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RURAL ENGENERING

Gas emissions from an agricultural compression-ignition engine using Diesel, biodiesel and ethanol blends

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ABSTRACT: *Partial fuel replacement strategies arising from fossil sources used in compression ignition engines involve mixtures of mineral Diesel oil, biodiesel and ethanol to minimize the gas emissions. In this study, experimental assessments were performed on a multi-cylinder, turbocharged aftercooler, compression-ignition, agricultural tractor engine provided with electronic injection management and an exhaust gas recirculation (EGR) gas treatment system. Diesel oil containing low (BS10 -10 ppm) and high sulfur concentrations (BS500 - 500 ppm) was utilized, with 10% of biodiesel as a constituent established by Brazilian legislation, in blends with 5, 10, 15 and 20% of the total volume, made up of anhydrous ethanol with additives. Thus, there were eight fuels blends and two reference conditions (without ethanol). The emissions of CO, HC, NOx and the HC+NOx gases were estimated, corresponding to the eight operating modes (M) of the ABNT NBR ISO 8178-4 standard. From the findings, it was evident that with the rise in the ethanol concentrations in the fuel blends there was a corresponding increasing in the CO, NOx and HC+NOx emissions. The HC, on the contrary, exhibited a pattern of higher emissions for the high-sulfur fuels (BS500) at low loads. No difference was observed for the NOx emissions at high loads. In the other operation modes, different behaviors were expressed for the BS10, which sometimes showed an increase, while at other times a reduction in the NOx emissions. Regarding the BS500, the NOx emission increased when the ethanol concentrations rose. As the specific emissions of the NOx were higher than those of the HC (in g.kW^{-1}.h^{-1}), the behavior exhibited by the HC+NOx showed similarity to that of the NOx. When the directly analysis of the operating modes was taken into consideration, the use of ethanol triggered an upswing in the emissions, exceeding the threshold of MAR-1 and EURO V standards.*
Key words: *Biofuels, electronic injection, Diesel-biodiesel-ethanol blends, emission regulations, tractor.*

Emissões de gases de um motor agrícola de ignição por compressão utilizando misturas de óleo Diesel, biodiesel e etanol

RESUMO: *Misturas de óleo Diesel mineral, biodiesel e etanol formam estratégias de substituição parcial do combustível de origem fóssil, aplicáveis em motores de ignição por compressão, com o intuito de redução das emissões de gases. Neste trabalho realizaram-se avaliações experimentais em um motor de trator agrícola de ignição por compressão, multi-cilíndrico, turboalimentado com aftercooler, gerenciamento eletrônico da injeção e sistema de tratamento de gases EGR. Foram utilizados óleo Diesel de baixo (BS10 -10 ppm) e alto teor de enxofre (BS500 – 500 ppm), com 10% de biodiesel em sua constituição, em misturas com concentrações de 5%, 10%, 15% e 20% do volume total, compostas por etanol anidro aditivado, totalizando oito combustíveis em mistura e duas condições de referência (sem etanol). Foram avaliadas as emissões de gases CO, HC, NOx e HC+NOx, segundo os oito modos de operação (M) da norma ABNT NBR ISO 8178-4. Dentre os resultados encontrados, com o incremento das concentrações de etanol nas misturas ocorreu o aumento das emissões de CO, NOx e HC+NOx. Já o HC apresentou um comportamento de maiores emissões para combustíveis com alto teor de enxofre (BS500) em baixas cargas. Não houve diferença para as emissões de NOx em altas cargas. Já nos demais modos de operação, para o BS10 ocorreram comportamentos diversos, em alguns momentos aumentando e em outros diminuindo as emissões de NOx. Já para o BS500, o comportamento das emissões de NOx foi de aumento com o incremento das concentrações de etanol. Devido as emissões específicas de NOx serem maiores que as de HC (em g.kW^{-1}.h^{-1}), o comportamento do HC+NOx foi similar ao do NOx. Considerando apenas a análise direta dos modos de operação, a utilização de etanol causa o aumento das emissões, superando os valores limites da MAR-1 e EURO V.*
Palavras-chave: *biocombustíveis, injeção eletrônica, misturas Diesel-biodiesel-etanol, normativas de emissões, trator.*

INTRODUCTION

From the time of the industrial revolution, the global energy demand has steadily grown, which increased with the development of the internal combustion engine and the usage of petroleum oil. Coupled with this huge consumption, the number of the pollutant gas emissions dramatically soared, particularly carbon dioxide, one of the gases that accounts for the greenhouse effect (MOFIJUR et al.,

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2016). Global energy-linked carbon dioxide (CO_2) emissions surged by 1.7% in 2018, achieving an alarming 33.1 Gt (gigatons) of CO_2. This was the highest growth rate recorded since 2013 and is 70% higher than the average rise since 2010 (IEA, 2019).

The energy industry focused its attention on identifying new and renewable fuel sources, as reliable substitutes for the petroleum derivatives used in the internal combustion engines. This is the outcome of the mounting global concerning energy insecurity, in the face of the steady and continual draining of the oil reserves and the development of standards to restrain and limit the pollutant emissions.

This high demand has forced researchers to seek and identify new fuels and additives that can be coupled with the new fuel injection strategies, in order to encourage the growth of the biofuel market and highlight awareness of the studies dealing with this subject, over the recent decades (PAUL; PANUA; DEBROY, 2017).

Besides conforming to these new gas emission limits, the search for more efficient engines and machines continues (JAMROZIK, 2015). This led to an increase in the offer of supercharged engines, with aftercooler, electronic fuel injection management and exhaust gas treatment systems, in order to satisfy the limits recommended by the emission regulations and raise the energy efficiency (BERTINATTO et al., 2022).

Biofuels such as biodiesel and bioethanol have a high potential for application in Diesel cycle engines (PRADELLE, F. et al., 2017). As their physicochemical properties bear close similarity to those of conventional fossil fuels, there is little or no necessity for modification of the engine based on their concentration (GUEDES et al., 2018; RAKOPOULOS, et al., 2006; VINOD BABU; MADHU MURTHY; AMBA PRASAD RAO, 2017). Several countries, like Brazil, have already started utilizing mixtures of Diesel and biodiesel in internal combustion engines (CARNEIRO et al., 2017; MURUGESAN et al., 2009; RIBEIRO et al., 2007).

However, the amount of biodiesel produced continues to be insufficient to meet the demands and ensure a hypothetical complete replacement of Diesel oil by renewable fuel. Therefore, although, ethanol is prominent among the renewable fuels as a good biofuel, some limitations are observed with respect to the proportion of ethanol mixed with Diesel caused primarily by the difference in polarity between the alcohols and hydrocarbons in Diesel oil (GUEDES, 2017; PIDOL et al., 2012).

In light of these factors, the use of ethanol in a mixture with mineral Diesel oil, without the additives to ensure homogenization and stability, can affect the functioning and durability of the engine, besides limiting the percentage of the mixture. Hence, from the perspective of engine durability and safety, emulsifying additives and co-solvents have been used, in addition to Diesel oil mixtures containing up to 15% of ethanol (LAPUERTA; ARMAS; GARCÍA-CONTRERAS, 2007; RAKOPOULOS, et al., 2011; SATHIYAMOORTHI; SANKARANARAYANAN, 2017; YILMAZ et al., 2014). From the various researches conducted, it appears that the incorporation of biodiesel with the mineral Diesel oil enhances the solubility with ethanol (KWANCHAREON et al., 2007).

PANG et al., (2006) used a Diesel oil-biodiesel-ethanol (D:B:E) mixture in the ratio of 75:20:5 by volume, in their investigation of gas emissions with respect to fossil Diesel oil. Their conclusion was that the blended fuel released higher emissions of nitrogen oxides (NOx), but with substantially reduced hydrocarbon (HC) emissions. SHI et al., (2006) employed a mixture of D:B:E in the proportion of 75:20:5 by volume. The inclusion of oxygenated fuels caused a drop in the HC emissions. However, a corresponding increase of 5.6 to 11.4% was noticed in the emissions of NOx. The carbon monoxide (CO) emission was inconclusive and dependent upon the operating conditions of the engine.

In the investigation of GUARIEIRO et al., (2009) various blends of Diesel oil and ethanol were used, with soybean oil, castor oil, soybean biodiesel and castor bean biodiesel, with ethanol being added, in 7 to 15% by volume. No significant difference was recorded in the CO emission. JHA et al., (2009) estimated the D:B:E mixtures in the ratios of 70:25:5, 70:20:10 and 70:15:15, by volume. From the results, it was evident that the use of the mixtures induced lowered NOx emissions in the two new engines, for the highest ethanol concentration, while the used engine revealed greater NOx emissions under similar conditions. The CO emission registered an increase when the proportion of ethanol was incorporated in the blends, in the case of the used engine, as well as the two new engines.

Using D:B:E blends, high in ethanol concentration, HULWAN & JOSHI (2011), assessed the characteristics of the performance and emissions of a three-cylinder engine. The D:B:E blends were composed of a blend in the ratios of 70:10:20, 50:20:30, and 50:10:40 compared against a reference variable (Diesel oil). Results revealed that the NO variations were dependent upon the operating conditions, and at low loads the CO emissions showed a substantial rise in comparison to the reference fuel.

ESTRADA et al., (2016) utilized an agricultural tractor engine to estimate the mixtures of Diesel oil containing high sulfur levels (500 ppm), with biodiesel and hydrated ethanol, in the ratios of 95:5:0, 92.15:4.85:3, 89 0.3:4.7:6, 86.45:4.55:9, 83.6:4.4:12, and 80.75:4.25:15. From the results, it was clear that, normally, the mixture of ethanol in Diesel oil lowered the pollutant emissions. In the case of the NOx and CO_2 gases, the reduction in their levels was on a lower scale and showed greater sensitivity to reduced engine speed than to any increased percentage of ethanol in the mixture. In fact, FARIAS et al., (2019) in their research, used the D:B:E blends in concentrations of up to 15% hydrated ethanol and reported a drop in the CO_2 and NOx emissions, with respect to the Diesel oil, in the order of 4.96 and 5.15%, and 6.59 and 9.70%, respectively. In summary, when 12 and 15% of ethanol were added to the Diesel oil, the engine emissions showed significant reduction.

Authors as PANG et al., (2006), SHI et al., (2006) and BARABÁS et al., (2010) recorded lowered HC emissions after the addition of ethanol. However, reports from the researches of other authors revealed that in general, the HC emissions rise as increase the ethanol levels in the mixtures with Diesel oil (LAPUERTA; ARMAS; GARCÍA-CONTRERAS, 2009; PARK; CHA; LEE, 2010; RANDAZZO & SODRÉ, 2011; SHAMUN et al., 2018). They also cited that this phenomenon could take place under particular conditions like low and medium loads (PARK et al., 2012; PARK; YOUN; LEE, 2011).

Overall, reports in the literature show contradictory findings, in which some studies record a rise in the CO, HC and NOx emissions, while others mention a lowering of these emissions or no trend at all. Certain factors that can exert some effect, range from the fuel type employed (quantity of sulfur in the Diesel, anhydrous or hydrated ethanol, presence of biodiesel), amount of ethanol added, inclusion of additives, engine specifications (injection with mechanical or electronic management, number of cylinders, embedded technology), and the gas treatment systems, besides others. Hence, more extensive research on this subject is crucial, besides the stratification of the results for each specific test condition.

In light of the contrary results given in the many studies investigated, the present study was conducted by an analysis of the gas emissions in an agricultural engine, when mixtures of Diesel oil, biodiesel and anhydrous ethanol were used along with additives, and assessment of the CO, HC, NOx and HC+NOx emissions.

MATERIALS AND METHODS

All the tests were performed in the Laboratório de Agrotecnologia (Agrotec), attached to the Núcleo de Ensaios de Máquinas Agrícolas (NEMA) of the Universidade Federal de Santa Maria (UFSM), situated in the municipality of Santa Maria, state of Rio Grande do Sul.

Equipment used

In the experiment, the engine tested was a Diesel cycle, AGCO Power brand, four-stroke, Bosch brand fuel injection system, of the Common Rail type, having electronic management and maximum injection pressure of 1800 bar, specifications as maintained by the manufacturer. It is provided with an internal displaced volume of 4400 cm³, four vertical in-line cylinders, turbocharged and having an aftercooler. According to the manufacturer, it has a rated power of 100 kW at an angular speed of 2000 revolutions per minute (rpm) and maximum torque of 540 N.m, at 1500 rpm of the engine.

Equipped with an exhaust gas recirculation (EGR) system to control the gas and particulate matter emissions, and having an electronic fuel injection management system, which based on the manufacturer claims, complies with the Brazilian MAR-1 emission legislation (Euro IIIA equivalent). This engine was tested directly by the power take-off (PTO) of a MF6713R Dyna-4Massey Ferguson agricultural tractor, 4x2 FWD (auxiliary front wheel drive).

In order to impose loads on the engine, a mobile, air-cooled dynamometer was used, which is operated through a magnetic brake, based on the eddy current principle (Foucault's currents). It is EGGERS branding, model PT301 MES, with a braking capacity of up to 600 kW.

Using the Saxon analyzer, model Infralyt ELD, the gases emitted from the engine exhaust were analyzed. The opacity of the gases was measured with a Saxon brand partial flow opacimeter, model Opacilyt ELD. Employing a probe inserted into the exhaust tube of the engine, samples were drawn, and the MW IELD 01030 software was used for data acquisition.

Experiment characterization

This study involved the use of eight different blends of ethanol with Diesel and biodiesel, apart from two reference conditions. The reference conditions included the two types of Brazilian marketed Diesel available to the final consumer, during the study period. The BS10 and BS500 Diesel already contained 10% biodiesel in their composition, with maximum sulfur concentrations of 10 ppm and 500 ppm, respectively. The anhydrous ethanol employed complied with the specifications of the Agência Nacional do Petróleo (ANP), through ANP Resolution No. 19 (2015), which sets 98% vol as the minimum ethanol content.

The mixture was promoted using Teccom10® and Teccom BX Ethanol®. The first additive, which acts as an antioxidant, homogenizer and lubricant, was added in a concentration of 1000 ppm into the Diesel oil; the second additive, Teccom BX Ethanol®, which acts as an antioxidant, stabilizer, and lubricant, was added in a concentration of 20000 ppm to the anhydrous ethanol. The constituents of the treatments are listed in table 1; the fuel specifications are shown in table 2.

To investigate the emission of the polluting gases, the CO, HC, NOx and HC+NOx emission levels were analyzed as the response variables, and expressed in the unit of $g.kW^{-1}.h^{-1}$. The results were compared with the standards set by the Brazilian legislation, Proconve MAR-1 and international Euro V, for emission control. The polynomials were determined for each tested mode to identify the emission behavior in response to the other levels of ethanol. Using the completely randomized design in a 2 x 5 x 8 three-factor experiment, the results of the interaction of both fuel types (Diesel oil BS10 and BS500), five ethanol concentrations (0, 5, 10, 15 and 20%) and eight modes of operation, was performed, with 60 repetitions.

The tabulated data drawn from the experiments were submitted to the analysis of variance (ANOVA). When significance was noted, the qualitative values of the means were compared using Tukey test while the quantitative values were subjected to regression analysis, at 5% probability (95% confidence), employing the SISVAR statistical program (FERREIRA, 2014).

Methodology used

Based on the ABNT NBR ISO 8178-4 (2012) standard, the opacity and exhaust gas emissions were measured. This standard is concerned with the measurement of the exhaust gases in alternative internal combustion engines, with the use of a test cycle in constant regime, applying different loads on the engine. The dynamometric curves of engine torque and power were required for this evaluation.

In figure 1, the percentages of the torque applied to the engine for a given engine speed were listed. Each point in this figure is termed the mode of operation (Mx). These modes are included in the vehicles classified by the ABNT NBR ISO 8178-4 (2012) standard as type C1. These are the off-road vehicles and Diesel-powered industrial equipment under which category the agricultural tractor is included.

Complementing the data shown in figure 1, the variable observed on the y (M) axis is the torque and the variable seen on the x (n) axis is the engine speed. Curve 1 represents the trend demonstrated by the engine torque, with acceleration at maximum and variations in the load. Point 2 corresponds to the idling speed of the engine. Point 3 indicates the mid-range or maximum torque rotation. Point 4 refers to the rated speed or maximum power speed. There are fixed engine speeds at which the collections need to be done (engine speeds 2, 3 and 4), which means in the M1, M2, M3 and M4 operating modes the same engine speed must be used, with the percentage of torque application being varied in each mode.

To analyze the gas emissions, the first two minutes of evaluation need to be eliminated, to ensure stabilization of the data reading, and the final minute needs to be considered for the assessment, which corresponds to 60 data (one collection per second). The methodology of HESEDING et al., (2010) is considered for the conversion of the measurement units of the polluting gases collected by Infralyt.

RESULTS AND DISCUSSION

From the results of the analysis of variance (ANOVA) significant differences were evident among all the variation factors, namely fuels (C), ethanol concentrations (E) and modes of operation (M). The interactions of these factors also revealed significant effects for (C x E), (C x M), (E x M) and (C x E x M).

Carbon monoxide (CO)

From the results, among the fuels, only at 5 and 15% ethanol concentration, did the BS500 reveal higher CO emissions than the BS10. However, the BS10 at 20% ethanol concentration, revealed the highest emissions (Table 3). At the other levels of concentration, the two fuels differed only for the medium and low loads (operating modes M3, M4, M7 and M8).

Table 1 – Composition, concentration and specific gravity of treatments from mixtures of Diesel oil, biodiesel and anhydrous ethanol with additives.

Treatments	--------Diesel oil (sulphur)------		Biodiesel	Anhydrous ethanol with additives	Specific gravity
	(10 ppm)	(500 ppm)			
	---(%)---				(kg.m^{-3}, 20 ºC)
BS10 – 0% ethanol	90	0	10	0	844.4
BS10 – 5% ethanol	85.5	0	9,5	5	840.2
BS10 – 10% ethanol	81	0	9	10	839.5
BS10 – 15% ethanol	76.5	0	8.5	15	834.8
BS10 – 20% ethanol	72	0	8	20	833.3
BS500 – 0% ethanol	0	90	10	0	848.0
BS500 – 5% ethanol	0	85.5	9.5	5	844.1
BS500 – 10% ethanol	0	81	9	10	842.3
BS500 – 15% ethanol	0	76.5	8.5	15	838.2
BS500 – 20% ethanol	0	72	8	20	836.6

As the CO emissions are usually lower than the legislated limit and do not require particular attention, the analysis of the CO level for lean mixtures (low loads) is not beneficial (MOREIRA, 2008).

In contradiction to the reported by MOREIRA (2008), among the operating modes, the BS10 as well as the BS500 emitted the highest CO levels at low loads, with the very lowest level at medium and high loads. The Diesel cycle engine; however, operating with D:B:E exhibited different distinctive emissions in accordance with the engine load, in which the lower the load applied the greater the specific emissions (emissions tended towards infinity in response to the loads tending to zero - % CO/load > 0). When the engine was at low (HULWAN; JOSHI, 2011) and medium loads (PARK et al., 2012; PARK; YOUN; LEE, 2011), the CO emissions were observed to increase.

At the time of employing the EGR at lower loads, the CO emissions were higher for the fuel

Table 2 – Characteristics of the fuels used (Adapted from ANP 2013, 2015).

Characteristics	Unit	BS10*	BS500*	Anhydrous ethanol	Test method
Total acidity (max)	mg.L^{-1}			30	ABNT NBR 9866
Electric conductivity (max)	µS.m^{-1}			300	ABNT NBR 10547
Total sulphur (max)	mg.kg^{-1} (ppm)	10	500	-	ASTM D 5453
Specific gravity	kg.m^{-3} (20 ºC)	844.4	848	790.1	ABNT NBR 7148 ASTM D 4052
Cetane number (min)		48	42	6	ASTM D 6890
Flash point (min)	ºC	38	38		ASTM D 93
Alcohol content (min)	wt%			99.3	ASTM D 4052
Kinematic viscosity	mm².s^{-1} (40 ºC)	2 a 4.5	2 a 5		ABNT NBR 10441

*With 10% of biodiesel.

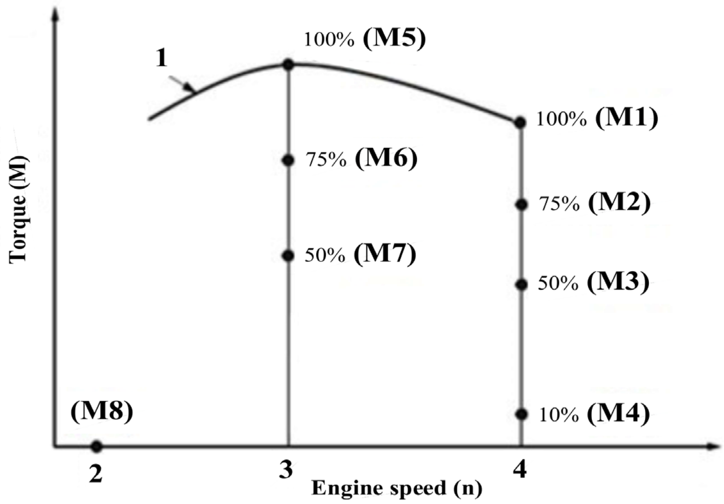

Figure 1 - Torque percentages in relation to the maximum torque and engine speed, to determine the eight operating modes for the emission tests (Adapted from ABNT NBR ISO 8178-4, 2012).

blends containing ethanol. However, when the load was increased, these emissions were seen to decrease because of the heightened combustion temperature, which provided the conditions favorable for the oxidation of these emissions, as well as the reduction in the ignition delay (SHAMUN et al., 2018). At high engine loads, on the other hand, due to increased oxygen content, the levels of CO emission were similar (PARK et al., 2012).

A tendency for the emissions to increase, corresponding to the rise in the ethanol concentrations, was evident for all the loads (modes of operation), for both the BS10 and BS500 fuels. However, at high loads, the BS10 at 15% ethanol concentration and the BS500 at 20% ethanol concentration, revealed CO emissions to equal those of the reference fuels (BS10 and BS500 at 0% ethanol).

It is obvious from figure 2A, revealing the regression curves, that the M4 and M8 alone registered CO emission values beyond the limits of the MAR-1 and Euro V standard values (5 $g.kW^{-1}.h^{-1}$) for BS10 (CONAMA, 2011; IBAMA, 2016). Applying the regression equations (Table 4), made it easy to determine that the M4 had crossed the limit value of the standards at the 15.53% concentration of ethanol, and the M8 at the 7.48% concentration of ethanol.

The BS500 showed similar results, in which the M4 and M8 alone revealed emission values that exceeded the MAR-1 and Euro V standard limit values (Figure 2B). Through the regression equations, it was easy to assess that the M4 had exceeded the limit value of the standards at 13.52% concentration of ethanol, and M8 exhibited similar behavior at 7.32% concentration of ethanol, values that bear close similarity to those of the BS10.

Hydrocarbons (HC)

In general, the HC emissions rise with an increase of ethanol in the Diesel oil blends (LAPUERTA; ARMAS; GARCÍA-CONTRERAS, 2009; PARK; CHA; LEE, 2010; RANDAZZO; SODRÉ, 2011; SHAMUN ET AL., 2018), which may happen under particular conditions, like low and medium loads (PARK et al., 2012; PARK; YOUN; LEE, 2011). In fact, PANG et al., (2006), SHI et al., (2006) and BARABAS et al., (2010) reported lower HC emissions with the addition of ethanol.

Among the fuels tested, the BS10 registered the lowest HC emissions (Table 3). However, such linear behaviors cited in the bibliography regarding the rise or reduction in the HC emissions, with the added ethanol was not evident in the present study. However, for the concentrations of 5, 10 and 20% for the BS10, and 5% and 20% for the BS500, the HC emissions were inclined to be lower; although, for the others they were higher. Inconclusive HC emissions

Table 3 - Results of the average emissions tests.

	Comb.	Ethanol	M1	M2	M3	M4	M5	M6	M7	M8
			-------------------------------Operating modes of the ABNT NBR ISO 8178-4-------------------------							
CO ($g.kW^{-1}.h^{-1}$)	BS10	0%	0.24^{aC2*}	0.17^{aCD2}	0.06^{aD3}	0.62^{bB5}	0.27^{aC23}	0.26^{aC3}	0.29^{aC2}	0.89^{aA5}
	BS500		0.33^{aC2}	0.28^{aCD2}	0.16^{aCD2}	0.95^{aA5}	0.32^{aC2}	0.28^{aCD3}	0.13^{bD4}	0.60^{bB5}
	BS10	5%	0.37^{aC12}	0.39^{bC1}	0.31^{bC2}	2.60^{bA4}	0.43^{bC12}	0.47^{bC2}	0.48^{bC1}	2.39^{bB4}
	BS500		0.47^{aD12}	0.52^{aCD1}	0.47^{aD1}	2.87^{aB4}	0.59^{aCD1}	0.64^{aCD1}	0.67^{aC2}	3.82^{aA4}
	BS10	10%	0.47^{aC1}	0.50^{aC1}	0.43^{bC12}	4.29^{aB2}	0.55^{aC1}	0.60^{aC12}	0.57^{bC1}	8.37^{aA2}
	BS500		0.52^{aD1}	0.59^{aCD1}	0.56^{aCD1}	3.64^{bB3}	0.62^{aCD1}	0.69^{aCD1}	0.73^{aC12}	6.57^{bA3}
	BS10	15%	0.25^{aD2}	0.16^{bD2}	0.46^{bC12}	3.96^{bB3}	0.23^{bD3}	0.22^{bD3}	0.09^{bD3}	5.58^{bA3}
	BS500		0.56^{aE1}	0.65^{aDE1}	0.62^{aDE1}	5.87^{aB2}	0.67^{aDE1}	0.77^{aCD1}	0.85^{aC1}	11.88^{aA2}
	BS10	20%	0.50^{aC1}	0.53^{aC1}	0.48^{aC1}	11.43^{aB1}	0.56^{aC1}	0.65^{aC1}	0.60^{aC1}	15.03^{bA1}
	BS500		0.34^{bCD2}	0.34^{bCD2}	0.24^{bD2}	9.96^{bB1}	0.41^{bCD2}	0.45^{bC2}	0.35^{bCD3}	20.12^{aA1}
HC ($g.kW^{-1}.h^{-1}$)	BS10	0%	0.03^{aB2*}	0.02^{bD2}	0.02^{bC2}	0.06^{bA2}	0.03^{bB2}	0.03^{bB2}	0.02^{bCD2}	0.00^{bE2}
	BS500		0.03^{aF3}	0.04^{aE2}	0.06^{aC3}	0.18^{aA3}	0.05^{aD1}	0.05^{aD1}	0.05^{aD3}	0.15^{aB3}
	BS10	5%	0.00^{bA4}	0.00^{bA4}	0.00^{bA5}	0.00^{bA3}	0.00^{bA4}	0.00^{bA4}	0.00^{bA3}	0.00^{bA2}
	BS500		0.03^{aD3}	0.03^{aD3}	0.03^{aD4}	0.09^{aB5}	0.04^{aC2}	0.04^{aC2}	0.04^{aC4}	0.11^{aA4}
	BS10	10%	0.01^{bA3}	0.01^{bA3}	0.01^{bA3}	0.00^{bB3}	0.01^{bA3}	0.00^{bB4}	0.00^{bB3}	0.00^{bB2}
	BS500		0.04^{aF2}	0.06^{aD1}	0.07^{aC1}	0.20^{aB2}	0.05^{aE1}	0.05^{aE1}	0.06^{aD2}	0.25^{aA2}
	BS10	15%	0.05^{aB1}	0.05^{bB1}	0.05^{bB1}	0.16^{bA1}	0.04^{bC1}	0.04^{bC1}	0.04^{bC1}	0.03^{bD1}
	BS500		0.05^{aF1}	0.05^{aE1}	0.06^{aD2}	0.22^{aB1}	0.05^{aEF1}	0.05^{aEF1}	0.07^{aC1}	0.27^{aA1}
	BS10	20%	0.01^{bA3}	0.01^{bA3}	0.00^{bB4}	0.00^{bB3}	0.01^{bA3}	0.01^{bA3}	0.00^{bB3}	0.00^{bB2}
	BS500		0.03^{aD3}	0.03^{aD3}	0.03^{aD4}	0.14^{aA4}	0.04^{aC2}	0.03^{aD3}	0.03^{aD5}	0.10^{aB5}
NOx ($g.kW^{-1}.h^{-1}$)	BS10	0%	2.70^{aD1*}	2.68^{aD12}	3.40^{aB2}	7.54^{aA4}	2.46^{aE1}	2.35^{aE1}	3.09^{aC12}	7.63^{bA5}
	BS500		2.54^{bD2}	2.50^{bD2}	3.30^{aC2}	7.13^{bB5}	2.27^{bE1}	2.17^{bE1}	2.62^{bD1}	8.27^{aA4}
	BS10	5%	2.79^{aD1}	2.79^{aD12}	3.61^{aB1}	9.46^{aA3}	2.54^{aE1}	2.48^{aE1}	3.10^{aC1}	9.63^{aA4}
	BS500		2.71^{aD1}	2.63^{bD12}	3.44^{bC12}	8.12^{bB4}	2.27^{bE1}	2.22^{bE1}	2.65^{bD1}	9.62^{aA3}
	BS10	10%	2.83^{aE1}	2.83^{aE1}	3.66^{aC1}	10.13^{aB2}	2.57^{aE1}	2.47^{aE1}	2.93^{aE23}	12.10^{aA1}
	BS500		2.69^{bD12}	2.67^{bD1}	3.53^{bC1}	8.54^{bB3}	2.34^{bE1}	2.26^{bE1}	2.70^{bD1}	11.37^{bA1}
	BS10	15%	2.82^{aC1}	2.82^{aC1}	3.68^{aB1}	10.46^{aA1}	2.41^{aD1}	2.38^{aD1}	2.78^{aC3}	10.39^{bA2}
	BS500		2.74^{aD1}	2.69^{bD1}	3.52^{bC1}	10.56^{aB1}	2.35^{aE1}	2.28^{aE1}	2.65^{bD1}	11.06^{aA2}
	BS10	20%	2.73^{aE1}	2.66^{aEF2}	3.54^{aC12}	10.43^{aA1}	2.51^{aFG1}	2.37^{aG1}	3.20^{aD1}	10.04^{bB3}
	BS500		2.67^{aD12}	2.60^{aD12}	3.47^{aC1}	9.80^{bB2}	2.36^{bE1}	2.26^{aE1}	2.72^{bD1}	11.15^{aA2}
HC + NOx ($g.kW^{-1}.h^{-1}$)	BS10	0%	2.73^{aD1*}	2.70^{aD12}	3.43^{aB3}	7.59^{aA5}	2.47^{aE1}	2.38^{aE1}	3.12^{aC1}	7.63^{bA5}
	BS500		2.58^{bD2}	2.55^{bD2}	3.36^{aC2}	7.32^{bB5}	2.32^{bE1}	2.22^{bE1}	2.67^{bD1}	8.41^{aA4}
	BS10	5%	2.79^{aD1}	2.79^{aD12}	3.61^{aB12}	9.46^{aA4}	2.54^{aE1}	2.48^{aE1}	3.10^{aC1}	9.63^{aA4}
	BS500		2.74^{aD12}	2.67^{bD12}	3.48^{bC12}	8.21^{bB4}	2.31^{bE1}	2.26^{bE1}	2.69^{bD1}	9.72^{aA3}
	BS10	10%	2.85^{aD1}	2.84^{aD1}	3.67^{aC12}	10.13^{aB3}	2.58^{aE1}	2.48^{aE1}	2.93^{aD2}	12.10^{aA1}
	BS500		2.73^{aD12}	2.73^{aD1}	3.60^{aC1}	8.74^{bB3}	2.39^{bE1}	2.30^{bE1}	2.75^{bD1}	11.62^{bA1}
	BS10	15%	2.74^{aD1}	2.86^{aD1}	3.73^{aC1}	10.61^{bA1}	2.44^{aE1}	2.41^{aE1}	2.82^{aD2}	10.61^{bB2}
	BS500		2.79^{aD1}	2.74^{bD1}	3.58^{bC1}	10.78^{aB1}	2.40^{aE1}	2.33^{aE1}	2.71^{aD1}	11.32^{aA2}
	BS10	20%	2.75^{aE1}	2.67^{aEF2}	3.54^{aC23}	10.43^{aA2}	2.52^{aFG1}	2.4^{aG1}	3.20^{aD1}	10.04^{bB3}
	BS500		2.70^{aD12}	2.63^{aD12}	3.51^{aC12}	9.94^{bB2}	2.40^{bE1}	2.29^{aE1}	2.75^{bD1}	11.25^{aA2}

*Means followed by the same lowercase letter in the column among the fuels at each level of ethanol concentration; uppercase in the row and number in the column between the ethanol concentrations in the same fuel show no difference by Tukey test at 5% probability ($P<0.05$).

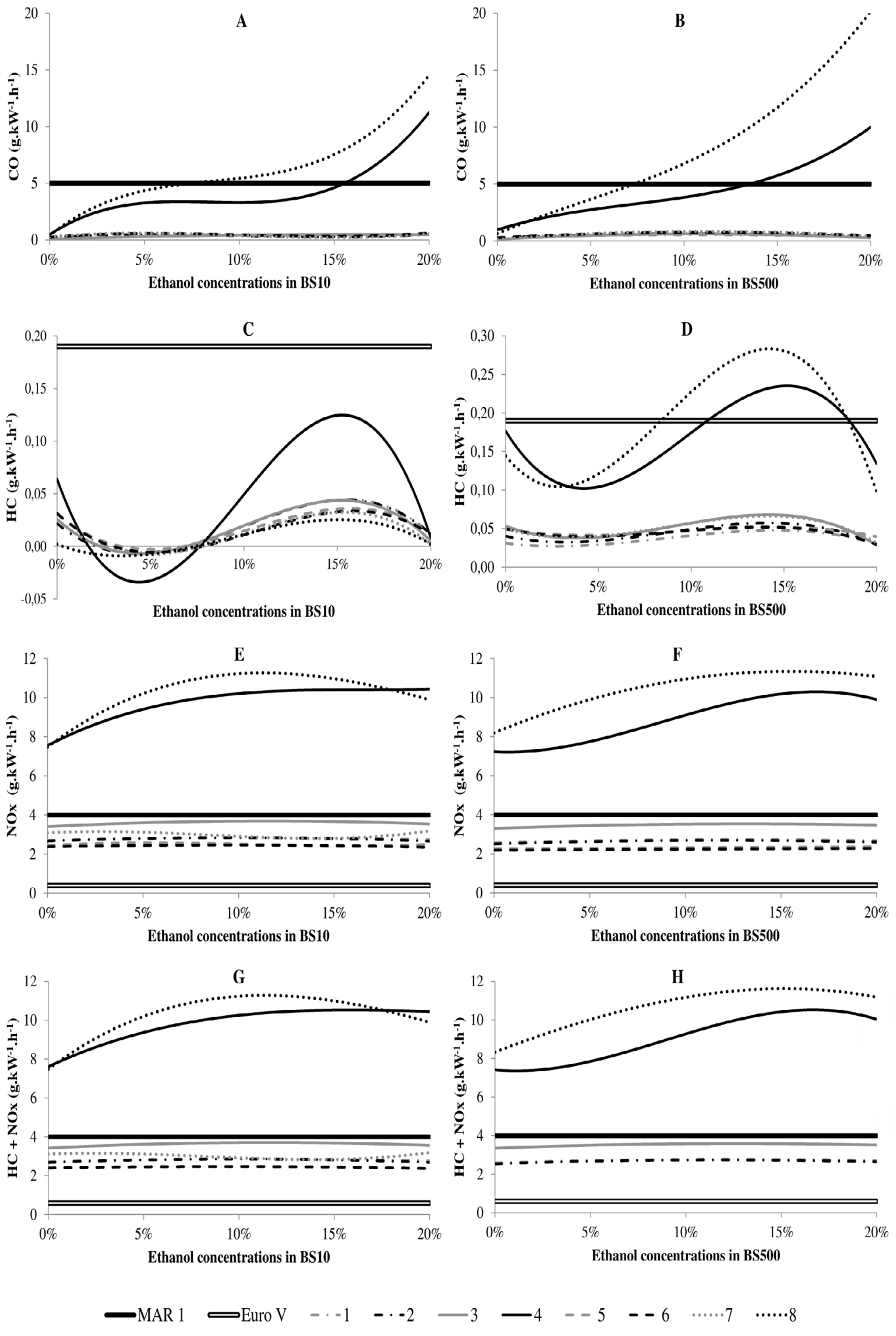

Figure 2 - Representation of the emission regression curves, in comparison with the limit values established by the MAR-1 and EuroV standards.

Table 4 - Emission regression curve equations, with the coefficients of determination (R^2), in the operating modes of the ABNT NBR ISO 8178-4 (M) standard.

	M	Equations BS10	R^2 BS10	Equations BS500	R^2 BS500
CO	1	$y = 332.03x^3-101.99x^2+8.3911x+0.2262$	0.71	$y = -21.005x^2+4.4328x+0.3148$	0.89
	2	$y = 544.75x^3-167.97x^2+13.607x+0.1479$	0.74	$y = -31.623x^2+6.8474x+0.2644$	0.93
	3	$y = -15.484x^2+5.0544x+0.075$	0.99	$y = -40.475x^2+8.6745x+0.1516$	0.94
	4	$y = 5397.4x^3-1362.9x^2+110.75x+0.4554$	0.97	$y = 2008.6x^3-436.51x^2+52.026x+0.983$	0.99
	5	$y = 460.24x^3-140.72x^2+11.198x+0.2493$	0.65	$y = -29.679x^2+6.4182x+0.3244$	0.93
	6	$y = 597.73x^3-181.74x^2+14.378x+0.2327$	0.71	$y = -37.98x^2+8.5045x+0.284$	0.95
	7	$y = 723.21x^3-214.88x^2+15.576x+0.262$	0.67	$y = -58x^2+12.854x+0.1318$	0.94
	8	$y = 5166.4x^3-1345.7x^2+133.18x+0.4052$	0.87	$y = 2.267.85x^3-319.56x^2+70.8x+0.64$	0.99
HC	1	$y = -80x^3+24.286x^2-1.7571x+0.0314$	0.91	$y = -25.357x^3+6.556x^2-0.3014x+0.0311$	0.99
	2	$y = -73.333x^3+21.714x^2-1.4595x+0.0216$	0.88	$y = -38.095x^3+9.9593x^2-0.5252x+0.0404$	0.87
	3	$y = -80.595x^3+23.76x^2-1.6327x+0.0259$	0.89	$y = -54.999x^3+14.847x^2-0.8962x+0.0535$	0.80
	4	$y = -246.67x^3+72.694x^2-4.9507x+0.0639$	0.75	$y = -203.1x^3+59.021x^2-3.8928x+0.1766$	0.87
	5	$y = -63.57x^3+19.76x^2-1.502x+0.0308$	0.96	$y = -20x^3+5.7143x^2-0.3929x+0.0496$	0.89
	6	$y = -64.761x^3+20.479x^2-1.6054x+0.0313$	0.87	$y = -28.572x^3+7.7553x^2-0.5082x+0.0496$	0.95
	7	$y = -69.047x^3+20.918x^2-1.5396x+0.0255$	0.80	$y = -46.547x^3+12.332x^2-0.6964x+0.05$	0.94
	8	$y = -43.809x^3+12.204x^2-0.6884x+0.0019$	0.71	$y = -244.29x^3+62.602x^2-2.9847x+0.1442$	0.96
NOx	1	$y = -11.816x^2+2.534x+2.7007$	0.99	$y = -11.107x^2+2.7825x+2.5603$	0.86
	2	$y = -17.439x^2+3.4613x+2.6689$	0.97	$y = -12.934x^2+3.0671x+2.5069$	0.98
	3	$y = -21.378x^2+4.9376x+3.4051$	0.98	$y = -13.622x^2+3.5773x+3.3013$	0.99
	4	$y = 592.5x^3-298.62x^2+50.471x+7.5534$	0.99	$y = -1471.5x^3+387.64x^2-5.3129x+7.2286$	0.92
	5	$y = 222.74x^3-71.643x^2+5.7449x+2.4378$	0.74	$y = 0.5086x+2.2671$	0.87
	6	$y = -9.9234x^2+1.8543x+2.3737$	0.64	$y = 0.4657x+2.1922$	0.78
	7	$y = 483.45x^3-121.61x^2+5.5199x+3.0859$	0.99	Not significant	
	8	$y = 591.19x^3-430.83x^2+74.584x+7.4828$	0.86	$y = -130.98x^2+40.613x+8.1968$	0.95
HC+NOx	1	$y = -11.561x^2+2.5272x+2.7184$	0.87	$y = -12.138x^2+3.0279x+2.5875$	0.90
	2	$y = -17.286x^2+3.4707x+2.6824$	0.87	$y = -14.464x^2+3.3903x+2.5406$	0.98
	3	$y = -21.423x^2+4.9643x+3.4213$	0.92	$y = -15.173x^2+3.8426x+3.3477$	0.97
	4	$y = 355.71x^3-229.07x^2+45.782x+7.6116$	0.99	$y = -1677x^3+447x^2-9.25x+7.4$	0.93
	5	Not significant		Not significant	
	6	$y = -9.0816x^2+1.6785x+2.3944$	0.83	Not significant	
	7	$y = 423.81x^3-103.19x^2+4.0971x+3.1126$	0.99	Not significant	
	8	$y = 550.24x^3-419.42x^2+73.94x+7.4845$	0.86	$y = -241.79x^3-69.209x^2+37.711x+8.3379$	0.95

were seen for the pure BS500 at high loads, whereas the emission values were intermediate among the ethanol concentrations at medium and low loads.

The Diesel cycle engine operating with the D:B:E mixtures exhibited characteristic emissions which differed, based on the engine load. When the engine ran at low and medium loads, high HC emissions were observed. However, when the engine was at high engine loads, the HC emissions bore close similarity because of the increased oxygen content (PARK et al., 2012; PARK; YOUN; LEE, 2011).

Among the various operating modes, the BS10 showed higher emission levels at medium and high loads (M1, M2, M3, M5 and M6). The BS500, conversely, revealed the most emissions at low and medium loads (M3, M4, M7 and M8), with the lowest emission level occurring at the high loads (M1, M2, M5 and M6), and concurring with the report of PARK, YOUN & LEE (2011) and PARK et al., (2012).

From the findings of SHAMUN et al., (2018) it was evident that the EGR used at lower loads on the engine induced higher HC emissions for the ethanol fuels. These emissions decreased as the load was increased, in response to the higher combustion temperature, which provided conditions favorable for these emissions to easily oxidize, as well as shorten the ignition delay.

None of the values recorded for the BS10, or the regression curve exceeded 0.19 $g.W^{-1}.h^{-1}$, the HC emission limit of the Euro V standard (Figure 2C). The M4 and M8 for the BS500 fuel alone showed HC emissions which exceeded the recommended limit of the Euro V standard (Figure 2D). Employing the regression equations (Table 4), it was clear that the M4 went beyond the Euro V threshold at 10.87% ethanol, and came back to a value that dipped under the threshold, after 18.52% concentration of ethanol. The M8 exceeded the Euro V limit at 8.38% concentration of ethanol, and reverted to a lower value after 18.45% concentration of ethanol. Regarding the MAR-1, none of the fuels registered emissions greater than 4 $g.kW^{-1}.h^{-1}$, which is the sum of the HC + NOx emissions. These results indicated a response of higher HC emissions for fuels containing high sulfur levels, at low loads.

Nitrogen oxides (NOx)

Among fuels, the lowest NOx emissions were recorded for the BS500 at the 0, 5 and 10% concentrations of ethanol (Table 3). For the operating modes, both the BS10 and BS500 exhibited the same behavior, revealing lower emissions at high loads and low speeds (M5 and M6), and high loads and high speeds (M1 and M2). These points normally have the least specific fuel consumption, establishing a relationship in which the more efficient the engine use, the lower the NOx emissions.

The highest NOx emissions were recorded at low loads and high speeds (M3 and M4) as well as at idle speed (M8). These higher emissions are largely due to the delay in the fuel injection time, a crucial factor in NOx formation (GIAKOUMIS, et al., 2013). The low angular speed of the engine, and low combustion temperature generated, caused the injection time factor to exert the greatest impact on the NOx generation.

According to PARK, YOUN & LEE (2011), the engine released emissions having different properties, based on the engine load. When the engine was at low loads, the NOx emissions decreased. However, at high engine loads, very slight differences were observed in the emissions between the blends with ethanol and the reference fuel.

In the present study, among the ethanol concentrations, for the BS10 no differences were noted for the NOx emissions in the M1 (maximum power), M5 and M6 (maximum torque). For the BS500, no differences were evident in the NOx and M5, M6 and M7 emissions. However, in the other operation modes, the results were contrary to those reported by PARK, YOUN & LEE (2011). For the BS10 different behaviors were evident, with the NOx emissions increasing in some cases and decreasing in others. In the case of the BS500, the NOx emission behavior showed an increase, corresponding with the rise in the ethanol concentrations.

For the BS500, the M7 showed no significant difference in the regression analysis (Figure 2F). For both fuels (BS10 and BS500), the M4 and M8 alone revealed NOx emissions which exceeded the recommended limit of the MAR-1 standard, for a total of the HC + NOx, (limit value of 4 $g.kW^{-1}.h^{-1}$) as shown in figure 2E. With respect to the limit value of the Euro V standard (0.4 $g.kW^{-1}.h^{-1}$), which treats the NOx emissions separately, both fuels revealed higher emissions at all operating modes.

H*ydrocarbons plus nitrogen oxides (HC+NOx)*

According to the established MAR-1 standard, the sum of the quantities of the HC and NOx gases is mandatory, so that the values may be compared with the legislation to check if they fall within the limits sector otherwise. In the vast majority of gases, it was evident that NOx appears to be the exclusive constituent, and the most recent standard emission limits, like the European Euro V, have already separated the values, causing greater difficulty in homologating an engine.

As the results showed lower specific HC emissions ($g.kW^{-1}.h^{-1}$), the behavior of the HC+NOx emissions was directly affected by the NOx emissions. Among the fuels, the BS500 revealed the lowest NOx emissions at the concentrations of 0, 5 and 10% of ethanol, for most operating modes (Table 3). Among the operating modes, the BS10 and BS500 exhibited similar behavior, releasing the lowest emissions at high loads (M1, M2, M5 and M6). At these points, the lowest NOx emissions were recorded. The highest HC+NOx emissions were observed at low loads (M4 and M8), with the emissions from medium loads and high engine speeds (M3) ranked after that. For the BS500 the emissions at high loads did not show any statistical difference from the M7 (medium loads and low engine speed).

As in the case of the NOx emissions, for the BS10, among the ethanol concentrations, no difference was evident for BS10 in the HC+NOx emissions at M1 (maximum power), M5 and M6 (maximum torque). For the BS500, no differences were reported in the HC+NOx emissions at M5, M6 and M7. For the BS10, at the other operating modes, different behaviors were exhibited, with the HC+NOx emissions rising in some and reducing in the others. As for the BS500, the HC+NOx emissions were noted to escalate as the ethanol concentrations increased.

From the regression analysis it is obvious that at M5 there is no significant difference in the HC+NOx composition from the BS10 (Figure 2G). Only the M4 and M8 displayed HC+NOx emissions exceeding the recommended limit according to the MAR-1 standard, which has set the value of 4 $g.kW^{-1}.h^{-1}$. With respect to the limit values set by the Euro V standard, which when added together produce 0.59 $g.kW^{-1}.h^{-1}$ (0.19 $g.kW^{-1}.h^{-1}$ for HC + 0.4 $g.kW^{-1}.h^{-1}$ for NOx), all the operating modes of the BS10 gave higher emissions.

From the regression analysis the M5, M6 and M7 revealed no significant difference in the HC+NOx from the BS500 (Figure 2H). The M4 and M8 alone showed HC+NOx emissions which exceeded the MAR-1 standard recommended limit. All the operating modes of the BS500 produced higher emissions than the Euro V standard limit values.

CONCLUSION

Emissions were observed to exceed the recommended limits by the MAR-1 and Euro V standards, particularly in the M4 and M8 modes, when the engine is operated at low loads and low angular speeds. However, because a weighting of these values is used, in keeping with the main standards, an isolated analysis of these operating modes does not negate the approval of an engine.

The CO emissions revealed a rising trend, corresponding to the increase in the ethanol concentrations, in all the loads (operation modes) for both the BS10 and BS500 fuels. The M4 and M8 alone (low load and low speed) showed emissions which exceeded the limit values of the MAR-1 and Euro V standards.

The HC emissions displayed higher emission for those fuels containing high concentrations of sulfur (BS500) at low loads. The BS500 emissions in M4 and M8 modes alone exceeded the limit of the Euro V standard, but all the fuels conformed to the MAR-1 standard.

No differences were noted for the NOx emissions at high loads. The BS10 exhibited different behaviors, in the other modes of operation, at certain times an increase was noted, while at other times the NOx emissions were reduced. The BS500 showed an increase in the NOx emissions corresponding to the rise in the ethanol concentrations. Under conditions of low load and low engine speed (M4 and M8) alone, both fuels registered NOx emissions which exceeded the recommended limit set by the MAR-1 standard, for the total HC + NOx emissions, in relation to the Euro V standard, all the operating modes displayed higher degree of emissions.

As the specific emissions of NOx were higher than the HC (in $g.kW^{-1}.h^{-1}$), the behavior exhibited by HC + NOx bore similarity to that of the NOx. In general, from the analyses conducted in the present and other researches, the effects of the added ethanol varied based on the Diesel oil type used, biodiesel type and concentration, and form of the ethanol employed (anhydrous or hydrated). Further, the technology embedded in the engine and gas treatment systems used also influenced the outcomes. From this perspective, for the purposes of comparison, the results of an engine must be compared only with the results of other engines, which have identical specifications, similar fuel conditions and tests.

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DECLARATION OF CONFLICT OF INTERESTS

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

AUTHORS' CONTRIBUTIONS

All authors contributed equally for the conception and writing of the manuscript.

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