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Prediction algorithm of fuel consumption for anhydrous ethanol mixture in high-altitude cities

Algoritmo de predicción del consumo de combustible para mezcla de etanol anhídrido en ciudades de altura

Fabricio Espinoza[1], Fredy Tacuri[1], Wilmer Contreras[1,*], Javier Vázquez[1]

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Abstract

In the present research work, a mathematical model is obtained for predicting specific fuel consumption in a 1.4-liter Otto cycle engine with electronic injection without making modifications, when using as fuel gasoline mixtures with concentrations in volume of 0%, 25%, 50%, 75% and 100% of anhydrous ethanol. For the analysis of results, a simplex lattice reticular mixture experiment design was carried out, which was subject to an urban driving cycle in the city of Cuenca at 2558 m above sea level in a roller power bank. The data acquisition and the development of the algorithm were carried out through an analysis of descriptive statistical methods. The validation of the algorithm was performed through residual analysis. As a main result, there is a mathematical model that enables predicting the engine fuel consumption, for ranges of ethanol concentration from 0% to 100% in the gasoline without needing to conduct real tests.

Keywords: Ethanol anhydride; explanatory model; fuel consumption

Resumen

En la presente investigación se obtiene un modelo matemático de predicción del consumo específico de combustible en un motor ciclo Otto de 1,4 litros con inyección electrónica sin hacer modificaciones, al usar como combustible mezclas de gasolina con concentraciones a partir de 0 %, 25 %, 50 %, 75 % y 100 % en volumen de etanol anhidro. Para el análisis de los resultados se realizó un diseño de experimento de mezcla reticular *simplex lattice*, el cual se sometió a un ciclo de conducción urbano de la ciudad de Cuenca a 2558 m s. n. m., en un banco de potencia de rodillos. La adquisición de datos y la obtención del algoritmo fueron a través de un análisis de métodos estadísticos descriptivos. La validación del algoritmo se realizó por medio del análisis de residuos. Como resultado principal se cuenta con un modelo matemático, el que permite predecir el consumo de combustible del motor, para rangos de concentración de etanol del 0 % al 100 % en la gasolina sin la necesidad de realizar pruebas reales.

Palabras clave: etanol anhídrido, modelo explicativo, consumo combustible

[1,*]Universidad Politécnica Salesiana, Cuenca-Ecuador. Corresponding author ✉: rcontreras@ups.edu.ec.
http://orcid.org/0000-0003-4559-4474 http://orcid.org/0000-0002-4160-2898
http://orcid.org/0000-0003-2300-9457 http://orcid.org/0000-0001-9678-5364

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1. Introduction

The concern about environmental pollution due to residues of incomplete combustion and the depletion of fossil fuels, motivates the study about the reformulation of mixtures with alternative fuels. A viable option is applying combinations of ethanol and gasoline, which may reduce air pollution and at the same time improve the performance of the motor compared with the unmixed oil fuel.

When evaluating the effect of these mixtures, there is a variation in the total consumption of fuel, in this line of study, according to the work by Al-Hasan, (2003) [1]. In a Toyota Tercel vehicle with a four-cylinder engine of 1.4 l capacity, four-stroke spark ignition, compression ratio of 9:1, and a maximum power of 52 kW at 5600 rpm, results in an approximate increase of 8.3%, 9%, 7% and 5.7% in fuel consumption.

When biofuels are used in internal combustion engines, consumption of such fuels increase [2]. This is due to the fact that if the air-fuel stoichiometric ratio decreases for the same revolutions per minute, same load level and same air mass, the required fuel mass should be greater [3].

Fernández, Mosquera, and Mosquera [4] demonstrated that the use of ethanol mixed with gasoline increases the consumption linearly with the mixture used.

In the research conducted in a Lada vehicle with a 1.3 l four-stroke engine and a carburation feeding system, the fuel used is a 10, 20 and 30% mixture of anhydrous ethanol in regular gasoline, of which Melo *et al.* [5] conclude that as the percentage of ethanol in the mixture increases, fuel consumption increases for all the evaluated experimental points.

In the study conducted by Delión and Rojas [6] in a 1.4 liter Ford vehicle with respect to fuel consumption for ethanol and gasoline mixtures, it was found that the «increase of fuel consumption is greater due to the increase in load or motor torque, maintaining the rpm constant, and the polluting emissions are lesser than with pure gasoline».

On the other hand, studies conducted in 1997, 1998 and 1999 by Kortum *et al.* [7], Apace [8] and Ragazzi and Nelson [9], respectively, match the research studies carried out in 2003 by Al-Hassan [1], He *et al.* [10] and Patzek [11], 2004 by Wu *et al.* [12], 2005 by Coelho *et al.* [13], Hansen *et al.*, Niven [14] and American Coalition for Ethanol [15], 2006 by Behrentz [16], Durbin *et al.* [17], Shapiro [18] and Yucesu *et al.* [19], 2008 by Acevedo *et al.* [20], as well as the more recent works by Doe *et al.* [21], in which fuel consumption increases from 1 to 6% in engines without modification using mixtures with 0-25% of ethanol, since the consumption depends on the electronic control system of the engine.

Research works conducted about fuel consumption for mixtures of anhydrous ethanol and gasoline, conclude that consumption increases as the concentration degree of ethanol in the gasoline increases.

These research works do not consider in their methodology, the development of an experimental design by mixtures together with the application of a driving cycle typical of high-altitude cities.

This work was conducted with the purpose of obtaining a mathematical algorithm that enables calculating the specific fuel consumption of a Hyundai Getz 1.4-liter vehicle, for different mixtures of anhydrous ethanol and gasoline at a height of about 2558 meters above sea level.

2. Materials and methods

The methodology applied consists of a simplex reticular (q, m) experimental design by mixtures, which considers q components and enables fitting a statistical model of order (m); this consists of all possible combinations of components or mixtures that may be formed considering that proportions may take the (m+1) values between zero and one, given by Equation 1 [22].

$$\boldsymbol{xi} = \frac{0.1}{m}, \frac{0.2}{m}, \ldots, \frac{m}{m} \tag{1}$$

The anhydrous ethanol-gasoline mixture is identified with the nomenclature (E) followed by a number, the letter represents the mixture, and the number indicates the percentage of ethanol added to the gasoline. This mixture is characterized by its density, which is obtained using the method of the pycnometer, the octane rating by means of an octane rating meter that meets the ASTM 2699 − 86 standard, and the high and low calorific value ($\boldsymbol{H}_{cs\ Ex}$), ($\boldsymbol{H}_{ci\ Ex}$) according to Equations 2 and 3, that enable calculating this property [23].

$$\boldsymbol{H}_{cs\ Ex} = \%\boldsymbol{E} \times \boldsymbol{H}_{Cs\ etanol} + \%G \times \boldsymbol{H}_{Cs\ gasolina} \tag{2}$$

$$\boldsymbol{H}_{ci\ Ex} = \%\boldsymbol{E} \times \boldsymbol{H}_{Ci\ etanol} + \%G \times \boldsymbol{H}_{Ci\ gasolina} \tag{3}$$

In order to obtain the mathematical model, the data are statistically validated using the test for outliers, and a statistical model is fitted to investigate the effect of the components on the response. A first approximation may be obtained fitting a first order model (Equation 4).

$$E(y) = \sum_{i=1}^{q-1} \beta_i \chi_i \tag{4}$$

When fitting a quadratic model, it is also necessary to incorporate the constraint $x1 + x2 + \ldots + xq = 1$, because this will give a special characteristic to the model. To illustrate the idea, it is assumed that there are three components, $x1$, $x2$, $x3$, and thus the second order polynomial is given by Equation 5.

$$E(y) = \sum_{i=1}^{q} \beta_i \chi_i + \sum_{i<j} \sum_{j=2}^{q} \beta_{ij} \chi_i \chi_j \tag{5}$$

If the quadratic model is not enough for describing the response, the special cubic model nay be used (Equation 6).

$$\begin{aligned} E(y) = \sum_{i=1}^{q} \beta_i \chi_i + \sum_{i<j} \sum_{j=2}^{q} \beta_{ij} \chi_i \chi_j + \\ + \sum_{i<j} \sum_{j=2}^{q} \delta_{ij} \chi_i \chi_j (\chi_i - \chi_j) + \\ + \sum_{i<j} \sum_{j<k} \sum_{j=3}^{fq} \beta_{ijk} \chi_i \chi_j \chi_k \end{aligned} \tag{6}$$

For obtaining the mathematical algorithm of fuel consumption, it is established the methodology indicated in Figure 1.

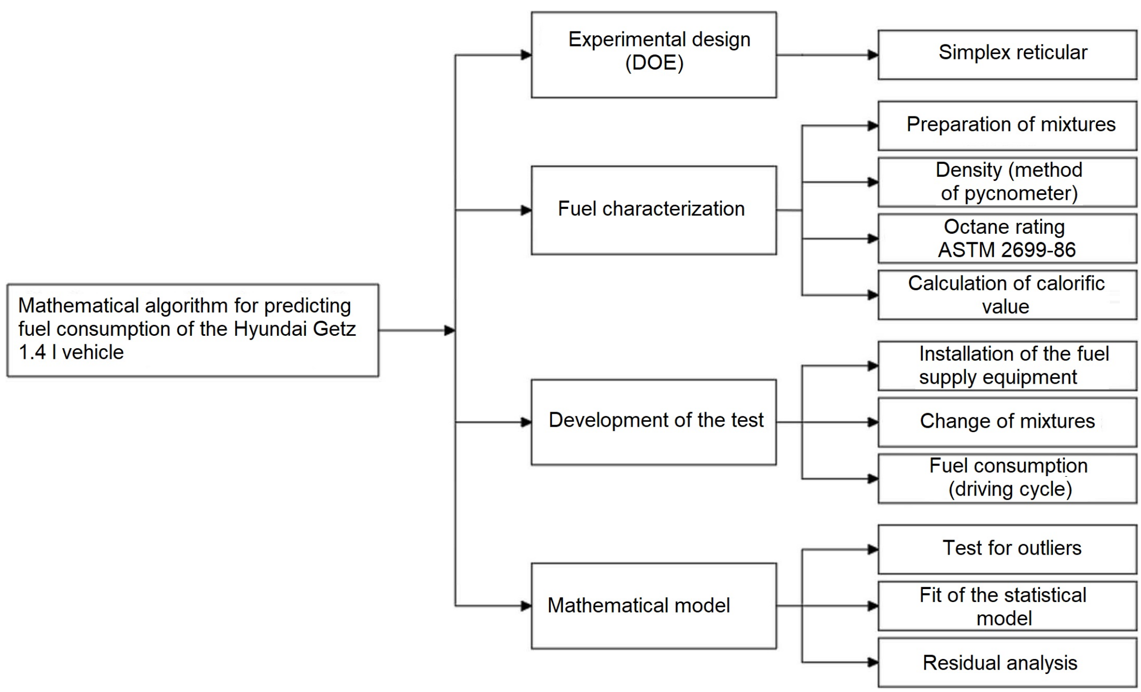

Figure 1. Methodology applied 1

2.1. Experimental design

The experimental design employed is reticular simple lattice by mixtures, using the Minitab 17 Statistical software, see Table 1, which indicates the number of components, anhydrous ethanol and gasoline for this case; design points, 21, degree of reticulum used, 4; in addition, the sequence of the experimental runs is random.

2.2. Characterization of the mixtures

The fuel used is a mixture of anhydrous ethanol with gasoline, which meet the specifications of the NTE INEN 2 478:2009 [24] and NTE INEN 935:2010 [25] standards, respectively. The used mixtures are characterized (see Table 2) indicating density, octane rating and calorific value.

Table 1. Random experimental design

Sequence established	Run sequence	Type Pt.	Blocks	ETHANOL	GASOLINE
17	1	0	1	0,5	0,5
16	2	2	1	0,25	0,75
3	3	0	1	0,5	0,5
14	4	–1	1	0,75	0,25
9	5	2	1	0,25	0,75
19	6	1	1	1	0
2	7	2	1	0,25	0,75
13	8	-1	1	0,25	0,75
10	9	0	1	0,5	0,5
1	10	1	1	0	1
12	11	1	1	1	0
21	12	–1	1	0,75	0,25
7	13	–1	1	0,75	0,25
15	14	1	1	0	1
11	15	2	1	0,75	0,25
18	16	2	1	0,75	0,25
20	17	–1	1	0,25	0,75
8	18	1	1	0	1
5	19	1	1	1	0
6	20	–1	1	0,25	0,75
4	21	2	1	0,75	0,25

Table 2. Physicochemical properties of the mixtures

Fuel	Physicochemical properties			
	Density (kg/m^3)	Octane rating (RON)	High calorific value (kJ/kg)	Low calorific value (kJ/kg)
E0	740	85,6	47 300	44 000
E25	760	90,95	42 900	39 725
E50	768,7	96,3	38 500	35 450
E75	782	101,65	34 100	31 175
E100	790,7	107	29 700	26 900

2.3. Measurement of fuel consumption

This research is developed in the city of Cuenca (Ecuador) located at 2558 meters above sea level, the fuel consumption tests are carried out in a 1.4-liter Hyundai Getz vehicle with electronic injection system and treatment of gases with a three-way catalytic converter; the compression ratio is 9,5:1, DOHC distribution system with four valves per cylinder and atmospheric type aspiration Hyundai Motor Company (2011) [26].

For performing the different tests of this research work, the original fuel feeding system of the vehicle is replaced by an alternate supply system meeting the technical specifications of the manufacturer, with the purpose of preventing alterations in the fuel mixtures.

The equipment utilized for measuring fuel consumption is the FLOW-MASTER MAHA CH-4123 flow meter. Figure 2 illustrates the installation of the equipment in the vehicle; Table 3 indicates the data obtained according to the design of experiment

Figure 2. Tests of operation 1

Table 3. Measurement of fuel consumption

Sequence established	Run sequence	ETHANOL	GASOLINE	Fuel consumption (g/km)
17	1	0,5	0,5	0,0435
16	2	0,25	0,75	0,0405
3	3	0,5	0,5	0,0405
14	4	0,75	0,25	0,037
9	5	0,25	0,75	0,0475
19	6	1	0	0,0475
2	7	0,25	0,75	0,0495
13	8	0,25	0,75	0,05
10	9	0,5	0,5	0,04
1	10	0	1	0,043
12	11	1	0	0,0515
21	12	0,75	0,25	0,045
7	13	0,75	0,25	0,0465
15	14	0	1	0,036
11	15	0,75	0,25	0,0475
18	16	0,75	0,25	0,047
20	17	0,25	0,75	0,04
8	18	0	1	0,036
5	19	1	0	0,0515
6	20	0,25	0,75	0,0355
4	21	0,75	0,25	0,049

To obtain specific fuel consumption, it was utilized the driving cycle representative of the city of Cuenca, which is identified in Figure 3; a micro-cycle is applied with the first five minutes, since they are the most distinctive ones as determined by means of a pre-experimental analysis. The test is carried out on a Maha LPS 3000 power bank.

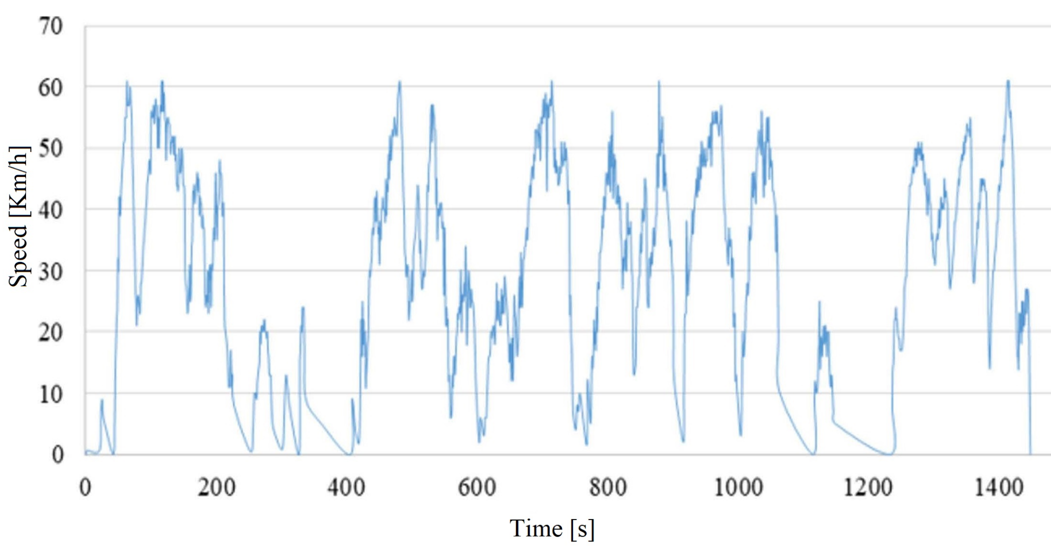

Figure 3. Driving cycle representative of the city of Cuenca

2.4. Data treatment for the response model

With the data of the experimental design as a function of the different mixtures, it is convenient to conduct validation tests of the results before proceeding to obtain the response model. The R22 Dixon test for outliers [27] was established for validating the results. After the data have been validated the model is constructed, and a residual analysis is performed with the purpose of verifying the hypotheses of normality, homoscedasticity, independence and linearity of the model.

3. Results and discussion

In order to determine the model that explains fuel consumption, a multivariable linear regression analysis is carried out with the data obtained from the DOE, and a higher order model is fitted as indicated in Table 4, where the different values of «R2» and «p-value» are observed. This information enables choosing the linear model, to meet the assumptions, and it is also observed in the «p-value» column that the higher order models are greater than the 0.05 significance level, and thus these models are not considered.

After the linear model has been selected, the estimated regression coefficients are determined (Table 5), and it is obtained the formula of the model for predicting consumption shown in Equation 7.

$$2Y = 0.05100(etanol) + 0,03455(gasolina) \quad (7)$$

Table 4. Summary of the models fitted for fuel consumption

Model	P-value	(%)	Predicted (%)	Adjusted (%)
Linear	0	94,2	93,04	93,86
Quadratic	0,274	94,6	92,66	93,94
Complete cubic	0,784	94,6	91,92	93,62
Complete cubic	0,126	95,3	91,59	94,17
Note. Value *p < 0,05				

Table 5. Regression coefficients estimated for fuel consumption

Term	Coeff.	EE of the coeff.	T	P	VIF
ETHANOL	0,051	0,000562	*	*	1,19
GASOLINE	0,03455	0,000562	*	*	1,19
Note. Value *p < 0,05					

The results indicated in Figure 4 are obtained after applying Equation 7.

In addition, in the variance analysis for the linear model, as indicated in Table 6, the «p-value» = 0,000, therefore, the model is significant and with a very good adjusted «R^2» of 93.86.

The remaining models are excluded because they do not meet the p-value assumption [28].

Once the standardized analysis of variance has been conducted, graphical results are shown in the following which confirm the fit of the model to the fuel consumption.

In order to evaluate the model of fuel consumption, a four in one residuals plot is utilized, as indicated in Figure 5. This graphical analysis with respect to the standardized residuals, enables verifying the fit of the experimental model obtained previously.

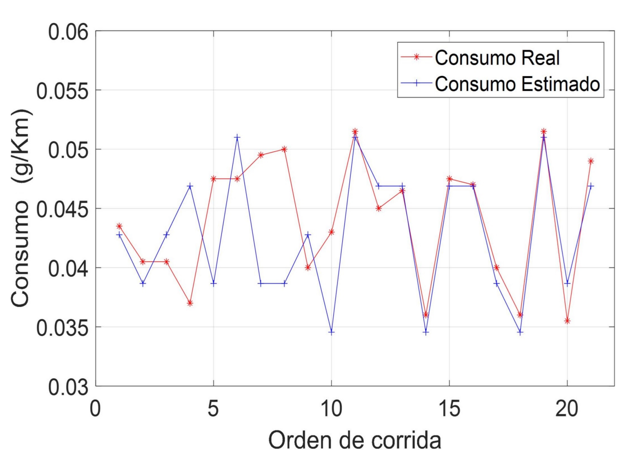

Figure 4. Result of the numerical algorithm

Table 6. Variance analysis for fuel consumption

Source	GL	SC Sec.	SC Adjust.	MC Adjust.	F	P
Regression	1	0,00061	0,000609	0,000609	306,5	0
Linear	1	0,00061	0,000609	0,000609	306,5	0
Residual error	19	3,8E-05	0,000038	0,000002		
Lack of adjustment	3	8E-06	0,000008	0,000003	1,34	0,3
Pure error	16	0,00003	0,00003	0,000002		
Total	20	0,00065				
Note. Value *p < 0,05						

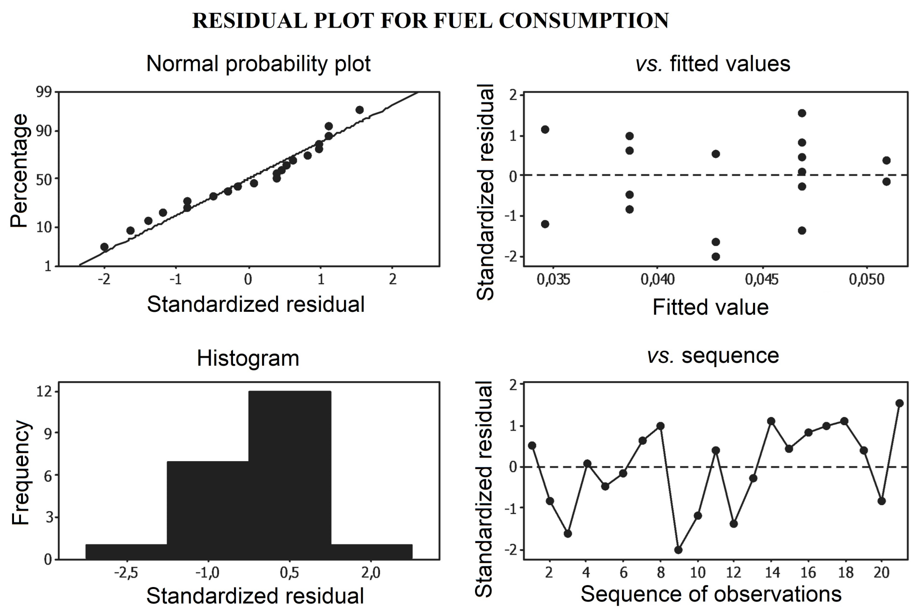

Figure 5. Residuals plots for the fuel consumption data

From the analysis of Figure 5, the following conclusions are drawn:

a. The normal probability plot shows that the residuals follow a normal distribution, since the fit to a normal trend line.

b. The Histogram plot of the residuals is bell-shaped, having a value of –2,02 for observation number nine, which is out of the allowed range (–2,0) in standard residual; however, this does not have a greater significance in the model, and the normality of the data is accepted.

c. On the other hand, in the plot of standardized residuals versus fitted values, no abnormal trend is observed that indicates a bad fit of the model, since the residuals are randomly distributed around zero, and thus it is considered that there is independence.

d. At last, in the plot of standardized residuals versus the sequence of observations, there is a random pattern around the central line, no ascending or descending trends of the observations occur that indicate a bad fit of the model.

With this analysis it is concluded that the variance is correct and that the model does not exhibit anomalies in the results, and thus it may be used to predict fuel consumption in a better manner.

Figure 6 shows a plot of the response of the mixture (ethanol-gasoline) in the fuel consumption. This enables evaluating how the components are related to the response using a fitted model.

The tracking plot of fuel consumption shown in Figure 6, provides the following information about the effects of the components:

It is observed that fuel consumption has a growing trend as the ethanol increases up to a maximum in E100, while decreases the concentration of the second component, in this case gasoline extra.

Also note that the slope of the curve is steeper in the section between 0 and 15% of ethanol, and in the section after 40%; therefore, in the range between 15 and 40% it is less step, corresponding to the zone of less fuel consumption.

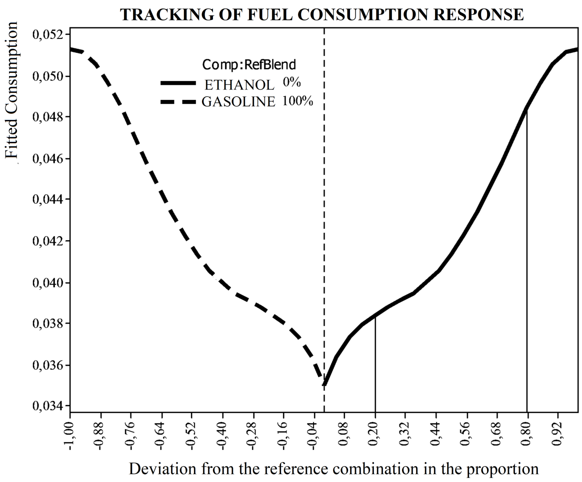

Figure 6. Tracking plot of fuel consumption response

4. Conclusions and recommendations

Specific fuel consumption is directly proportional to the percentage of ethanol in the mixture, i.e., as the percentage of ethanol in the mixtures increases, specific fuel consumption increases as well. Therefore, with an E20 mixture there is a 7% increase in fuel consumption, while in an E100 mixture there is 31.3% more consumption with respect to the gasoline of 86.5 octanes.

It was established a mathematical model that enables determining fuel consumption for different percentages of ethanol in the gasoline, which can be applied for contrasting real tests.

The increase in fuel consumption is due to the reduction of the calorific value of the mixture as the concentration of ethanol varies.

During the development of the tests, the vehicle operated correctly without showing anomalies for concentrations greater than 30%.

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