Chapter 9

Study About Nitrogen Oxide Emissions and Fuel Consumption in Diesel Engines Fueled with B20

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Additional information is available at the end of the chapter

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Abstract

The use of biodiesel is one of the alternatives to reduce oil dependence in the transport sector and to reduce greenhouse gas emissions. One of the most common engines in Europe was subjected to some tests, aiming to discover the efficiency effects and the emission characteristics when consuming a fuel containing 20% of biodiesel and 80% of diesel (B20), and comparing the results with the use of 100% diesel (B0). Using an engine test bench, several working points of the engine were chosen considering different engine rotation from idle speed to 3500 rpm and from residual torque to 120 Nm, covering the great majority of the normal running operation of this kind of engines when installed in light vehicles. The results revealed a non-proportional effect for fuel consumption for different engine regimes where the energetic differences were, in some operation regimes, totally compensated with efficiency increase. The NOx emission analysis allows to admit that the use of biodiesel in the fuel leads to a consequence on emissions increase that is not always obvious, since in some regimes that increase is noticeable, but for other regimes a slight decrease or no significant change was detected.

Keywords: biodiesel, alternative fuel, energy, greenhouse gases, sustainability, NOx emissions

1. Introduction

The use of oil as a source of energy was a key factor in the development of industry, economy and world's society. Actually, society is strongly addicted to this energetic source, revealing an enormous inability to free itself from this submission. The world is also subjugated to the incessant desire to consume more energy, becoming increasingly degraded, subordinating all other aspects to be consumed almost exclusively in the control of privileged access to oil.

In 2009, the European Commission unveiled its intentions of promoting the use of renewable energy sources. In the so-called Energy Policy Objectives, this commission defined sustainability criteria for the use of biofuels, making it mandatory for each of the member states of the European Community to define concrete objectives in such a way that, in general, it could be possible, to reach a quota up to 20% of the European Union's final energy consumption from renewable energy sources by the year 2020. In order to achieve this goal, each Member State should promote and encourage energy efficiency and energy savings [1].

In order to reduce energy dependency on oil and CO_2 emissions, some measures have already been taken by the European Community [1] by setting targets for 10% of the energy used in the transport sector by 2020 to be obtained from biofuels. In the European Union, between 2005 and 2010, consumption of biofuels increased from 1.03 to 4.42% of total fuel consumption by the transport sector, but remained below the target set for 2010, with 5.75%. In parallel, there was a reduction in CO_2 emissions from transport of 16.4 megatonnes (Mt) in 2008 and 26.6 Mt in 2009, with a total of 920.74 Mt of CO_2 emissions [2].

The bet on biofuels is increasing and is an obvious alternative to the automotive sector, given the enormous amount of energy used by road vehicles, adding to the difficulty of finding alternative solutions to oil guaranteeing the essential energy mobility for this sector. In fact, the biggest problems in implementing solutions with lower environmental impact reside in the processes of distribution and storage of energy, making it accessible and allowing autonomy and reliability close to the existing solution. The European Community has determined the need to increase the production of commercially viable biofuels which are CO_2-efficient and compatible with combustion engines for motor vehicles [1] and also intends to ensure the development of biofuels from sources other than food sources [3]. From the European point of view, the use of biofuels increases security of energy supply, reduces greenhouse gas emissions and increases the yield and employability of agricultural activity [4].

The most widely used biofuel in Europe is biodiesel, an ester produced from vegetable or animal oils, through a transesterification process. This renewable energy source accounted for 82% of total biofuels produced in Europe (27 members) in 2003 [4] and in 2007 a share of 84.7% of all biofuels consumed [5]. The European Union is the largest producer and consumer of biodiesel, with a production of 9164 million liters of biodiesel in 2008, about half of the world's biodiesel production [6]. The world average of biodiesel production in the years 2013–2015 was 31.1 billion liters, and it is expected to reach 37.9 billion liters by 2020 [7]. The consumption of vegetable oils to produce biodiesel has been increasing in the World, mainly due to its renewable nature and to the fact that it is less polluting when compared to petroleum-based diesel. Biodiesel is a renewable fuel which can alternatively be used in internal combustion engines of compression ignition, without having to make any changes, substituting part or all of the fuel of fossil origin. The efficient use of biodiesel in the transport sector brings some important environmental, economic and social benefits, resulting in job creation, reduction of pollutant emissions, reduction of the country's dependence on petroleum and reduction of CO_2 emissions levels for the transport sector. The International Energy Agency believes that in 2050 it will be possible for biofuels to account for 27% of the total amount of fuels in the

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transport sector, which would reduce CO_2 emissions per year by 2.1 gigatonnes (Gt) if a sustainable system was considered [8].

Considering the use of biodiesel, savings in terms of CO_2 emissions can range from 36 to 83% when compared to conventional diesel [9]. However, for this fuel to be economically profitable, it will be necessary to use subsidies to balance the difference in the price of production and to account for the savings effects per tonne of CO_2 not emitted.

2. Literature review

Given the lower amount of available energy per unit mass of biodiesel compared to diesel, to provide the same amount of energy required by the engine, it would be expected an increase in fuel consumption when biodiesel was used. However, biodiesel affects engine combustion and the consequent emissions [10] existing several conditions that contribute to this behavior. These conditions are higher density of biodiesel, because fuel supply control is made on a volume basis; the existence of oxygen in biodiesel that can affect the thermal yield and other properties such as viscosity; the cetane number among others that affects how the fuel mixes in the heated air inside the cylinder and influences the way energy is released. It is still necessary to consider the cumulative effect of these parameters with the different interactions promoted by the use of diverse blends of biodiesel in diesel.

Analyzing what is reported by various researchers, there is often an association between increased fuel consumption caused by the lower calorific value of biodiesel [11]. In concrete terms, the heat-based calorific value of biodiesel is 10–14% lower than that of diesel [12] [13]. In this way, it will be expected that the mass consumption of fuel will increase in the same proportion. However, as already mentioned, the fuel supply to the engine is made on a volumetric basis, so given the density differences, where biodiesel is denser between 3 and 4% [13], it would be expected that specific fuel consumption (g/kWh) would increase by 10–14% and the volume (l/km) should increase by 5–10%. In the case of using a B20 blend, with 20% biodiesel and 80% of fossil diesel, it means that the difference in terms of amount of energy in that blend only implies a reduction of 2–3%.

Graboski and McCormick [14] explicitly state that regardless of whether the consumption of biodiesel is pure or mixed with diesel, a proportional fuel economy is revealed in the difference between the calorific value and there is no improvement or degradation of energy efficiency. In fact, the question is whether the use of biodiesel will promote an increase in energy efficiency. Deviations in this efficiency relative to diesel can be justified when considering other properties such as viscosity and density that promote changes in the type and shape of the spray and which affect the way the fuel is mixed in the air [15, 16] or when assessing the impact of the existence of oxygen on the molecular structure with biodiesel that modifies the way how combustion reaction is performed [15, 17–22]. It is explicitly referred by Demirbas [22] that despite the lower calorific value of biodiesel the oxygen content in this fuel promotes more complete combustion due to improved homogeneity in the local fuel mixture in the air.

Most of the authors report that the consumption of biodiesel in substitution of diesel fuel induces an increase in NOx emissions [11]. As possible causes for the variation in NOx emissions due to the use of biodiesel, pointed out by Graboski and McCormick [14], are the increase of the flame temperature and the decrease of the radiate effect that promotes the increase of the temperature in the combustion chamber, since the heat transfer by radiation is carried out by particles. Since biodiesel has reduced particle emissions, it decreases this ability to radiate heat, resulting in higher temperatures and consequently higher NOx emissions. In fact, the increase in the in-cylinder temperature is the most relevant parameter that causes an increase in NOx emissions [23].

The engine regime and the way how fuel flow interacts in the injection process for each regime shows to some significant differences with respect to the energy efficiency of the combustion process for the different fuels [24–33]. It is expressed by several authors that the use of 20% biodiesel in a mixture with 80% of fossil diesel (B20) corresponds to the optimum mixture where the maximum value of thermal efficiency is revealed and logically a minimum value of specific consumption is expected [11–13, 31, 33]. The study performed by Suresh et al. revealed that the engine presents different heat release rate behaviors with partial load and full load for diesel when compared with B10, B20 and B30, where B20 presents the most significant results [34]. Also the goals imposed by the European Union point out that in the near future the amount of biodiesel incorporated in the commercial diesel is close to 20%. This lead to the analysis that was done in the present work considering the realization of tests with a B20 blend covering all the operation regime of the engine, finding how this fuel affects engine in terms of energetic efficiency and in terms of NOx emissions, that is the most controversial emission for diesel engines, after the introduction of diesel particles filters (DPF).

3. Experimental methodology

Tests were completed using an engine test bench, equipped with a Schenk hydraulic dynamometer with a capacity to test engines up to 230 kW at a maximum engine rotation of 13,000 rpm and a torque limit of 600 Nm. It also has an AVL gravimetric fuel consumption measurement system and a Horiba gas analyzer. The schematic of the experimental setup is represented in **Figure 1**.

A data acquisition system collects the engine data, the equipment measurements (fuel consumption, exhaust emissions, temperature and pressure sensors). The acquisition system is integrated with a control system that defines the parameters specified by the test cycle imposed, without the intervention of the technician, which allows a better accuracy and reliability of the obtained results [20].

The engine used for these tests was a VW 1.9 TDI with four cylinders in line and 1896cm^3, developing a maximum power of 66 kW, with EuroII exhaust emission technology. This engine equipped a large part of the VW group of vehicles with great success, such as the VW Passat, VW Golf, Audi A3, A4 and Seat Ibiza. The main characteristics of the engine are presented in **Table 1**, including that it is a direct injection supercharged engine with EGR. This engine is known to have high reliability, allowing having a maximum torque a relative low engine rotation (202 Nm at 1900 rpm).

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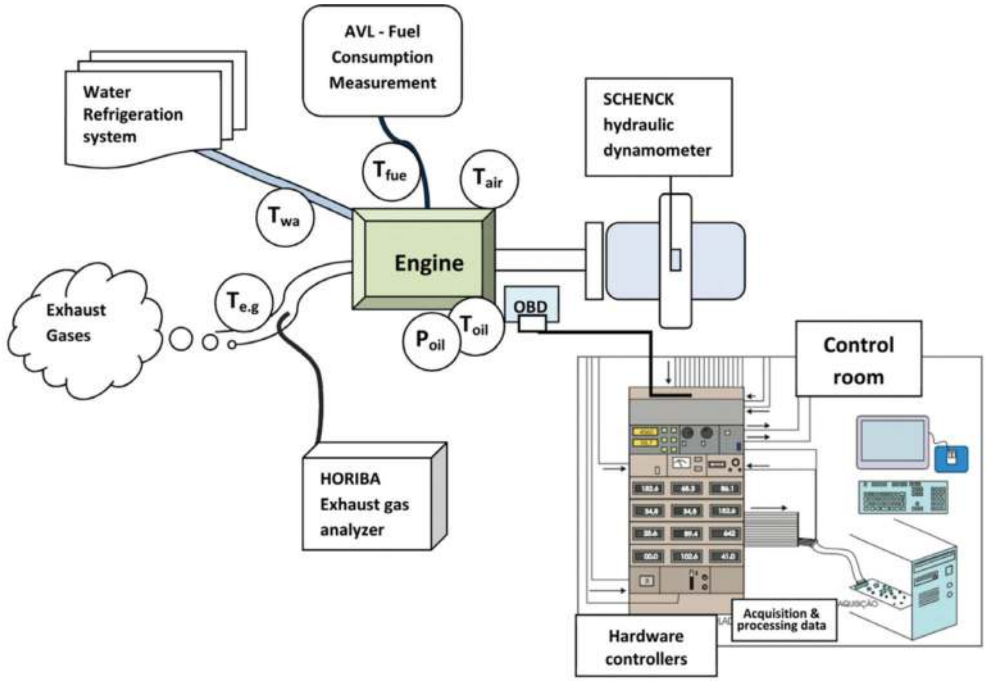

Figure 1. Engine test bench.

Tests were made using two different biodiesel blends (B0 and B20). The properties of the fuels, biodiesel and commercial diesel, are presented in **Table 2**. B0 is fully constituted by a petroleum-based fuel, and the B20 was made by mixing this base fuel with biodiesel constituting a blend in proportion 80 diesel – 20 biodiesel. This B20 blend was selected considering that the amount of petroleum diesel incorporated in diesel is of 5–7%, so it seems important to better characterize the expected blends in the next few years, considering that the use of 20% biodiesel will be a highly plausible scenario.

Since all engines are produced assuming that they will consume petroleum diesel fuel, it is important to define a specific methodology for this kind of studies, including the way how different fuels affect engine efficiency and performance. It is expected that the use of biodiesel, with different properties that interact differently with injection system and combustion process, will certainly produce effects on emissions and consumption [10]. Furthermore, there is a certain inadequacy of the regulated cycles for engine homologation to reflect the proper effects of changing from petroleum diesel to biodiesel in a certain proportion.

In the first evaluations of the engine's operation, it was verified that there were some problems that conditioned the test's performance. The original idea was to carry out a detailed analysis of the entire motor parameter map. In this way, a series of tests were carried out in stabilized regimes to obtain the consumption and emissions of exhaust gases relative to the engine

Engine	VW 1.9 TDI
Engine code	1Z/AHU
Type	4 cylinders in line, 8 valv.
Swapped volume	1896 cm^3
Compression ratio	19.5:1
Ignition system	Rotate pump with direct injection electronic controlled
Supercharged	Yes, with intercooler
Exhaust emissions technology	Yes (Euro II)
Power máx.	66 kW (89cv) @ 4000 rpm
Torque máx.	202 Nm @ 1900 rpm

Table 1. Main characteristics of the engine used in the bench tests.

Parameter/Unit	Biodiesel (BD) (Soybean 86.5% + Palm 13.5%)		Fossil diesel (FD)
	Results	Method	Results
Density at 15°C (kg/m^3)	**882**	EN ISO 3675	**840**
Ester Content [% (m/m)]	**97.7**	EN ISO 14103	—
Kinematic Viscosity at 40°C [mm^2/s]	**4.15**	EN ISO 3104	**2.43**
Flash Point (°C)	**>120**	EN ISO 3679	**>55**
Water Content (mg/kg)	**216.8**	EN ISO 12937	—
Iodine Value (g iodine/100 g)	**117**	EN ISO 14111	—
Sulfated ash content [% (m/m)]	**<0.02**	ASTM D 874	—
Cetane number	**51**	EN ISO 5165	**>51**
Higher heating value (HHV) [kJ/kg]	**39,909**	ASTM D 240	**45,620**
Oxidation stability, 110°C (hours)	**6.3**	EN 14112	—

Table 2. Biodiesel and fossil diesel properties.

operation from idle to 4000 rpm in successive increments of 500 rpm, and from 0% load up to 80% load, in increments of 20%.

However, it was found that in certain schemes engine operation became quite unstable due to several occurrences: the opening and closing of the exhaust gas recirculation "EGR" valve; the functioning of the turbocharger and the waste gate valve which adjusts its operating pressure, and the excessive heating of the engine in higher load conditions. Thus, after a few attempts to establish a procedure that would allow reliable data to be obtained and at the same time guarantee the operability and reliability of the engine without damaging it, a 30-point table was chosen, shown in **Figure 2**. This distribution covers the major part of the engine operating regime when in normal operation to drive a light vehicle.

The sequence of the tests was as follows: after ensuring the stabilized normal operating conditions of the engine on the test bench, the speed of rotation is set at 1250 rpm, with the brake torque at its minimum value, corresponding to the residual torque which is the sum of the energy losses due to friction and to the inertia that must be overcome in order to keep the engine at the desired speed.

After reaching a stable operation, reading and acquiring the information about the performance of the motor at this operating point, the torque value is increased to 40 Nm, for the same rotation, waiting for the stabilization of the operation of the various parameters to make the data acquisition. This process is repeated in successive steps for various values of resistant torque until reaching the value of 120 Nm. At this point and after data collection, the rotation is increased to 2000 rpm. Following the stabilization at this rotation value, the cycle already performed is repeated, but successively decreasing the torque value by 20 Nm, with the corresponding lowering of the throttle position.

The process is repeated by maintaining the descending torque sequence until the throttle reaches the minimum position. When this operating point is properly characterized, the whole process will be repeated with the increase of rotation to 2500 rpm, followed by the addition in terms of torque to the value 120 Nm, doing the same in the downward direction, with successive increments of 500 rpm, repeating this sequence until the rotation reaches 3500 rpm. In the most demanding conditions, such as rotations above 3000 and 3500 rpm with torque

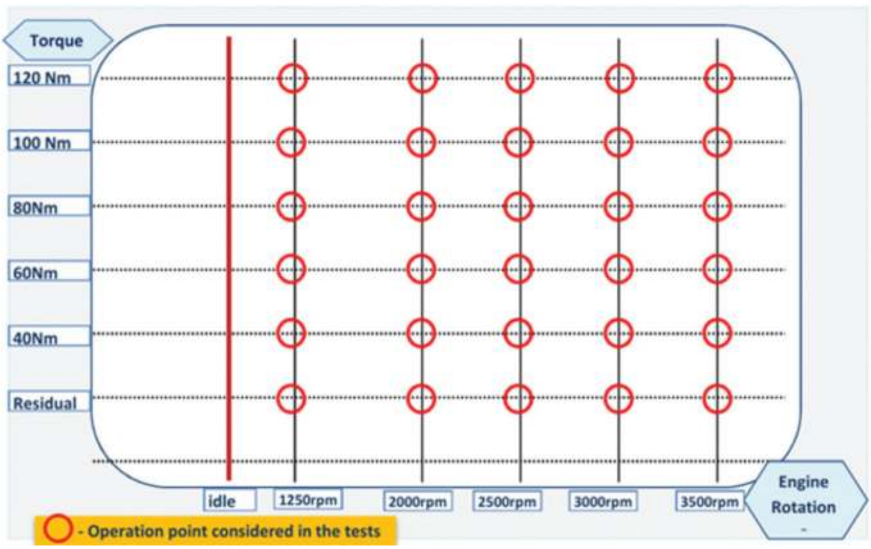

Figure 2. Operation points chosen for the tests.

values above 80 Nm, it was found necessary to interrupt the sequential process to allow engine cooling. Thus, when the engine oil temperature was no longer stable, the cycle was interrupted so that some of the accumulated energy could be dissipated and the established process could continue.

4. Results

Each of the cycles defined in the methodology was repeated two times, according to a certain sequence that would allow analyzing possible degradations in the operation and in the performance of the motor. As such, two measurements were performed with B0, followed by three measurements with B20 and a new measurement with B0. The results obtained are the average of the three measurements whenever they do not differ by more than the standard deviation of the three measurements made. When this happens, the value that shows higher deviations from the average value is not considered, resulting in the final value considered from the average of the two values that meet the defined criteria.

Of all the information collected a large part served as a way of controlling the process in order to guarantee the comparability of the results and to verify the occurrence of some situations, as was verified for the control of the exhaust gas circulation and the turbocharger, for example.

The data presented are related to the two most relevant aspects of this work, fuel consumption and NOx emissions, which are more controversial about how the use of biodiesel affects the engine. The emissions of CO and HC are not the most problematic emissions for this type of motor and, considering the low resolution of the equipment in the measurement of CO, it was decided to devote more attention to the emissions of NOx, having not considered the emissions of CO and HC, although the data on these combustion products were collected.

4.1. Fuel consumption

The results presented relate to the consumption on a mass basis, through the result of the specific consumption (g/kWh), taking into account that the measurement was carried out according to a gravimetric process to avoid problems with fuel density. Considering the importance of the efficiency process in the evaluation of the engines, the results in terms of energy conversion efficiency (ECE) are also presented, using the different energy values available in each of the fuels. This will allow evaluating the way how the engine can avail this energy at useful power from different available energy levels.

The energy conversion efficiency (ECE) is a very useful concept to compare different fuels since it allows having quantification about the way how the available energy in the fuel can be converted into work. This parameter can be determined with the mathematic expression (1) where: “sfc” (g/kWh) is the specific fuel consumption obtained through the gravimetric measurement of the fuel consumed in each operation point divided by the developed engine power at that same point; “PCS” is the higher heating value (HHV) of the fuel that characterizes the amount of energy that fuel releases in an ideal combustion and that can be obtained in an laboratorial experience.

$$ECE = \frac{1}{\frac{sfc}{3600*1000}*HHV}*100 \quad (1)$$

The graphical presentation of the results is based on the representation of the consumption values measured with the two types of fuel in the narrow bars, read on the vertical axis on the left and correspondent representation of the relative difference in the wide bars read on the vertical axis on the right. The value of the relative difference is calculated with reference to the case of consumption for B0. Thus, if the bar is above the red dashed line it translates into an increase of consumption, efficiency or emissions for biodiesel; if, on the other hand, the bar is below the red line it represents a decrease of the parameters in question.

The analysis of the results obtained with this engine reveals that the mass fuel consumption shown graphically in **Figure 3a** and **b** does not exhibit a behavior proportional to the introduction of biodiesel and the corresponding slight decrease in energy associated with the use of this type of fuel. It is apparent that in certain regimes, usually associated with high torque values, specific consumption increases when using B20; however, the variations are very slight for torque values of 40 and 60 Nm. In this situation there is some variation in terms of specific fuel consumption, with a slight increase for low rotation (1250 rpm), as opposed to the slight reduction corresponding to 2000 rpm, with an increase of more than 5% to 40 Nm at 2500 rpm and a reduction of about 5% to 60 Nm. An abnormally high amount of consumption occurs at 3000 rpm with residual torque when using B20, however, given that this situation is quite unlikely to occur under normal vehicle use and that the engine has a somewhat unstable behavior at this rate, because of the rather oscillating operation of the turbocharger, a more in-depth study of this situation was not considered relevant.

Overall, it cannot be stated in full that the use of biodiesel in a blend containing 20% biodiesel and 80% diesel results in a direct increase in specific fuel consumption, but there is a tendency for that increase to occur when the engine is subjected to high torque demanding situations in high revs (3000 and 3500 rpm) and very low rotation (1250 rpm).

If the evaluation of the results obtained account for the higher fuel density promoted by the incorporation of biodiesel, comparing the consumptions on a volumetric basis, it is possible to emphasize what was already pointed out in the mass analysis, that is, only in the situation of torque of 40 Nm at 2500 rpm and 60 Nm at 1250 rpm there is an increase in consumption, except for cases of higher torque (100 and 120 Nm). It may even be considered that in volumetric terms, the use of B20 promotes very few changes in the total fuel consumption. In the most normal conditions of engine operation when under normal road conditions, which correspond to low torque values and low and medium engine rotation, it may be possible to observe an overall slight reduction in volumetric fuel consumption.

The analysis of the energy conversion efficiency (ECE) results, shown in **Figure 4**, accentuates what has already been verified in the evaluation of consumption results, that is, for loads up to 80 Nm there is a similar efficiency of conversion of the existing energy in the B20 relative to the

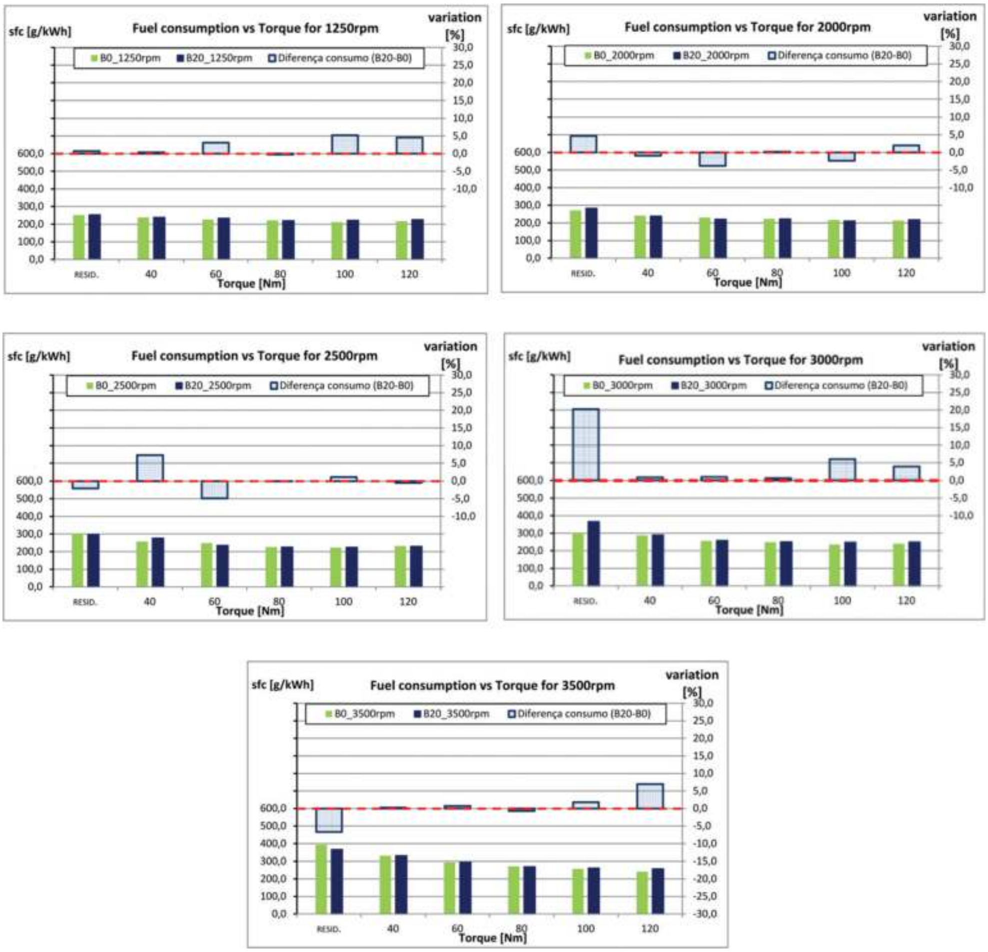

Figure 3. Results for specific fuel consumption (g/kWh) with B0 and B20.

B0. Although only slight, it is an aspect that needs to be analyzed in detail in order to enhance this energy gain. Considering that the maximum torque for this engine is obtained with 1900 rpm, it is interesting to observe that the results for 2000 rpm with biodiesel reveal an overall increase of ECE for all load conditions evaluated.

As indicated above, somewhat different values occur in terms of magnitude in cases of high rotation (3000 and 3500 rpm) under residual torque conditions, where the minimum required effort is to overcome the mechanical losses. In these circumstances which are very rare to occur in actual circulation, the engine exhibits an unstable behavior, in which the turbocharger exhibits some sudden deviations and the consumption is relatively low, allowing that small variations, due to the behavior of the engine in terms of control, become most noticeably in global terms.

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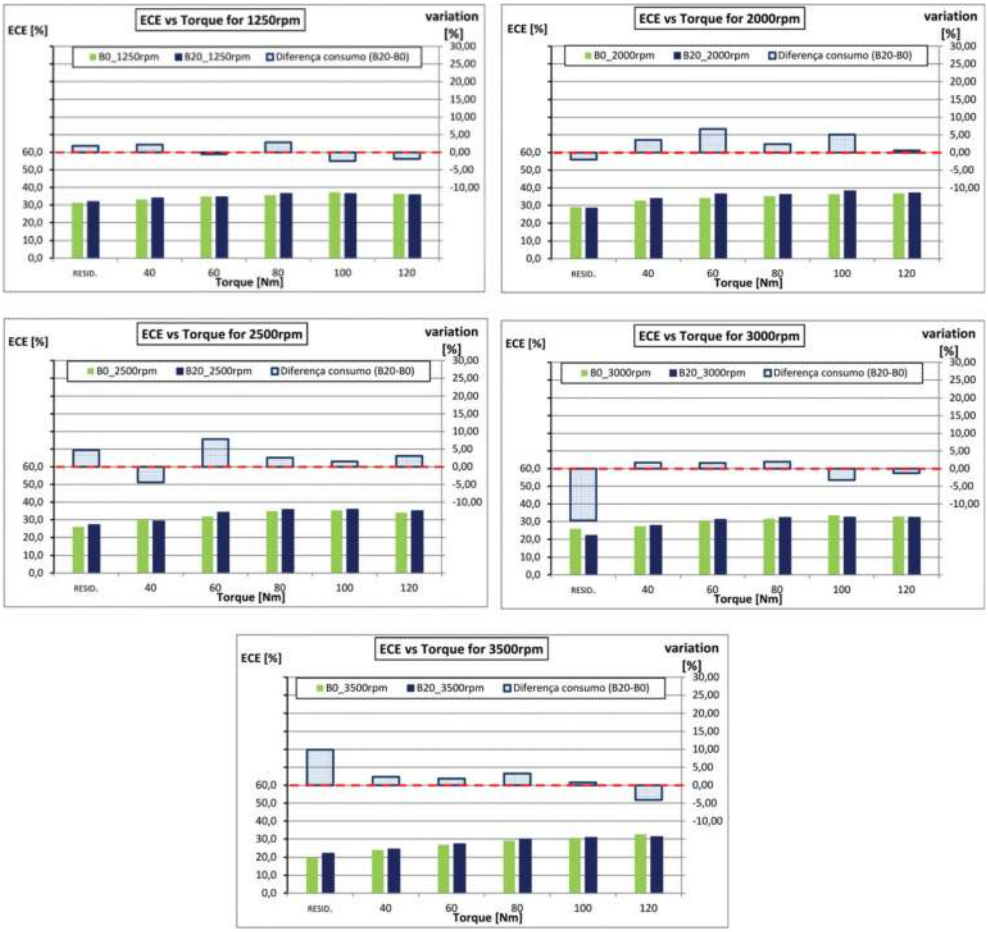

Figure 4. Results for energetic conversion efficiency (ECE) (%) with B0 and B20.

In the remaining points analyzed and considering the normal operating conditions of the engine, when installed in a vehicle subject to actual driving on the road, it can be stated that there are serious indications of the possibility of slight increases in engine efficiency when supplied with B20 compared to the consumption of B0, mainly when low and medium operating regimes are required, corresponding to the urban and extra-urban circuit operation. In a more demanding operating regime, such as high-slope or high-speed road traffic, where the required engine operation is supported at higher torque values, the use of B0 indicates a slight advantage over the B20 in energetic terms.

Analysis of fuel or energy consumption results reinforces the need to evaluate the behavior of the vehicle in real road situations so that it will become possible to see how this behavior will affect fuel consumption. An assessment can be made of these results and try to fit the type of behavior expected on the road for a light vehicle and realize the perspectives for overall results of consumption. In this way, it is possible to verify that the specific mass consumption presents small oscillations that were already expected, given the little significant difference in calorific value of the two evaluated fuels (B0 and B20). However, the differences became more significant only in the relative circumstances of higher rotation and high load, which may correspond to the typical high-speed freeway circulation, which implies a high engine speed and also high loads since the aerodynamic drag force becomes very relevant. For the other situations, corresponding to urban and extra-urban traffic, characterized by low and medium speeds and low and medium loads, the differences in consumption are minor, revealing a tendency to small decrease in fuel consumption when fueling the engine with B20, especially if a consumption analysis is made on a volumetric basis.

4.2. NOx emissions

As mentioned above, the study on the impact on NOx emissions by the use of B20 compared to the use of B0 was established. The results below are the reflection of this study allowing evaluating the influence that the B20 consumption has on the NOx emissions when compared to the consumption of diesel, for the various selected engine operating regimes. In order to make the analyzed results more comparable, the value of the NOx volumetric percentage present in the exhaust gas was divided by the power obtained corresponding to each selected engine operating point, and the results of **Figure 5** in (ppm/kWh) corresponding to specific NOx emissions.

The analysis of the specific NOx emission results presented in the graphs of **Figure 5** reveals an interesting behavior and probably explains what has been the major focus of controversy regarding the use of biodiesel.

In fact, depending on the engine operating regime, there is typically an increase or a decrease in NOx emissions due to the use of biodiesel. The analysis of the graphs related to the representation of the NOx emission results allows to conclude that: when the engine operates at low RPM and high RPM, the use of biodiesel leads to a decrease in emissions; however, for average engine rotation regime (2000 and 2500 rpm), the use of B20 conducts into an increase in specific NOx emissions. It appears that there is not a discernible direct relation between the load and the differences in NOx emissions related to the two fuels considered, except in the case of the tests carried out at 2500 rpm where, as the load increases, there is an increase in NOx emissions caused by the use of B20.

The relative effect of NOx emissions may be associated with increased energy conversion efficiency, which will enhance an increase in the combustion temperature responsible for the eventual formation of NOx compounds via the thermal process (Zeldovich formation process). Nevertheless, the increase in energy conversion efficiency is not the only responsible for the fluctuations in NOx emissions.

In fact, the presence of oxygen in the fuel allows the combustion process to be carried out differently from the two fuels, creating a different evolution of the heat release to take place, which could enhance or reduce NOx formation. These differences are surely also justified by the formation of the fuel spray, driven by the different properties introduced with biodiesel and the different levels of saturation of the molecules that constitute it.

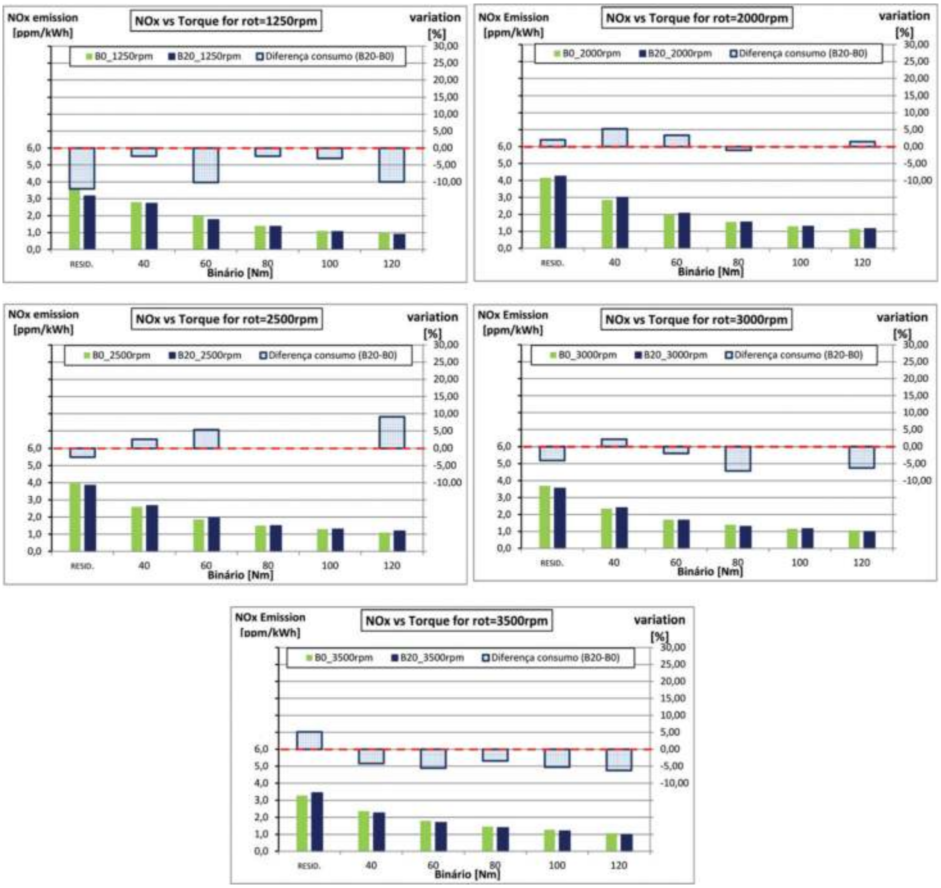

Figure 5. Results for specific NOx emission [ppm/kWh] with B0 and B20.

What is clear from the present study is that it is not possible to directly express an increase or decrease in NOx emissions caused by the use of biodiesel, without it being possible to characterize the way in which the vehicle equipped with a given engine operates under normal operating conditions. However, variations in NOx are not significant either in terms of increase or decrease and, given that the results were obtained without the exhaust gas passing through any treatment system, it can be concluded that any negative connotation on the use of biodiesel associated with NOx emissions, considering that the small variations in the use of B20, whether positive or negative, are always below 10% and will therefore be practically canceled out by the use of an efficient exhaust treatment system.

The present work on NOx emissions allows clarifying the existing doubts on this subject with the existence of disparate results from different studies, evaluating the behavior of the engines at a given rotation or a given torque. In reality, only through a study like the one carried out in the present study, considering a large number of points of operation, it is possible to draw a real range of results that allow to cross with the typical characterization of an engine when installed in a vehicle, leading to authentic values of NOx emissions emitted by that engine into the atmosphere when fueled by biodiesel or other fuel.

Comparing the results obtained with those of other researchers it is clear that only in similar situations, where a very wide set of engine operating points was considered, it was possible to register positive and negative oscillations in NOx emission values due to the use of [15, 35, 36]. Most of the works report an increase in NOx emissions, but it also becomes obvious that this situation reflects the testing in a narrow range of the normally operating engine.

As indicated by Yanowitz and McCormick [37] when averaging NOx emissions, masks the complex variability that occurs with the emission of these substances when using biodiesel in the engines, it is also important to remember what is reported by Hribernik and Kegl [38] confirming that the influence of biodiesel on combustion and emissions in an engine cannot be generalized, since they are engine-specific parameters. In fact, the engine type, circuit typology and driving mode completely change the way the engine operates when fueled with fuels containing biodiesel in different proportions. The different fuels offer different properties, namely in the presence of oxygen, density and viscosity, volatility, energy content and degree of saturation, being these factors responsible for the occurrence of different behaviors in the process of fuel injection. It is also important to note that the results obtained with single-cylinder engines, light-duty engines and engines of heavy vehicles lead to different conclusions, so it is necessary that the analyzes should also be different. This complexity is confirmed by the analysis performed on the results obtained by the present work, which helps to understand that the conclusions obtained by the work of other researchers in this area are, once again, emphasizing the need to evaluate the behavior of vehicles in circulation on the road, complementing those results with those obtained in the laboratory tests.

5. Conclusions

The energy dependence of the transport sector is evident, being effectively minimized by the use of biodiesel. It may be argued that this energetic option will only be transitional and that in the near future some other solution will emerge with other potentialities, given that despite the decrease of greenhouse gas emissions impacts, this decrease is not as relevant as desired. However, in the current circumstances, this is effectively a real solution and already with some evidence given, arising with the ability to replace part of the diesel fuel consumed in the world.

The present work is a concrete evaluation of the effects that the use of biodiesel in substitution of diesel would bring in terms of fuel consumption and greenhouse gas emissions. It can be concluded that there is no significant impact due to the use of biodiesel, especially when considering the use of incorporations of up to 20% biodiesel in diesel. Contrary to what is stated in several publications, it is not absolutely clear that the use of biodiesel, because it has lower energy content per liter of fuel, translates this characteristic directly into an increase in consumption. There is a reason to believe that in certain situations there is an increase in energy efficiency, and it is possible that, even with the use of a fuel with less energy results

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greater energy availability. It is also clear, through the results obtained, that due to the behavior of engines when subjected to different types of requirement, corresponding to different types of route, a distinct evaluation in terms of consumption and NOx emissions occurs when the engine is supplied with a mixture of biodiesel in diesel.

It should be noted that currently engines are designed to use diesel, not considering the use of biodiesel at the outset. A step has already been taken by the European Union to ensure the mandatory incorporation of biodiesel into diesel and to ensure that the biodiesel used effectively corresponds to a reduction in greenhouse gas emissions. By guaranteeing the use of a sustained form of production of this energy source, it will also be important that the development of engines corresponds to the preferential use of a given amount of biodiesel incorporated in the diesel fuel, so that it can derive the maximum yield.

Still, in relation to the obtaining results, as already recognized by the European community itself, it is not enough to have characterized a certain cycle of tests for approval of engines and use it in characterizing the behavior of these engines when fueled by fuels from different sources. It will be necessary to integrate the use of in-service vehicle tests under real traffic, road and environmental conditions, allowing for a more faithful and less standardized characterization in order to provide a more adequate response to the actual conditions in which the vehicles will be used.

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