda factor, and on this will depend the operation of the catalyst [5]. This is why in their design some catalytic converters use some type of material to reduce the levels of oxygen [6]. The elements usually applied such as the cerium (Ce) and the zirconium (Zr) store the oxygen and then release it according to the operating conditions when its presence decreases in the combustion gases [6].

2. Materials and methods

For the present research it has been chosen an experimentation strategy based on a Deming cycle, which is extended to the planning, implementation, verification and actuation founded on a spiral toward the continuous improvement [7].

The established operating parameters of an Otto cycle combustion engine (which uses a two-way catalyst in the exhaust line) are compared with the emission values of the same engine under the same characteristics, but eliminating the catalytic converter from the outlet line of the exhaust gases.

2.1. Experimental unit

For carrying out this study, a Sedan vehicle with a FS-ZM engine and a two-way catalyst in the exhaust line is utilized. Table 1 shows the characteristics of this engine.

Table 1. Characteristics of the FS-ZM with two-way catalyst

Engine	FS-ZM
Cylindrical	1600 cm^3
Maximum power	97 kW
Torque	120 Nm
Number of cylinders	4
Compression ratio	9:01
Fuel system	Multipoint injection
Type of catalyst	Oxidation – two-ways

A gas analyzer, brand MAHA, model Met 6.3, was utilized for obtaining the values of emission of polluting gases. Table 2 shows the characteristics of the measuring equipment.

Table 2. Characteristics of the gas analyzer MAHA Met 6.3

Measurable Gases	HC, CO, CO_2, O_2
Measuring principle infrared spectrometry	HC, CO, CO_2
Measuring principle electrochemical detection	O_2
Flow index	3.5 l/min
Precision class	O (OIML)
CO - Measuring range/ Measuring accuracy (max.)	-15 % Vol. / 0,01
CO_2 - Measuring range/ Measuring accuracy (max.)	-20 % Vol. / 0,01
HC - Measuring range Measuring accuracy (max.)	-9999 ppm / 0,1
O_2 - Measuring range/ Measuring accuracy (max.)	-25 % Vol. / 0,01
Lambda (calculated)	0,5 - 9,99 / 0,01
Measuring principle	Extinktionsmessung
Measuring range concentration of particles	-1100 mg/m³
Resolution concentration of particles	1 mg/m³
Measuring interval opacity	-100%
Measuring area absorption coefficient	-9.99 m^{-1}
Resolution absorption coefficient	0.01 m^{-1}

2.2. Experimental design

For the development of this work, it has been applied an experimental design based on obtaining a mathematical model that forecasts the difference that exists after eliminating the catalytic converter from the outlet line of the exhaust gases, considering as output variables of the study the values of emission of exhaust gases in a four- cylinder engine whose design uses an oxidation catalyst [8, 9].

2.3. Response variables

The response variables have been selected based on other research studies that have been conducted; taking into account the determination of the concentration of exhaust emissions at tick over conditions or Idle Static Test, 2000 [7, 10, 11]. Table 3 shows the response variables.

Table 3. Response variables

Variable	Symbol	Unit
Carbon monoxide	CO	%
Hydrocarbons	HC	ppm
Carbon dioxide	CO_2	%
Lambda	λ	-
Oxygen	O_2	%

2.4. Running speed

For the present study it has been considered as running speed what is established in the INEN standard, Environmental Administration. Air. Motor Vehicles. Determination of the Concentration of Exhaust Emissions at Tick Over Conditions or Idle Static Test, 2000, and the INEN, Vehicular Technical Revision. Procedures, 2003; procedures used in other similar emissions studies [7]. The first running speed considered was the idle condition at 700 rpm, and the second was at 2500 rpm [7].

3. Results and discussion

The emissions control equations define the prediction model of the emissions data, but the more relevant datum to stabilize such model is the comparison with the lambda factor, thereby finding the smallest amount of polluting emissions of CO_2, CO and HC.

The catalyst is the control element for reducing the pollutants; for the analysis they are of two-ways, in this case for the same model of vehicle, which will enable obtaining the control data for vehicles that have the same style or type of catalyst. The tests were carried out at normal environmental conditions at a height of 2850 m.a.s.l., and instantaneously to ensure the truthfulness and inherency of the data.

The control prediction model is represented in Equation 1 that adapts to the behavior of the control surface. Figure 1 indicates the behavior of the data dispersion, which demonstrates that at low operating conditions (idle) the vehicle generates non-stable alteration peaks (without catalyst), which produce that the lambda soars, with which the CO_2 and CO progressively increase and the emissions destabilize, as can be checked in Equation 2 of Figure 2.

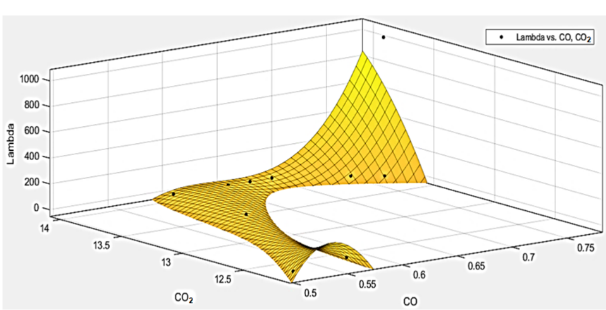

Figure 1. Surface of the behavior of the lambda *vs.* CO_2 *vs.* CO at idle condition without catalyst.

$$f(x,y) = p00 + p10x + p01y + p20x^2 + p11xy + p02y^2 + p30x^3 + p21x^2y + p12xy^2$$

Coefficients:

$$p00 = -127.4(-891.9, 637)$$
$$p10 = -164.1(-671.2, 343)$$
$$p01 = 321.7(-343.1, 986.4)$$
$$p20 = 114.3(-497.1, 725.7)$$
$$p11 = 386.1(-731.3, 1504)$$
$$p02 = -185.9(-2177, 1805)$$
$$p30 = 130.4(-213.5, 474.2)$$
$$p21 = 84.29(-912.1, 1081)$$
$$p12 = -108.7(-1627, 1409)$$

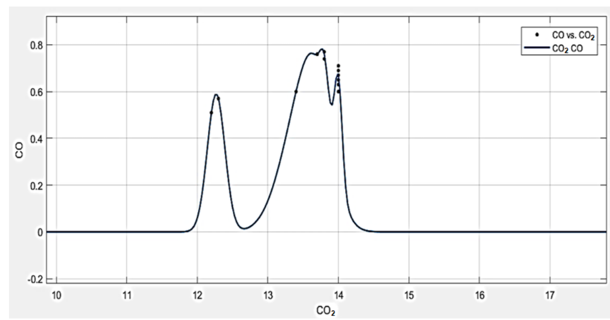

Figure 2. Behavior of the CO and CO_2

$$f(x) = a1 \cdot exp\left(-\left(\frac{x-b1}{c1}\right)^2\right) + a2 \cdot exp\left(-\left(\frac{x-b2}{c2}\right)^2\right) + a3 \cdot exp\left(-\left(\frac{x-b3}{c3}\right)^2\right) + a4 \cdot exp\left(-\left(\frac{x-b4}{c4}\right)^2\right) + a5 \cdot exp\left(-\left(\frac{x-b5}{c5}\right)^2\right)$$

Coefficients:

$$a1 = 0.1629(-1.753e^{+42}, 1.753e^{+42})$$
$$b1 = 13.8(-4.279e^{+41}, 4.279e^{+41})$$
$$c1 = 0.08264(-6.414e^{+41}, 6.414e^{+41})$$
$$a2 = 0.4192(-1.066e^{+41}, 1.066e^{+41})$$
$$b2 = 14(-8.979e^{+43}, 8.979e^{+43})$$
$$c2 = 0.07769(-1.604e^{+43}, 1.604e^{+43})$$
$$a3 = 0.3826(-1.532e^{+35}, 1.532e^{+35})$$
$$b3 = 13.41(-6.356e^{+34}, 6.356e^{+34})$$
$$c3 = 0.3917(-3.071e^{+34}, 3.071e^{+34})$$
$$a4 = 0.5899(-9.371e^{+28}, 9.371e^{+28})$$

$$b4 = 12.27(-4.638e^{+30}, 4.638e^{+30})$$
$$c4 = 0.1762(-9.03e^{+30}, 9.03e^{+30})$$
$$a5 = 0.5032(-1.75e^{+34}, 1.75e^{+34})$$
$$b5 = 13.7(-1.107e^{+35}, 1.107e^{+35})$$
$$c5 = 0.3243(-9.532e^{+33}, 9.532e^{+33})$$

The control prediction model is Equation 3 that adapts to the behavior of the control surface; and Figure 3 indicates the behavior of the data dispersion, which demonstrates that at low operating regime (idle) the vehicle generates a stable condition (with catalyst), which produces that the lambda generates an invariable sinusoidal curve, causing that the CO_2, CO and the emissions stabilize as can be checked in Equation 4 of Figure 4; each value of CO_2 stabilizes with respect to a value of CO.

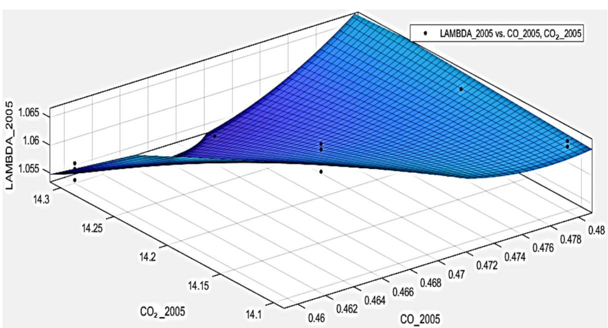

Figure 3. Surface of the behavior of the lambda *vs.* CO_2 *vs.* CO at idle condition with catalyst.

$$f(x, y) = p00 + p10x + p01y + p20x^2 + p11xy$$

Coefficients:

$$p00 = 63.85(34.8, 92.9)$$
$$p10 = -161.1(-235.9, -86.2)$$
$$p01 = -3.437(-5.027, -1.846)$$
$$p20 = 62.83(32.05, 93.61)$$
$$p11 = 7.167(3.839, 10.49)$$

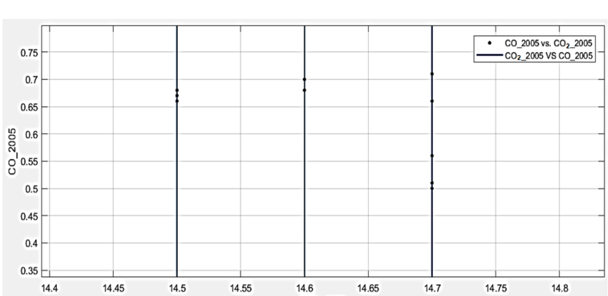

Figure 4. Behavior of the CO and CO_2

$$f(x) = p1x^3 + p2x^2 + p3x + p4$$

Coefficients:

$$p1 = 1.257e^{+10}(-1.901e^{+09}, 2.705e^{+10})$$
$$p2 = -5.508e^{+11}(-1.185e^{+12}, 8.326e^{+10})$$
$$p3 = 8.041e^{+12}(-1.216e^{+12}, 1.73e^{+13})$$
$$p4 = -3.913e^{+13}(-8.418^{e+13}, 5.916e^{+12})$$

The stability of the emissions based on the use of the catalyst at low conditions is inherent in the behavior of the injection, moreover regarding fuel consumption, generating a greater amount of emissions. As a consequence, a similar analysis can be made for the high regime conditions at 4000 rpm which is the optimum range of operation with respect to the manufacturer of the model under study (Mazda allegro).

In high regime, the engine without catalyst generates the stability wave, but the values of CO and CO_2 are still very oscillating, which generates an excessively rich control lambda, as can be observed in Figure 5 of Equation 5.

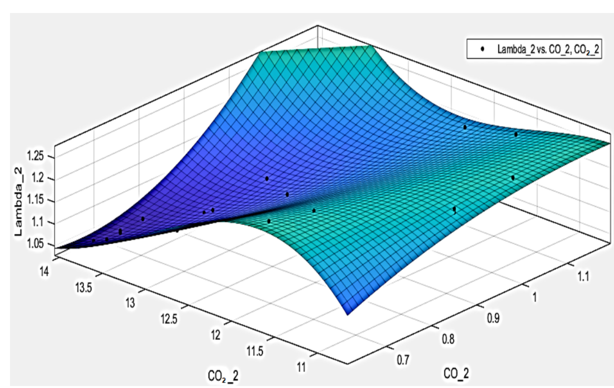

Figure 5. Surface of the behavior of the lambda *vs.* CO_2 *vs.* CO at high regime (4500 rpm) without catalyst

$$f(x, y) = p00 + p10x + p01y + p20x^2 + p11xy + p02y^2 + p30x^3 + p21x^2y + p12xy^2 + p03y^3$$

Coefficients:

$$p00 = -66.85(-111.5, -22.22)$$
$$p10 = 37.06(2.801, 71.32)$$
$$p01 = 14.25(5.461, 23.03)$$
$$p20 = -6.703(-17.69, 4.28)$$
$$p11 = -5.262(-9.398, -1.126)$$
$$p02 = -0.9794(-1.572, -0.3871)$$
$$p30 = 0.1117(-1.636, 1.86)$$

$$p21 = 0.5634(-0.04962, 1.177)$$
$$p12 = 0.1778(0.05104, 0.3045)$$
$$p03 = 0.02223(0.008537, 0.03593)$$

In the engine with catalyst, it is noted that the sinusoidal wave is of greater period, generating a linearity in the emissions of CO and CO_2, because the control lambda is more stable, as can be observed in Figure 6 of Equation 6, indicating that the injection system generates a constant stoichiometry in the work phases.

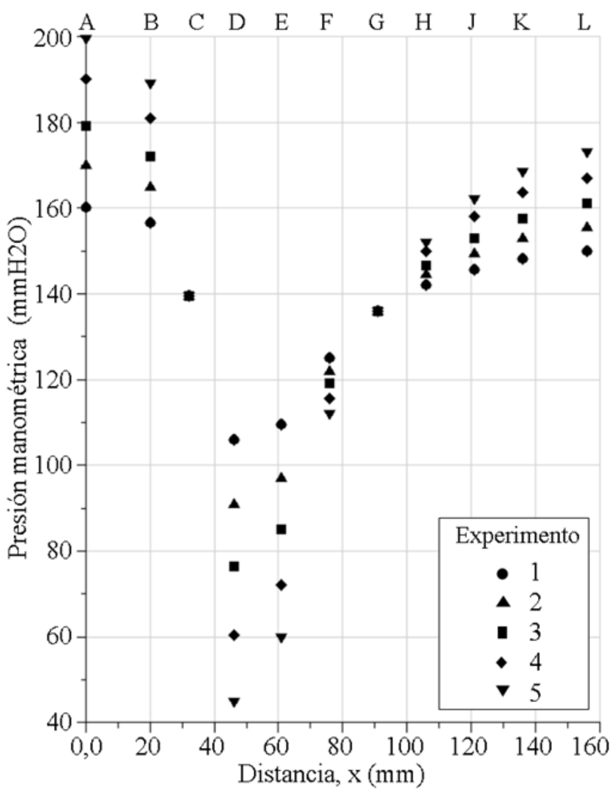

Figure 6. Surface of the behavior of the lambda *vs.* CO_2 *vs.* CO at high regime (4500 rpm) with catalyst

$$f(x, y) = p00 + p10x + p01y + p20x^2 + p11xy + p02y^2 + p30x^3 + p21x^2y + p12xy^2$$

Coefficients:

$$p00 = -653.5(-2064, 756.7)$$
$$p10 = 899.3(-979.2, 2778)$$
$$p01 = 92.64(-109.8, 295.1)$$
$$p20 = 99.1(-229.7, 427.9)$$
$$p11 = -132.2(-416.8, 152.4)$$
$$p02 = -3.273(-10.52, 3.974)$$
$$p30 = -0.3921(-1.442, 0.6578)$$
$$p21 = -6.694(-29.06, 15.67)$$
$$p12 = 4.832(-5.854, 15.52)$$

The fundamental difference in the surface of the control lambda is the stable sinusoidal and the linearity, indicating again that in a range of 4000 rpm the working velocity per cycle is larger and thus the emissions are much larger, as indicated in Figure 5, while in Figure 6 the surface is stable and thus the emissions are of lower level of variation.

4. Conclusions

The stability of the emissions based on the use of the catalyst at low conditions is inherent with the behavior of the injection system, moreover regarding fuel consumption, generating a greater amount of emissions.

At high regime, the engine without catalyst generates the stability wave, but the values of CO and CO_2 remain very oscillatory, which generates an excessively rich control lambda

In the engine with catalyst, it is noted that the sinusoidal wave is of a larger period, generating a linearity in the emissions of CO and CO_2, because the control lambda is more stable.

In the analysis of the surface of the control lambda the sinusoidal and the linearity are stable, indicating again that in a range of 4000 rpm the working velocity per cycle is larger, and thus the emissions are much larger.

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