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Effects of the use of 100% Biodiesel (B100) obtained from used vegetable oils on the consumption, emissions, and performance of vehicles and equipment.

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Abstract:

The transportation sector is one that has had more hurdle conversion to renewable energy sources. The purpose of this research is to determine whether a renewable source of energy like 100% biodiesel (B100) could be used in the vehicles and equipment of a fleet that supports an air force squadron instead of conventional diesel fuel. To accomplish this, a selection of vehicles and machinery was examined for three months while the working procedure remained as usual, and then introduce a change in the fuel type, using biodiesel considering the same monitoring process during a similar period. This made it possible to compare any modifications that might have been made to fuel consumption, performance, emissions, maintenance, and reliability. The findings demonstrated that, with an average increase of less than 5%, using biodiesel does not result in a noticeable rise in fuel consumption. Additionally, there is a slight decline in the power that is available from the engine, however at less severe levels than anticipated. Depending on the engine, and the operation mode, there are a variety of emission-related scenarios, but overall, NOx and CO_2 emissions were reduced. Additionally, it was confirmed that there were no important concerns with the operation of the machinery or vehicles; the only issue of notice was the requirement to anticipate the replacement of a few fuel filters.

Keywords:

Biodiesel; Internal Combustion Engines; Vehicles; Energy; Sustainability.

1. Introduction

Biofuels, such as biodiesel, contribute very little to the accumulation of greenhouse gas emissions. Biodiesel is a versatile fuel that may be combined with diesel in 7% (B7) mixes, like the mixture provided in 2022 in all fuel stations in Portugal, and potentially in 20% or even 100% blends, known as B20 and B100 respectively.

The conversion of biomass feedstocks into biofuels is a low-impact process. The usage of biofuels as transportation fuels can help to reduce atmospheric CO_2 by using this renewable fuel instead of diesel in different ways: it prevents the some of the emissions associated with diesel engines, it allows the CO_2 content of fossil fuels to remain stored and give a mechanism for absorbing CO_2 through the growth of fresh biomass for fuels.

Biofuels are the most advantageous solution for decreasing greenhouse gases from the transportation sector since they are compatible with the natural carbon cycle and can be used in vehicles actual technology. Increased use of biomass would hasten the deposition of fossil fuels and reduce greenhouse gas emissions in transport sector.

1.1. Research question

The use of biodiesel in actual vehicles is a possibility and some authors present that has a real path to reduce greenhouse gas emissions and the fossil fuel transport sector dependence.

The real-world exhaust emissions and fuel consumption of on-road diesel vehicles was an issue that deserves a particular attention. Two light-duty diesel trucks and two heavy-duty diesel trucks were fuelled by waste cooking oil biodiesel blends, considering four mixed fuels with blend ratios of 0% (neat diesel), 5% (B5), 20% (B20), and 100% (B100) (biodiesel in traditional fossil diesel). The results show that the total fuel consumption (biodiesel + traditional fossil diesel) did not clearly decrease, but blending biodiesel into traditional fossil diesel

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could clearly decreased the consumption of traditional fossil diesel, reduce the countries' dependence on oil imports. The CO, HC, and PM emissions for all of the tested vehicles decreased with increasing biodiesel content in the blend, and the NO_X emissions also showed a decrease with increasing biodiesel content in the blend, not for all, but for most vehicles in this study [1].

Other research [2] examined several biofuels blends on a 2019 performance diesel EURO VI heavy-duty truck, with the objective of preparing a fuel consumption measurement and a performance analysis, an experimental procedure was developed based on the homologation cycles and processes of heavy-duty truck on a chassis bench roll, testing the following samples: B7, B15, B100 and a HVO15.

The powertrain performance results reveal that the fuel which presented higher power values was the HVO15, followed by B7, B15 and B100. With B100, the maximum power output decreases 4,5%, compared to B7. On fuel consumption, the smaller results were obtained for B7 and B15, without reasonable differences, followed by B100 and then HVO15. With B100, the fuel consumption increases 9%, compared to B7. To evaluate the fuel economy performance of neat biodiesel compared to fossil diesel on a real road use, three buses on their daily utilization were analysed. In this experiment, the biodiesel buses had an increase on fuel consumption about 4,5%.

1.2. Objective of the work

The use of biodiesel has been analyzed in different laboratory studies, with different levels of incorporation of biodiesel in commercial diesel, either using engine test bench or using chassis dynamometers. There are also some works that consider the use of biodiesel blends in vehicles in road use, analysing the effects that blending small amounts such as 15, 20, or 30% biodiesel have on the use of these vehicles.

This study attempted to employ a more severe change, such as switching from commercial diesel to a wholly renewable fuel, i.e., 100% biodiesel, in a wide range of vehicles and equipment in real-world use, over an extended length of time. This allows to understand what changes occur as a result of this fuel change in conditions as close to reality as possible, allowing to effectively evaluate the environmental impacts, energy, and performance of using this fuel in vehicles, as well as analyse the potential effects on the reliability and maintenance of these vehicles.

2. Experimental Methodology

As mentioned earlier, the study was divided into three types of tests: fuel consumption, emissions, and bench testing. Therefore, this chapter will be subdivided into each of the tests performed. However, firstly, we will discuss some important properties of diesel fuel for this study.

2.1. Fuel Properties

The fuels considered in this study are quite similar, however they have significant differences that could explain some discrepancies in engine and fuel injection system behaviour. A quick description of the engine's most influential characteristics is presented.

Density relates the mass of the fuel to the volume it occupies. Therefore, the higher the density, the greater the mass in the same volume, and consequently, the greater the energy. Thus, since fuel is quantified by volume, higher density results in greater fuel economy. Biodiesel has a density between 873 and 883 kg/m^3, while petroleum diesel has a density between 820-845 kg/m^3. These values are for a temperature of 15°C [3,4].

Viscosity is a measure of a fluid's resistance to flow. If the viscosity is high, the injection cone decreases and concentrates on a narrower and more concentrated jet, resulting in poor atomization. Poor atomization leads to poor engine performance. Additionally, the greater resistance to fluid movement creates greater difficulty in operating the fuel pump. According to the European standard EN14214:2008, diesel viscosity at 40°C must be between 3.5 and 5 mm^2/s. The viscosity of biodiesel is approximately 4 to 5 mm^2/s under the same conditions. In very cold temperatures, the increased viscosity can compromise proper fuel circulation, resulting in starting and initial engine operation problems [3].

Calorific Value is defined as the amount of energy available per unit mass, during the combustion process in which the reactants are at 25°C and the products cool to the same 25°C. Generally, two values are defined as "higher" and "lower", HHV and LHV, depending on the physical state of water in the products, liquid or vapor, respectively. In the context of internal combustion engines, LHV is usually used. The Lower Heating Value (LHV) of diesel has a range of values that varies between 42.9 and 43.3 MJ/kg. The calorific value of diesel is about 10 to 14% higher than that of biodiesel [5].

Cetane Number Indicates the ease with which the fuel enters in self-ignition. The higher this value, the easier and faster the fuel will ignite when injected. This characteristic is critical in compression ignition engines, as it is essential that the fuel quickly self-ignite after injection. In the previously mentioned standard (EN14214:2008), a minimum value of 51 is defined for the cetane number. The cetane number of biodiesel depends on the base raw material used to form the fuel, however, a large percentage of them remain above this mentioned limit [1].

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The equivalent amount of oxygen content present in the fuel is one of the most altered characteristics of the mineral and renewable fuels. In petroleum-based fuel, this content is zero, whereas in biofuel, it can have a value between 10 and 12% oxygen [6].

Oxidative stability is closely related to the Iodine value, as it reflects the tendency of a fuel to react with other substances. Therefore, oxidation stability decreases with an increase in the Iodine value. The value of this parameter varies depending on the composition and storage of the fuel. Biodiesel, due to its chemical unsaturation, becomes more susceptible to deterioration, which can have various implications such as an increase in fuel viscosity and acidity, the development of contaminations, and the formation of insoluble products, which can damage the engine or compromise its performance [7].

The Cold Filter Plugging Point (CFPP) indicates the minimum temperature at which significant crystal formation does not occur, in other words, the minimum temperature at which the fuel is liquid enough to be filterable under certain conditions. As previously mentioned, this property complements the pour point and cloud point.

To determine the CFPP value, a certain volume of fuel is subjected to a rapid and constant cooling process and, by vacuum action, forced to pass through a filter. The value is fixed at the minimum temperature that allows this filtration within a stipulated time interval. Naturally, all these parameters and equipment are standardized to develop a universal test and enable comparison between fuels. The required CFPP values vary depending on the climatic conditions of the country or region where the fuel operates.

Biodiesel shows a significantly higher tendency than diesel to form crystals at low temperatures, acquiring higher CFPP values. This can be problematic in colder climates, as previously mentioned, since the presence of crystals in the fuel causes clogging of filters, the injection system, and consequently affects the performance of the engine. The solution may be to include additives in the fuel that counteract this tendency or reduce the percentage of biodiesel in the fuel blend [7].

In summary, Table 1 presents the characteristics of the two fuels considered in this work and it reveals a comparison between biodiesel and petroleum diesel for the previously mentioned parameters, indicating the typical changes introduced by B100 relative to B7.

Table 1. Indicative comparison of fuel B100 relative to B7.

Proprieties	**B7**	**B100**	Comparison with petroleum diesel (B7)
Density (kg/m^3, at 15ºC)	843,3	881,7	↑
Viscosity (mm^2/s, at 40ºC)	3*	4,6*	↓
Calorific Value (MJ/kg)	42,62*	37,21*	↓
Cetane Number	52,5*	56,2*	↑
Oxygen content (%)	0	10-12	↑
CFPP (ºC)	-15	-1	↓

2.2. Fuel consumption test

To carry out this type of test, initially, equipment and vehicles were selected for study, with the primary objective of avoiding any situation that could compromise the normal operation of the fleet.

Analysing the series of vehicles under study, it is visible that there is a great variety of typologies, from light to heavy-vehicles, both for goods and passengers, and even tanker trucks. The great variety previously mentioned is also noticeable in the engine displacement of the engines under study, where the smallest has a total displacement of 1868 cm^3, and the largest has a total displacement of 12760 cm^3. All are diesel cycle, and operate at 4 strokes, varying between 4, 6 and 8 cylinders. These characteristics can be seen as an advantage in carrying out this study. However, the vehicles do not have the most current injection and exhaust gas treatment systems, since the newest vehicle has 18 years old, and the oldest has 42 years old. In summary, the influence of ZeroDiesel was analysed in 14 vehicles.

Analysing the series of equipment used in the study, it is evident that there is a wide range of typologies with engines ranging in displacement from 916 cm^3 to 9050 cm^3. All of them are Diesel cycle, operate in 4-stroke, varying between 3, 4, and 6 cylinders, with both in-line and V configurations, except for one equipment that operates in 2-stroke. These characteristics can be seen as an asset in conducting this study. The influence of the use of ZeroDiesel was analysed in 8 pieces of equipment.

After the selection of vehicles and equipment, there was a period of monitoring the kilometres and litters of commercial diesel fuel (B7) consumed by the vehicles and monitoring the corresponding operating hours of the equipment with the litters of diesel fuel consumed. The monitoring was scheduled to start on January 31,

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2022, and end on March 21, 2022, however, this period was extended until April 28. After this period, the same monitoring occurred but with ZeroDiesel (B100). It began after the end of B7 use and extended until August 8. The counting of hours or kilometres travelled, and fuel consumed was considered for both periods allowing to have the comparative information of

2.3. Emissions testing

The main objective of this type of test is to evaluate the influence of fuel types (B7 and B100) on pollutant and CO_2 emissions. For this purpose, two representative vehicles and two ground support equipment were selected from the analysed fleet. The operating regimes were also representative of the normal operation of each vehicle and equipment, with tests performed with the engine cold (immediately after starting) and at normal operating temperature. However, no load was imposed on the engine during the vehicle tests, deviating from normal operation.

The measurement of emitted gases was carried out with the TESTO brand equipment, model 350 XL. The analyser unit includes several gas sensors, allowing for the measurement of the concentration of CO, CO_2, NO, NO_2, SO_2, H_2S, or C_XH_Y, among others. The range extension allows measurements to be made without restrictions, even when there are high gas concentrations. To protect the sensor technology, the range extension (dilution) is automatically activated when unexpectedly high gas concentrations are detected. Of all the substances that can be measured, the acquisition of data on the concentration values of O_2, CO, NO_X, CO_2, C_XH_Y, and also the lambda factor and the temperature of the exhaust gases was considered most important. The last two parameters were only used to ensure that the regimes considered with B7 and B100 were identical. The lambda value and hydrocarbon emissions could not be considered for the study because the measuring equipment had an anomaly that prevented the presentation of these parameters. Two sets of data were collected: one when the vehicles and equipment had been operating for more than a month with B7 and another when they had been operating for more than a month with B100.

2.4. Power and Consumption Test – WLTP

The main objective of these tests is to accurately evaluate the fuel consumption and performance of a vehicle using B7 and B100. Both tests are carried out on a roller dynamometer. For the power test, three tests are performed to obtain data from both the dynamometer and the vehicle via OBD. Afterwards, an arithmetic mean is calculated for the acquired torque and power values, provided there are no incongruent values. The present study aims to perform a comparative analysis of the engine performance results when using B7 and B100 fuel.

The dynamometer used in this study is the MAHA LPS 3000, a brake-type roller test bench based on the principle of eddy currents. This equipment enables testing of various situations, such as instant maximum power, power at pre-defined rotation speeds, and simulation of loads (constant traction, constant speed, etc.). Furthermore, it is possible to measure vehicles with 2 or 4-wheel drive, with a maximum permissible power per axle of 257 kW and 522 kW respectively, for a maximum speed of 260 km/h.

To evaluate the power of the vehicle, it is accelerated to maximum rotation speed, covering the range of engine rotation speeds in a controlled manner by the dynamometer (roller bench). This control is continuously performed throughout the engine's rotation range (continuous test). Alternatively, it can be performed discretely at pre-defined rotation points, which are established to allow for a more effective comparison between different tests (discrete test).

To obtain the desired results (engine power and torque), the dynamometer measures the power at the wheel, to which the power losses in the transmission (resistive power) obtained in the deceleration process are added. After obtaining these two parameters, the value of the engine power is obtained, which is already corrected based on environmental conditions, assuming the designation of "Norm power". Through this power value, dividing by the corresponding rotation, the value of the engine torque is obtained. The correction selected is according to the standard also used by the manufacturer when announcing the engine characteristics. In this study, continuous and discrete performance tests were performed.

In the case of fuel consumption evaluation, the test performed follows the standardized WLTP cycle, considering its use on a roller bench. For this test, a series of sensors are added to monitor the vehicle's fuel consumption, such as a flow meter (to obtain volume flow) and a scale, to obtain mass flow. The cycle is divided into 4 phases, one called "low" with an average speed of 18.9 km/h, a medium with an average speed of 39.8 km/h, a high with an average speed of 56 km/h, and an extra-high with an average speed of 92.9 km/h, with a total cycle duration of approximately 30 minutes. Data acquisition was performed at a frequency of 5 Hz. To ensure data synchronization, data processing was based on the definition of the initial point of the test, for which the average fuel mass present on the scale was considered over a period of 2 seconds, 5 seconds before the vehicle's movement began. Similarly, the transition point between each stage was the average of the mass measured on the scale for a period of 2 seconds, 5 seconds after the cessation of the vehicle's wheel movement.

As previously mentioned for the power test, in each WLTP cycle, 3 tests are performed, and the arithmetic mean of the results obtained in these tests is then considered. Similarly, to the previous procedure, a comparative analysis was intended to be carried out regarding the use of the two fuels in the same vehicle, so the entire procedure was repeated considering a first test in which the vehicle was fuelled with B7 fuel, and then a second test was performed fuelling the vehicle with B100 fuel. The vehicle chosen for the study was a passenger car of the Citroën Berlingo make/model equipped with a direct injection engine with a displacement of 1900 cm^3.

3. Results and Discussion

Similarly, to the presentation of the experimental procedure, this chapter of results discussion will be divided into 3 subheadings, one for each test previously mentioned.

3.1. Fuel consumption test

To obtain the average fuel consumption values, the averaging of consumption for each refuelling was considered, assuming that all kilometres travelled (or hours of operation) were performed with the corresponding fuel of that refuelling. This assumption is not entirely valid, however, the fluctuations in the obtained averages are compensated by the multiple refuelling's existing in each equipment or vehicle, since the final average was considered as the average of each refuelling. In a careful analysis of the averages of each refuelling, if they presented values that were very discrepant from expected, they would not be considered for analysis. Therefore, the average consumption was calculated for each fuel and the percentage difference between them. The results obtained are presented in Table 2 for equipment and in Table 3 for vehicles. The same results are also presented in the following Figure 1 and Figure 2 for fuel consumption and percentage difference for equipment and vehicles, respectively.

Table 2. Indicative comparison of fuel B100 relative to B7.

Equipment	B7 Fuel consumption (l/h)	B100 Fuel consumption (l/h)	Difference
EE01	4,62	4,28	-7,25%
EE03	1,18	0,98	-16,95%

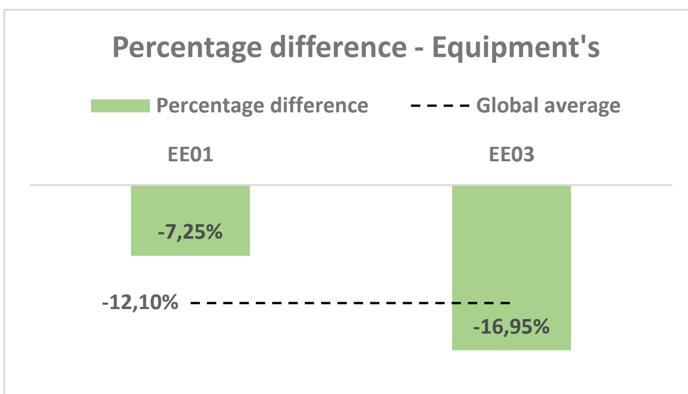

Figure. 1. Difference percentage in fuel consumption of the equipment.

Initially, it is noticeable that results for all vehicles and equipment under study are not presented. This is due to the lack of refuelling data for a particular type of fuel under study. It should be noted that for equipment EE01, there is no certainty in the results presented since only data from one refuelling for both fuels was available. Similarly, for vehicles AM05 and AMV12, the average consumption presented for fuel B7 is based on only one refuelling.

From the analysis of the results obtained, it is not possible to prove an increase or a decrease in fuel consumption when using biodiesel. For example, there is an increase in consumption of vehicle AMV03 in the order of 15% (corresponding to 1L/100km) and a decrease in consumption of vehicle AMV13 of about 13% (corresponding to 2L/100km). This difference in consumption can be justified, not due to differences in the chemical properties of the fuel but rather due to uncertainties in the obtained data, since there are several variables not controlled, such as different routes and drivers, which lead to different consumption rates, which is normal and corresponds to the operation of these vehicles even when fuelled with the same fuel. Additionally, since the consumption of vehicles is based on the distance travelled, it is not possible to determine whether they were stationary, consuming fuel without covering any distance. This aspect is particularly critical, for

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example, in tanker trucks, where the pumps that transfer the fuel are operated by the vehicle's engine. Therefore, it is not possible to directly correlate an increase in fuel consumption when using B100, in the order of magnitude of the difference in calorific value between this and B7, as would be expected. Overall, in vehicles, the use of biodiesel increased consumption by 1.36%, while in equipment, there was an average decrease of 12.10%.

Table 3. Fuel consumption for each vehicle for both studied fuels and their respective percentage difference.

Vehicle	B7 Fuel consumption (l/h)	B100 Fuel consumption (l/h)	Difference
AM01	4,94	5,30	7,24%
AM02	7,37	8,04	9,10%
AM03	6,33	7,27	14,91%
AM04	8,31	7,84	-5,69%
AM05	10,89	10,64	-2,28%
AM06	10,27	10,94	6,54%
AM07	13,37	12,59	-5,78%
AM08	8,74	8,98	2,77%
AM09	75,62	80,48	6,42%
AM10	83,41	86,07	3,19%
AM11	17,65	17,64	-0,02%
AM12	10,90	10,24	-6,08%
AM13	17,41	15,20	-12,69%

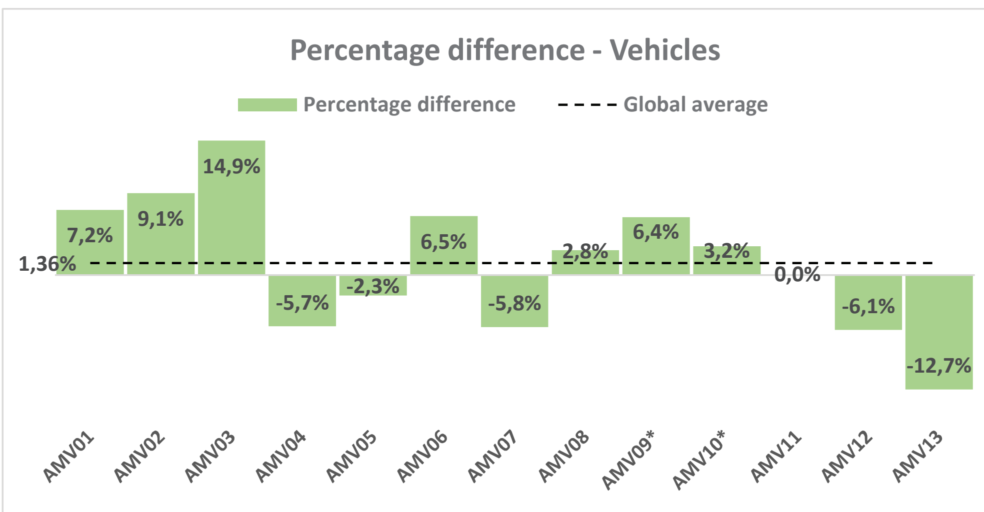

Figure. 2. Percentage difference in fuel consumption per vehicle.

3.2. Emissions testing

Analysing now the results obtained for emissions, Table 4 and Table 5 present respectively the vehicles and equipment results, with the representative operating conditions of their normal operation, the percentage differences in emissions between B100 and B7 with the overall average by chemical substance. It should be noted that, in the equipment, all tests were carried out considering their normal operating temperature.

The cases where the value presented is negative, for example, it indicates that after using B100 fuel, there was a decrease in the emission of the chemical substance being analysed, like it is clearer in the figure 3.

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Table 4. Percentage difference in vehicle emissions.

Vehicle	Engine speed	O_2	CO	NO_x	CO_2
AM09	Hot Idle	0,24%	42,29%	-10,48%	-2,91%
AM09	1300 RPM (Hot)	0,79%	14,91%	-8,21%	-7,94%
AM09	1800 RPM (Hot)	0,79%	3,55%	-5,88%	-6,12%
AM11	Cold Idle	1,53%	59,81%	-63,32%	-7,28%
AM11	Hot Idle	-0,13%	201,02%	-49,03%	1,00%
AM11	2000 RPM (Hot)	-1,09%	12,70%	-28,33%	6,79%
AM11	3000 RPM (Hot)	-2,86%	1,36%	-16,16%	14,01%
Global Average		-0,06%	32,86%	-34,81%	0,37%

Table 5. Percentage difference in equipment's emissions.

Equipment	Engine speed	O_2	CO	NO_x	CO_2
EE03	Idle	-0,27%	51,68%	-4,06%	1,20%
EE03	Under Load	-1,12%	36,16%	0,67%	3,16%
EE04	Idle	-0,16%	-16,22%	7,49%	0,71%
EE04	1700 RPM	-0,88%	0,00%	12,03%	1,65%
EE04	2400 RPM	-3,77%	22,41%	1,27%	6,06%
Global Average		-1,12%	26,57%	5,78%	3,01%

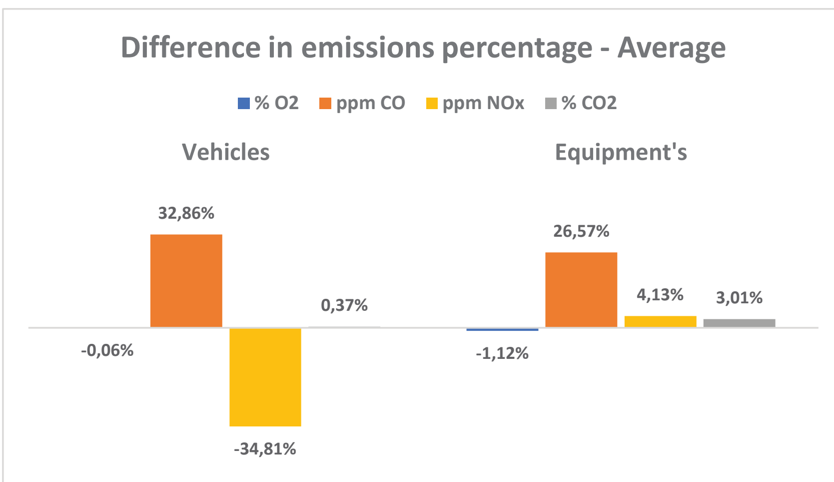

Figure. 3. Differences in global average, for both fuels, by chemical species.

3.2.1. Oxygen (O_2)

The changes obtained in oxygen (O_2) emissions were insignificant, demonstrated by the difference in the global average of -0.06% in vehicles and -1.12% in equipment, so it was considered an unchanged parameter when using biodiesel. The differences presented may be related to inaccuracies in the measurement device, meteorological differences, among others. When using B100, an increase in the emission of this compound derived from the higher percentage of O_2 present in the fuel would be expected, however, this was not observed.

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3.2.2. Carbon monoxide (CO)

An increase in carbon monoxide (CO) emissions was observed in all regimes studied, except for one measurement at idle for the EE04 equipment, which is visible by analysing the difference in the global average, both for vehicles and equipment. The increase in the emission of this substance was more significant at idle with a warm engine, since it is mainly formed in rich mixing zones. Therefore, the increase in its concentration when using B100 can be explained by the higher viscosity of this fuel, which hinders atomization and subsequent combustion. This greater difficulty in atomization is more prevalent at idle due to the lower injection pressure associated with this regime. Although the values presented have a very significant percentage increase (on the order of 200%, for example), the emission of CO in diesel engines is not noticeable, as they always operate on lean mixtures, since the concentration values of this substance are quite low. Therefore, it is natural and expected that the percentage differences present more significant values.

3.2.3. Nitrogen oxides (NO_X)

Overall, there was a decrease in nitrogen oxides (NO_X) in all regimes, except for equipment EE04, where the emission of these substances increased. This is visible by analysing the difference in the global average in vehicles, which decreased by 34.81%, contrary to what happened in the equipment (which increased by 5.78%), solely provided by the aforementioned equipment. An explanation for the decrease in the emission of this substance, given that in the case of vehicles the tests were performed without load, is the lower temperature reached when the vehicle operates with biodiesel due to the lower calorific value of this fuel. Therefore, since temperature is the most important factor in NO_X emissions, a decrease in this chemical substance would be expected. In situations where the engine was tested under load, there may be greater emissions of this substance due to the greater amount of oxygen in the combustion, derived from the biodiesel itself. It should be noted that if the vehicles or equipment had gas treatment systems, the emission of this compound would be more controlled.

3.2.4. Carbon dioxide (CO_2)

It is not possible to correlate the presence of CO_2 emissions with the use of biodiesel in all equipment and vehicles. While there was a decrease in emissions for AMV09, the emission of this substance either slightly increased or stabilized in the other machines. CO_2 emissions are directly related to fuel consumption. As it was not unequivocally found that there was an increase in fuel consumption, only slight fluctuations in the emission of this compound would be expected for the various vehicles and equipment. Overall, there was a very slight increase in carbon dioxide emissions with the use of biodiesel, at 0.37% for vehicles and 3.01% for equipment.

3.3. Power and Consumption Test – WLTP

The power tests obtained are represented in the following Figure 4, where the power and torque developed as a function of rotation speed are visible for the two fuels under study.

The percentage difference between the values obtained for power is presented also in the same Figure 4. In this case, when the value presented is positive, it translates to a higher power obtained when the vehicle was operating with B100 compared to when it was operating with B7.

From the analysis of both graphs, it is visible that the differences obtained between the use of B7 and B100 are minimal. A decrease in power, in the order of magnitude of the difference in the calorific value of the fuel, i.e. 10%, could be expected, which could be attenuated by the greater volumetric mass of the fuel. However, this was not the case, and there was even an improvement in the delivered power at high speeds, after 4000 RPM. A slight decrease in the developed power occurred at low and medium speeds, which was less noticeable between 1500 and 2500 RPM. The increase in power at high rotation speeds would not be expected and may be related to some measurement problem, fundamentally in the final part of the test where the transition from measuring the power at the wheel to measuring the transmission losses occurs. The average numerical results for maximum power and torque are presented in the following Table 6. Therefore, the following percentage differences are obtained, visible in the same Table 6. If the presented value is negative, for example, it indicates that there was a decrease in this parameter after the use of B100 fuel.

Analysing the numerical results, it is visible that, contrary to expectations, an increase in the engine's delivered power occurs when using biodiesel. This may be related to some intervention that the vehicle has undergone or the alteration of any mechanical component that affects the maximum power delivered by the engine, mainly in high speed. A decrease of approximately 10%, corresponding to the difference in the calorific value of the fuels, would be expected when using biodiesel. On the other hand, the maximum torque obtained when using B100 decreased and was reached earlier.
Examining the results corresponding to the WLTP test, Table 7 presents the values of the average fuel mass flows obtained for each speed profile for each of the analysed fuels and also the results considering the percentage difference.

From the analysis of the results, it is possible to observe an increase in the average fuel mass flow for B100 in all speed profiles considered from 1% to 5%. This difference has a greater impact in the low-speed profile, decreasing with increasing speed, with a slight increase in the high-speed profile. The increase in fuel consumption can be explained by the lower calorific value present in biodiesel. However, since the result is shown on a mass basis, it makes sense to also analyse consumption on a volumetric basis, as is typically considered in vehicle usage. The average fuel consumption obtained, considering a typical volumetric mass for B7 of 839.8 kg/m³ and for B100 of 881.7 kg/m³, is visible in Table 8 and graphically in Figure 5.

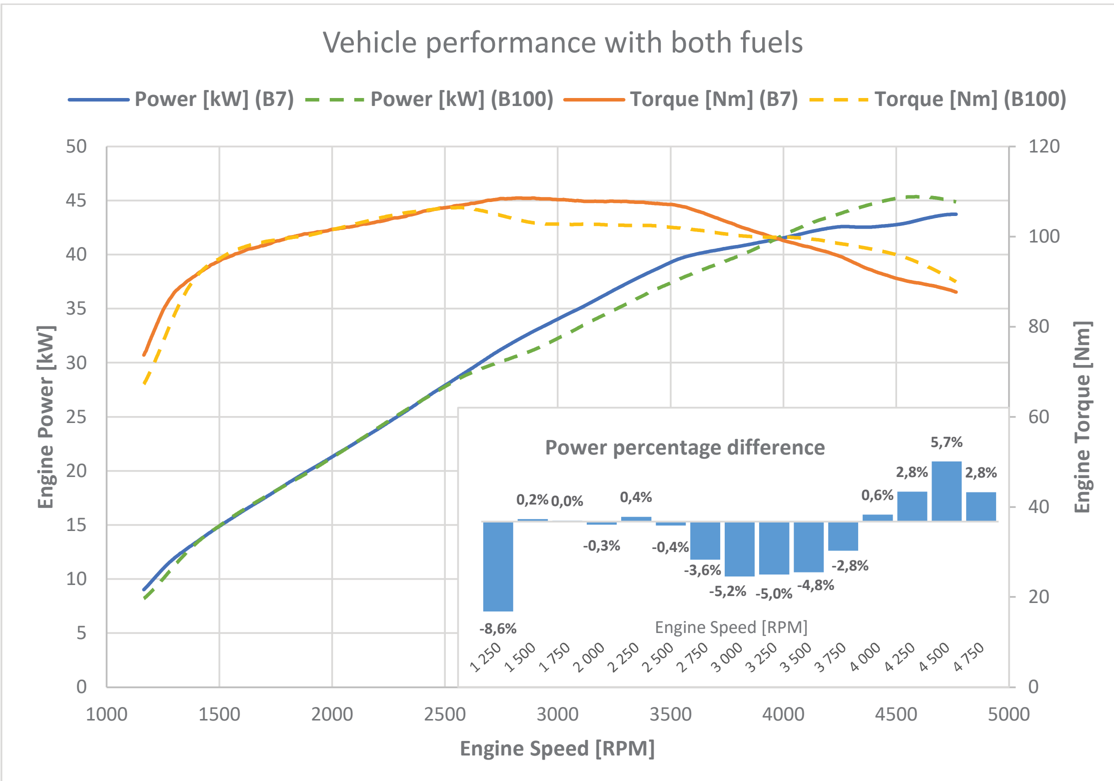

Figure. 4. Power and torque chart, and power percentual difference obtained between both fuels.

Table 6. Percentage difference and Maximum power and torque obtained.

Parameter	B7	B100	Unit	Percentage difference [%]
Standard power	43,8	45,4	kW	3,8
Engine power	44	45,2	kW	2,7
Wheel power	29,8	33,2	kW	12,6
Resistive power	14,1	11,6	kW	-18,2
@	4760	4590	rpm	-3,5
Standard torque	108,7	106,5	Nm	-2,0
@	2870	2600	rpm	-10,6

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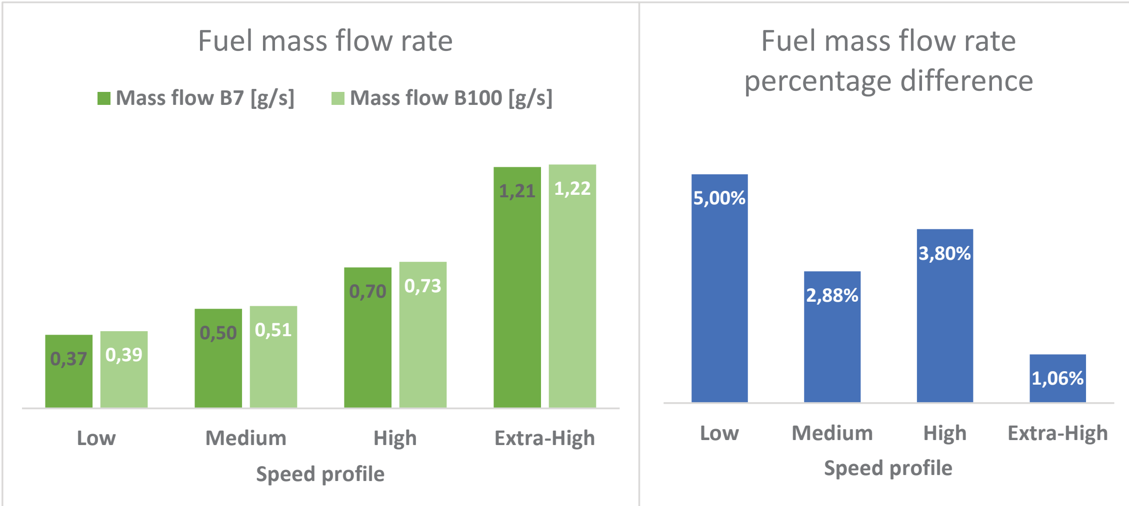

Figure. 5. Mass flow rates of fuel and percentual differences obtained in the WLTP test, for B7 and B100.

Table 7. Mass flows and percentage differences obtained in the WLTP test, for B7 and B100.

Speed profile	Mass flow B7 [g/s]	Mass flow B100 [g/s]	Percentage difference
Low	0,367	0,386	5,00%
Medium	0,497	0,511	2,88%
High	0,705	0,732	3,80%
Extra-High	1,206	1,219	1,06%

Table 8. Fuel consumptions and percentage differences obtained in the WLTP test, for B7 and B100.

Speed profile	Average consumption [l/100km] - B7	Average consumption [l/100km] - B100	Average consumption [l/100km]
Low	7,426	7,336	-1,21%
Medium	6,234	6,104	-2,08%
High	5,836	5,687	-2,54%
Extra-High	6,567	6,441	-1,93%

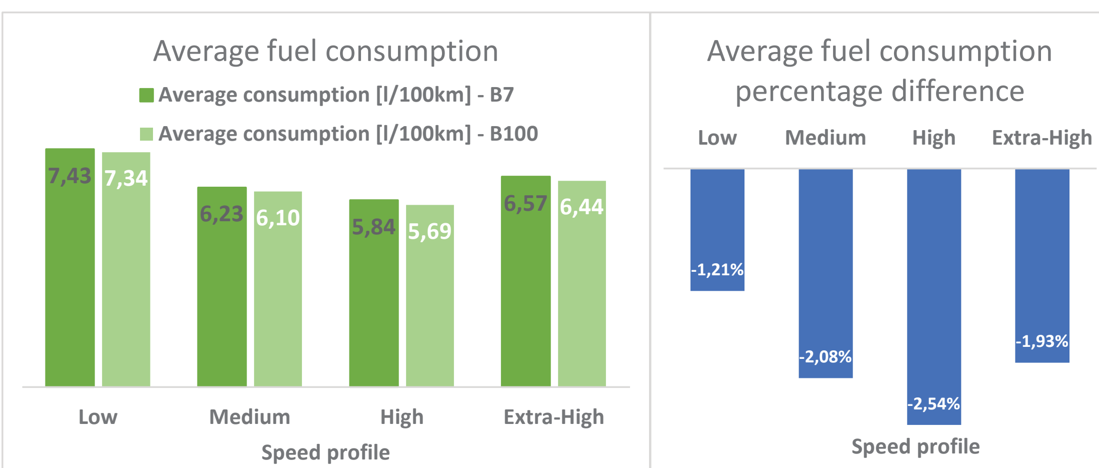

Figure. 7. Fuel mass flows and differences percent obtained in fuel consumption for WLTP test, with B7 and B100.

4. Conclusion

Just like the body of the work, the conclusions that can be drawn from this work can be grouped by the typology of the tests used:

4.1. Fuel consumption test

From the analysis of the results, it can be concluded that the use of biodiesel does not necessarily increase fuel consumption, as there were vehicles that showed increases and others that showed decreases. These fluctuations occur not only due to differences in fuel properties but also due to natural causes associated with the use of vehicles by different drivers on different routes, among other factors, which implies a fluctuation in vehicle consumption. Overall, there was a very slight increase of about 1% in the vehicles analysed. In the equipment, there was even a decrease in fuel consumption. This is not only due to differences in fuel properties but perhaps more to the different modes of operation to which they may have been subjected. Overall, in the equipment, there was a decrease in consumption of about 12% when B100 was used.

4.2. Emissions test

Analysing the exhaust gas emissions, it is evident that, in vehicles, the use of biodiesel causes an average increase in CO emissions (32.86%) and a decrease in NOx (34.81%), while there was virtually no change in O2 and CO_2. The increase in CO is not critical in diesel engines since they always operate in a lean mixture. The decrease in NOx is beneficial because it is one of the most critical pollutants associated with the use of diesel engines. For the equipment, globally, the same as in vehicles occurred, except for NOx emissions, which increased by about 6%, although this increase was only observed in one of the two pieces of equipment considered in this study. In both cases, there was no significant increase in CO_2 emissions, so it is possible to conclude that, by using biodiesel, there will be a decrease in emissions of this substance when considering the entire life cycle given the renewable nature of this fuel.

4.3. Power and Consumption Test – WLTP

Analysing the differences in power output by the vehicle under study when using biodiesel, there is no decrease in the vehicle's performance, with even a slight increase in the maximum power output by the engine. This may be related to some intervention that the vehicle has undergone or alteration of a critical component that affects the maximum power reached at higher engine rotation. Nevertheless, in a typical case, there would not be a significant decrease in the power output by the engine.

For the power bench consumption tests (WLTP), there is a visible increase in the mass fuel consumption in all speed profiles, between 1 and 5%. Even so, this value was lower than expected, which would be around 10%. Analysing the average volumetric consumption per distance travelled (l/100km), there is a slight decrease, around 2%. This is explained by the higher density of biodiesel.

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Nomenclature

$\dot{m}$ mass flow rate, kg/s

LHV Lower Heating Value

HHV Higher Heating Value

CO2 carbon dioxide

CO carbon monoxide

NOx nitrogen oxides

HC hydrocarbons

B7 fuel mixture of 7% biodiesel in diesel

B100 fuel containing only biodiesel

O2 Oxygen

PM particle matter

WLTP World Light-duty Test Procedure

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