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Performance study about biodiesel impact on buses engines using dynamometer tests and fleet consumption data

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ABSTRACT

The problem of reducing harmful emissions, mainly particulate matter (PM) and nitrogen oxides (NO_xs) originated in compression ignition combustion engines, and also the mandatory intention of lowering the CO_2 impacts of road transportation define the need to improve our knowledge on biodiesel use in engines.

A 6 in line cylinders Volvo engine was submitted to a 100 min cycle with 27 stabilized steps for seven different fuel blends from pure fossil diesel (B0) to pure biodiesel (B100), considering also B10, B15, B20, B30, B50 fuel blends. The cycle imposed tries to simulate a normal use of a bus in an urban and extra-urban circuit, considering different engine rotation and loads applied.

An analysis on consumption data obtained of a fleet was made. The fleet had near 200 buses, used different fuel blends, and operated in the north of Portugal.

Results reveal that the cycle imposed reflects very well the tendency of consumption, allowing to confirm the methodology and also to check influences on consumption, mainly associated with possibilities to decrease CO_2 emissions by using some biodiesel blends on buses. This allows increasing the quality of data in vehicle real use and tightening the uncertainties on the actual effects of using biodiesel.

1. Introduction

The use of vegetable oils to produce biodiesel, due to its less polluting and renewable nature when compared with conventional petroleum diesel fuel is becoming more frequent. Biodiesel is a renewable fuel that can be used as an alternative in diesel engines without modifications, replacing part of the dominant diesel fuel originated from petroleum. The valorization of biodiesel by an efficient use in transportation sector, will bring great benefits for the environment and the local population, job creation, provision of modern energy carriers to rural communities, avoidance of urban migration, and the reduction of CO_2 and sulfur levels in the atmosphere [1].

In 2009, the European Commission revealed its intention to promote the use of energy from renewable sources, among other renewable energy issues; it established sustainability criteria for biofuels. It turns mandatory, for each of the European members, overall targets that should help reach at least a 20% share of energy from renewable sources in the Community's gross final consumption of energy by 2020. In order to achieve the targets, each Member State shall promote and encourage energy efficiency and energy saving [2]. In this document it is assumed that, in Portugal, in 2005 there was already a share of energy from renewable sources in gross final consumption of energy of 20.5%, but this should increase by 2020 up to 31%. However, more than 1/3 of energy in Portugal is consumed by transportation sector and, as it can be verified analyzing Table 1, a big effort should be made on this sector, since this is the area where the penetration of renewable is only residual. In fact, numbers for 2007 reveal that renewable energy consumed by this sector represents only 2.1% of the total energy used in all transports in Portugal [3,4].

At this point, biofuels are the only energy source which can be applied with guaranteed success. The most commonly biofuel reported as a possible substitute for petroleum use in compression ignition combustion engines has been biodiesel, although the use of bio-alcohols also be presented encouraging results [5–9]. There are several other possibilities to raise the introduction of renewable in energy consumed by transportation sector, like electric vehicles or fuel cells vehicles, but all these technologies need some time to be matured and to prove their effectiveness.

To accomplish the targets until 2020, it is essential that the population understands what is involved when using biodiesel in their vehicles. Society accepts better what they know, even if it is not so good, than accepting the unknown, even if it is better.

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Table 1
Renewable sources in transportation sector in Portugal.

Energy consumption by transportation sector in Portugal			
2007	*Source*: International Energy Agency	ktoe	%
Petroleum products		6176	97.1
Gas		12	0.2
Electricity		43	0.7
Combustible renewable and waste		133	2.1
Total		6363	100.0

This renewable energy policy puts things rolling, which leads society to move. Portuguese biodiesel producers are interested in better knowing the diesel engines' performance when they are using their biodiesel, mainly to inform their potential customers and to raise confidence in their product. One of these customers owns a fleet of more than 200 buses, and he is also interested in knowing the advantages and problems associated to the use of biodiesel in his fleet. This leads to the present work, which is divided in two main tasks. Task one considered the use of an engine dynamometer to develop some performance and emissions tests, using several blends of biodiesel in petroleum diesel. The fuel which only has fossil diesel is represented by B0, meaning that the amount of biodiesel present is zero. By analogy the fuel totally constituted by biodiesel is B100, becoming evident that the identification of the fuel is made using the letter B followed by the percentage of biodiesel incorporated in it. The second task tries to make a fleet recognition, using several biodiesel blends in these buses, and understand how this can affect overall consumption and how the fleet deals with these changes, taking in consideration the results for future developments.

2. Preliminary research

As it is expressed [10], biodiesel is not commercially feasible. Only with governmental measures and more research and technological development it is possible to consider this fuel as a sustainable option. In the European Union, in 2003, biodiesel is by far the biggest biofuel and represents 82% of the total biofuels production, which in EU-25 corresponds to 1,504,000 tons of biodiesel obtained using around 1.4 million hectares (ha) of arable land in the EU. In 2005 biodiesel production in EU represented 89% of the world's biodiesel production [11]. It presents the inherent advantages of being a liquid at atmospheric conditions, facilitating the energy transport, it is renewable, and reveals lower sulfur and aromatic content, with a high cetane number and viscosity.

For biodiesel, the CO_2 equivalent emissions savings range between 36% and 83% compared with conventional diesel [12], but in order to make the biodiesel economically efficient it is necessary to subsidize the price difference between European biofuels and fossil fuels per ton of saved CO_2 emissions.

Disregarding the process of CO_2 absorption on plants growth, considering only the production and the utilization of biodiesel, the dominant source of CO_2 in biodiesel lifecycle is the fuels' combustion, just like what happens with petroleum diesel. In fact, considering the case of soybean oil and the use in buses [13], the analysis for petroleum diesel reveals that, of the total emissions of CO_2 across the entire life cycle of the fuel, the tailpipe emissions represent 86.54% and 9.6% of the total of CO_2 comes from emissions at the oil refinery. In the case of biodiesel, the combustion produces 84.43% of the CO_2 emissions at the tailpipe and the remaining CO_2 emissions comes from agriculture, material crushing, and oil conversion to biodiesel.

The main feedstock used for biodiesel production are soybean and rapeseed oils, by United States and European Union respectively. There are also other feedstock used, mainly in tropical areas, like coconut oil or palm oil, but with lower productions. The origin and type of feedstock is very important to define the cost and the life cycle of the biodiesel.

In summary [11], for a fuel to become a real alternative to diesel fuel it has to be technically feasible, economically competitive, environmentally acceptable and easily available. The only alternative to diesel fuel that is close to these requirements is biodiesel.

Tests were developed using a fleet of 44 school buses in largely rural county near to the city of Philadelphia [14]. This fleet was divided in half, one part using B20 fuel and the other half operated with 100% diesel. On these tests 500.000 l of B20 were used and there were no differences revealed on basic performance between the buses, it was also possible to detect independence with the year of the buses.

A study [15] conducting an assessment of North American heavy-duty engine emission test results for biodiesel from 49 experimental studies, including both engine dynamometer and vehicle test results. In this study, an emission inventory of US. Environmental Protection Agency (EPA) was used and it estimates that in 2000, diesel vehicles emitted only 7% of total on-road HC, and 5% of on-road CO. However, diesel engines were responsible for 60% of on-road emissions of Particle Matter (PM) and 45% of on-road NO_x. This reveals the importance that the reductions of PM and NO_x have on studies about diesel engines and biodiesel fuels.

Nine buses were operated in a 16.1 miles route over 2 years in real road conditions and in a laboratory chassis dynamometer using the CSHVC cycle [16]. Five buses of the fleet were fueled with B20, and the other four used petroleum diesel fuel. When lab tests were considered, a small decrease in fuel economy was detected, however, in the real road results, the fuel consumption was the same for both bus groups. For the vehicles with B20, in chassis dynamometer tests, it was verified a reduction in all regulated pollutants, even a small decrease for NO_x.

Several tests were made on two engines fueled with biodiesel originated from several feedstoks (canola oil, beef tallow, soybean oil and yellow grease) used neat and in a blend of 20% biodiesel incorporated in petroleum diesel [17]. Results for B20 demonstrated an average reduction of 25% on PM emissions and an increase in 3% of NO_x. This PM reduction is higher than observed in older engines (10%), but NO_x emissions seem to be insensible to engine age. Since in common rail injection system, the bulk modulus effect of the fuel is not so visible, then it cannot take full responsibility for the NO_x increase.

It has been reported in literature [15,18,23,24], that standardized and regulation specifications tests do not represent the real vehicle response under on-road conditions. It is not easy to establish a common procedure that tries to simulate the real road conditions that some kind of vehicles may be subjected to. There is some difficulty to simulate the transient conditions, and even so, the different kinds of response of an engine could be more adequate than other which can give misleading results [19–25].

It was developed a study [18] with 30 passenger cars tested over the three real-world Artemis driving cycles (Assessment and Reliability of Transport Emission Models and Inventory Systems), considering urban, rural road and motorway, representative of European driving. Those 30 cars also have been tested fulfilling the specific driving cycles. The emission aggregated data demonstrates that the usual test procedure can lead to strong differences, particularly in the more recent vehicle categories.

There are two main reasons for these discrepancies. On one hand, there is a unique set of driving cycles, disregarding the vehicle characteristics. This can result in a representativeness weak point, since each vehicle has its own behavior regarding some energetic demands. On the other hand the regulations and standards were made with the main objective of setting specifications for vehicle approval, not to define differences on fuel characteristics and combustion results.

There are some uncertainties about how much representative are the cycles used on certification of new engines of the actually heavy-duty trucks operation. "There is evidence that biodiesel effects on NO_x can vary with driving cycle, and a detailed examination of driving cycle should be another focus of future research", has been concluded [15].

It was also observed that the application of biodiesel has an impact that strongly depends on driving conditions [23,26,27].

The integration of engine dynamometer results and on-road tests, could give some indications about the real effect of using biodiesel in engines, and how these vehicles performance and emissions can be improved with the right fuel blend.

Table 2
Fuel properties.

Parameter (unit)	Biodiesel (soybean 40% + rapeseed 60%)		Commercial diesel
	Results	Method	Results
Density at 15 °C (kg/m^3)	884	EN ISO 3675	840
Ester content [% (m/m)]	99.8	EN ISO 14103	–
Kinematic Viscosity at 40 °C (mm^2/s)	4.33	EN ISO 3104	2.43
Flash point (°C)	135	EN ISO 3679	>55
Water content (mg/kg)	102	EN ISO 12937	–
Iodine value (g iodine/100 g)	116	EN ISO 14111	–
Sulfated ash content [% (m/m)]	<0.02	ASTM D 874	–
Cetane number	52.1	EN ISO 5165	51
Oxidation stability, 110 °C (h)	7.64	EN 14112	–

3. Engine dynamometer tests

The Laboratory of Industrial Aerodynamics (LAI) has an engine test bench, equipped with a Schenk hydraulic dynamometer with a capacity to test engines till 230 kW at a maximum engine rotation of 13000 rpm and a torque limit of 600 Nm, showed in Fig. 1. It has also an AVL gravimetric fuel consumption measurement system, an AVL smoke meter and a Horiba gas analyzer.

All the equipments, temperature and pressure sensors are connected to a data acquisition and control system that collects the engine data, the equipment measurements and can control the test, with the parameters specified by the cycle imposed, without the intervention of the technician. This allows a better accuracy and reliability of the obtained results [28].

The engine used for these tests was a Volvo TD41 with six cylinders in line and 3590 cm^3, developing a maximum power of 110 kW, with pre-Euro technology.

Tests were made using seven different biodiesel blends (B0, B10, B15, B20, B30, B50, B100). The properties of the fuels, biodiesel and commercial diesel, are presented in Table 2. Diesel is a commercial fuel constituted fully by petroleum fuel. The blends selected are those that represent the most probable to be used in the years to come. Nowadays, the amount of biodiesel incorporated in diesel is 5–6%, so it seems important to better characterize the near blends till 30%, expecting that the perspective of reaching 20% is already very positive. The results on B50 and B100 can give data to estimate what can happen with the rise of biodiesel in the mixture.

The specifications given in standards to test heavy-duty vehicles show a weak representativeness of real on-road use of the fleet of buses, especially marked in Europe. Those fleet data are intended to be compared with the engine dynamometer results. That led to a new test cycle, with low and medium loads, where the buses spend more than 90% of their operation.

It is important to define a specific methodology for this kind of studies, involving different fuels, since all engines were produced assuming that they will consume petroleum diesel fuel. However when it changes to some amount of biodiesel, the properties and initial conditions change, which will produce effects on emissions and consumption. Plus 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.

The first part of the cycle purpose is to recreate the operation associated to a more urban circulation, with frequent stops and goes, and second part where it is imposed an extra-urban operation, with higher engine speeds.

The base for this cycle was the chassis dynamometer test imposed by the European Transient Cycle (ETC) defined in European

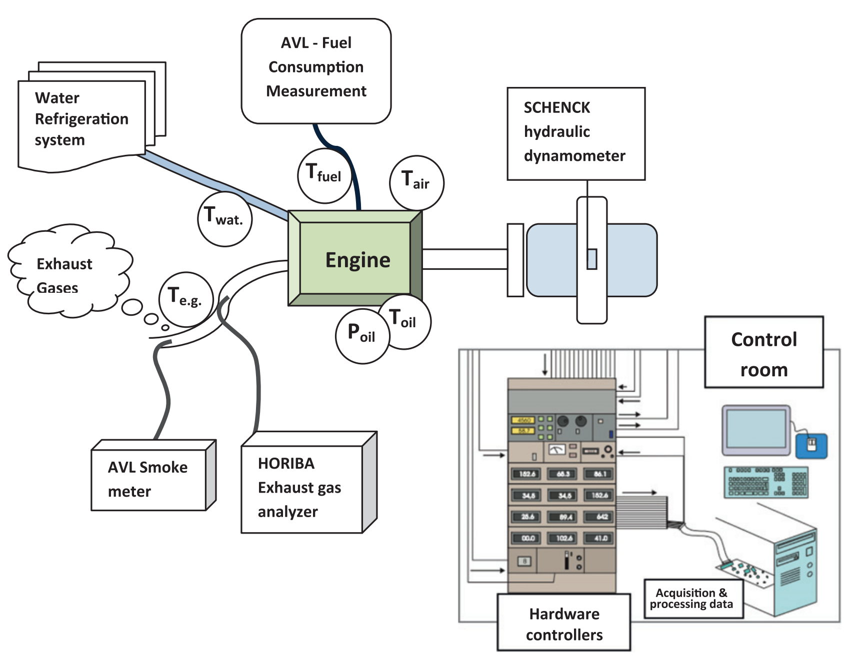

Fig. 1. Engine test bench in LAI.

Directive 2005_55_CE [29]. However, it was not possible to have accurate emissions results with a transient cycle, so 27 steps were chosen, with 2 or 4 min duration, involving 100 min overall test duration. The representation of the cycle is made in Fig. 2. For each blend tested, the cycle was done three times. For each step, the results were validated only if the dispersion among the trials was less than 3%. The results presented are the average of the three valid measurements obtained for each blend in each step of the cycle.

The results obtained on fuel consumption are represented in Fig. 3 and reveal that for different operation regimes, the engine consumption is diverse; however there is some trend for the fuel blends B10 and B20 to have slightly consumption reductions in some regimes, which corresponds to the lower engine speeds and for instances to steps 11 and 25, with 2000 rpm engine speed and 100 N m torque. There are some variations also in higher blends (B50 and B100), but in these cases it is possible to note an increase in consumption for almost all regimes. On average, considering all cycle as it is, the variations on consumption for the lower blends (B10–B20), concerning the petroleum diesel fuel (B0) consumption, are very smooth (<2%) and in the range of uncertainty of the tests. It is possible to detect some variations with higher values, but this occurs in idle steps, where the consumption is minor and small variation implies higher percentage values, but its absolute result is not so relevant.

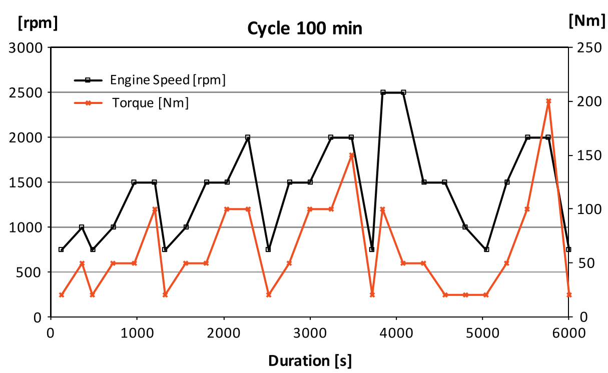

Fig. 2. Cycle 100 min representation.

The obtained results reveal very high reliability and coherency, once even with very small oscillations in consumption, they maintain the trends for every step with the similar operation requirements.

It is possible to point out that the lower heating value of the biodiesel, cannot be the only aspect that commands the energetic efficiency on the combustion of a fuel containing biodiesel. It surely has a fundamental contribution, like it is proven by the blends with higher amounts on biodiesel, but for the lower biodiesel content blends some other aspects contribute to the production of the same power, with lower amounts of available energy. The oxygen content, the higher viscosity, evaporation ratios and density are some aspects that could play an important role in this process, demonstrating the need to raise the research in these fields [30–37].

For a better comprehension of the emissions results, they were grouped in order to take the effect of the raise on engine rotation and torque. The values of B30 were not considered because they were not realistic.

Some high NO_x emissions values appear, and for lower loads, the highest biodiesel blends almost double the results considering B0. But over increased torque and increased engine speed, these values decreased, and for 2500 rpm and 200 N m, a reduction on NO_x emissions becomes visible, which for B10 corresponds to a 20% decrease.

However, in Fig. 4 it is possible to detect a trend for increased values on NO_x emissions with the introduction of biodiesel, for all the blends tested.

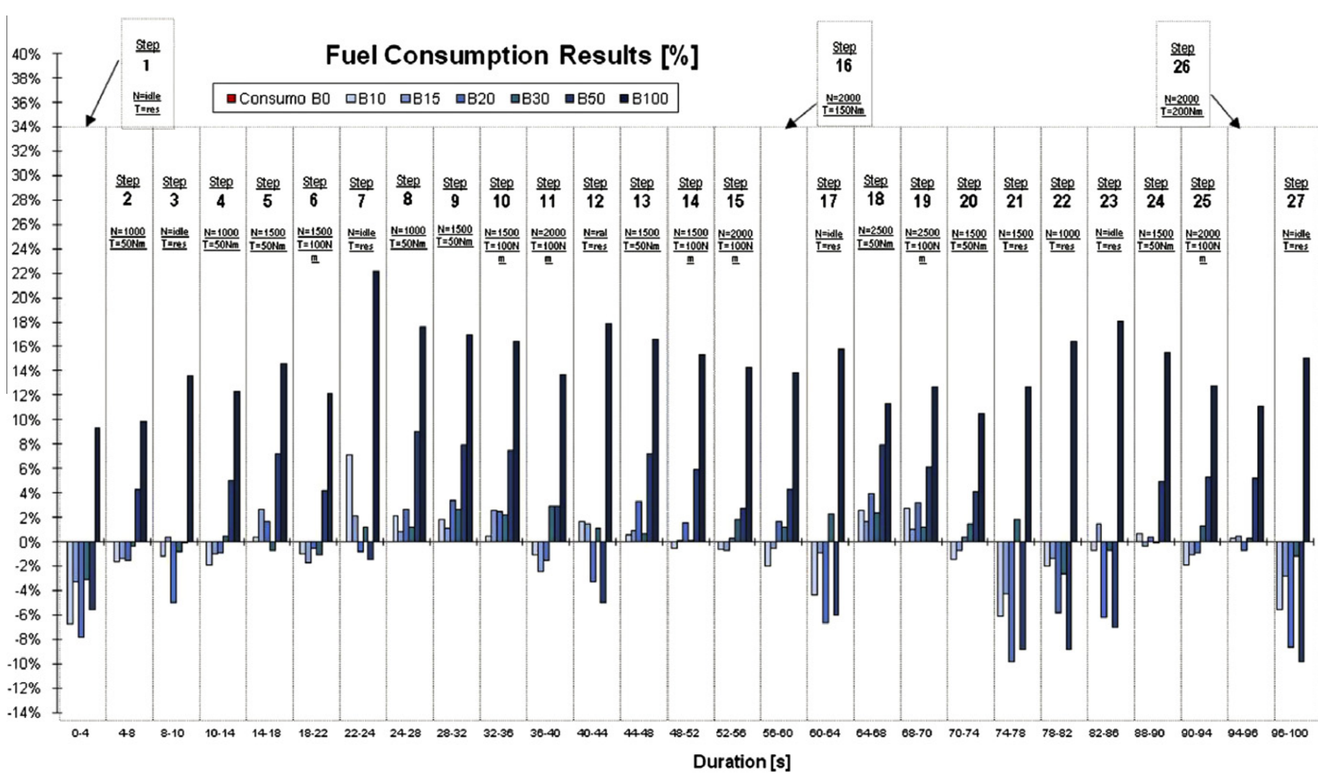

Fig. 3. Fuel consumption on cycle 100 min, considering the results for each step.

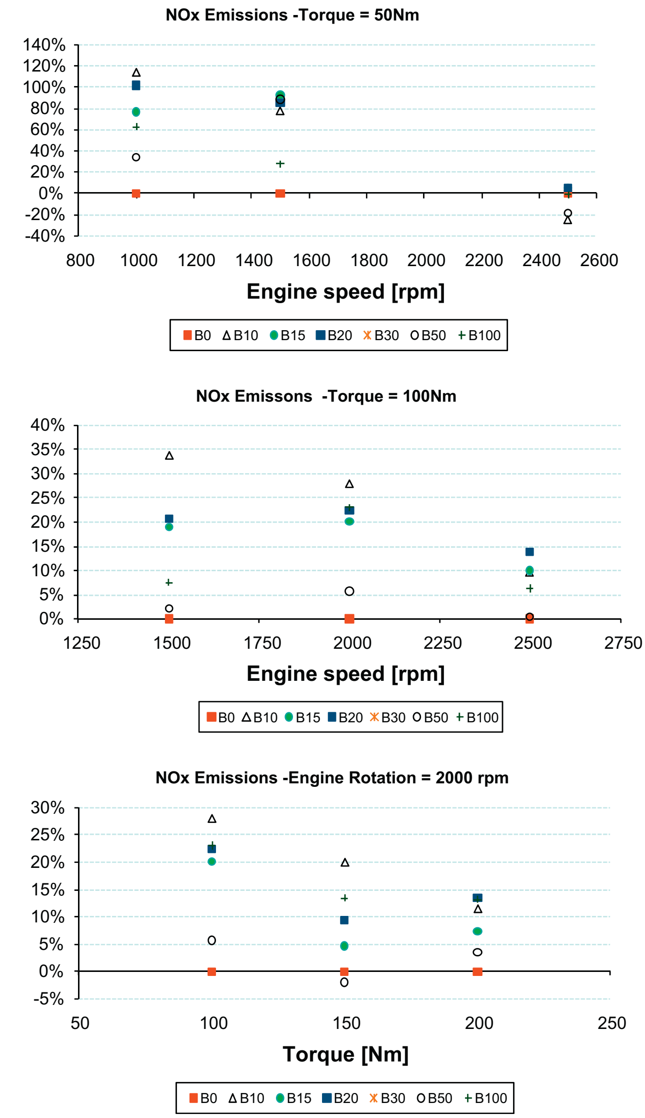

Fig. 4. NO_x emissions comparison results.

It is also important to note the behavior of blends B10, B15 and B20, presenting a similar behavior corresponding to higher NO_x emissions than the ones obtained for B0, B50 and B100. This supports the behavior on consumption analysis, revealing a better energetic efficiency in the combustion process, for those lower blends leading to higher combustion temperatures that can justify this NO_x emissions increase.

4. Fleet analysis

A fleet of buses working mainly in the north of Portugal was considered and divided into two small fleets for the purpose of the present work. The first group named TUG, constituted by 33 buses, circulates mainly in the urban area of Guimarães, through traffic, with constant stop and go operation. The second group, identified as ARRIVA includes 168 buses, and has an extra-urban type of circulation. This larger fleet has a more diversified operation, varying between sloped to smoother roads, including motorways.

Driving cycles have an important contribution for performance and emission results. The results obtained in engine dynamometer, and in the fleet reflect that contribution.

The fleet was supplied with the same fuels from the same producer used in the engine tests. The amounts of consumed fuel made it impossible to control all fuel supplies. However it is possible to verify that any eventual uncontrolled fuel supply does not have any significant relevance, considering the amount of fuel consumed by the buses.

The fleets started to be supplied with B10 in January 2008, while before that date they used B0, or B2. Regarding the fuel that was commercialized at that time, it was not possible to know exactly if it contained any part of biodiesel and what quantity. However, it was assured that the amount was certainly below 2%, if it had any biodiesel.

In September 2008, they changed from B10 to B20. In January 2009, the supplies started to be of B30. In November 2009, another test started, in which some vehicles of the extra-urban fleet started to use the commercial diesel fuel, which is assumed to be B6, while the other part of fleet continued to use B30.

The fleet was constituted by vehicles of three different heavy duty manufacturers, Mercedes, Volvo and Scania, with different ages, from 1989 to 2007, with exception of 2 or 3 cars that were older (1983/1984). All vehicles belongs to an exhaust gases emission categories pre-Euro to Euro 4, but almost half of the fleet ARRIVA buses were from 1989 to 1991 period corresponding to a pre-Euro classification. The rest of the fleet is constituted by balanced diversified categories. TUG fleet was constituted mainly by Euro 1 to Euro 3 categories, but with a bigger representation of Euro 1, according to Table 3.

Due to the organization and the peculiarities of the fleet demands, it was not possible to readjust the circuits, or the drivers. It was guaranteed that the vehicles and the drivers remain the same but there were several arrangements between these two categories. This assures that, besides the existence of some uncontrolled variables, they result in neutral impacts in an overall consumption analysis. This global analysis allows establishing two major purposes: it can give overall information about the influence of biodiesel in fleet consumption, defining trends; and the results will certainly provide data to characterize a future focused and detailed study that can guaranty more precise results, obtained with a small part of the fleet.

To define a baseline, February 2007 data and November 2007 data were compared, since the meteorological conditions were similar and the comparison on fuel consumed in those periods does present not big differences. The two results of those periods were used to define the consumption variations with the introduction of the blends, and the period when they were used. Accordingly, the consumption data corresponding to February 2007 was used to be compared with the results of Feb 2008 (B10) and Feb 2009 (B20). The consumption data corresponding to November 2007 was used to analyze the variation with the data period of November 2008 (B20) and November 2009 (part on B30 and other part on B6).

The consumption results were obtained with the quantities of fuel supplied and the kilometers traveled between tank refilling.

The obtained results for the use of B0 in 2007 reveal the differences between urban and extra-urban type of utilization. Even noting that diversity exist, due to different circuits and different

Table 3
Number of buses composing the fleet according to Euro classification.

	ARRIVA	TUG
Pré-Euro	106	0
Euro 1	29	18
Euro 2	11	5
Euro 3	8	9
Euro 4	14	1
Total	168	33

vehicles, the fluctuations between the results reveal that this approach is correct, and that the consumption variations tend to oscillate between vehicles, but in general there are not big differences in the overall consumption. This is valid for the two partial fleets studied, and is associated with the routes that each bus travels with each driver.

The most amazing results obtained from the TUG fleet data is the consistent reduction in overall consumption when biodiesel is introduced. Fig. 5 shows that this trend is consistent for the February and November month's comparisons, and reveals a tendency not proportional with the introduction of higher levels of biodiesel, since it points out that no big differences exist between B10, B20 and B30. These consumption results present a reduction between 4% and 6%. Analyzing the data collected in engine bench tests, it is possible to point out that these results could be related with the amount of time that the buses spent in idle mode, and the lower velocities and high loads imposed, which represent the biggest part of fuel consumed. In fact, considering the operation points corresponding to this engine behavior, it presents more favorable consumption values when B10, B20 and B30 was used, and with no significant differences between this blends results, corresponding to similar trends, just as the ones revealed in the urban fleet.

Having these results in mind and taking in consideration the different fuel properties, it is possible to point out that the reason for the reductions in fuel consumption can result in an obvious increase in thermal efficiency, that can outcome from a better air/fuel mixture. This can be explained with lower engine velocities which decrease air turbulence, and in turn affects the mixture of fuel in air. This result in some loss of efficiency that could be improved with the use of biofuels, offering some oxygen already introduced in the fuel. By increasing the amount of biodiesel it augments the quantity of inside oxygen available but decreases the fuel's amount of energy. These two factors have an opposite contribution to the final effect of fuel consumed, which is felt with the comparable reduction between B10, B20 and B30. Another contribution comes from better lubricity of the fuel injection system, presented by higher viscosity of biodiesel. It is important to note that a small advance in injection is also a reason for those consumption differences. However this is not so significant since the cetane number of petroleum diesel and biodiesel are not so different, because the European fuel regulation requires a 51 cetane number as a minimum for petroleum diesel which is closer to the value of 52 for biodiesel.

Arriva fleet consumption results, represented in Fig. 6, reveal a more expected behavior, with an increase in fuel consumption as the percentage of biodiesel incorporated increases. These results mainly from the deficit in energy content of biodiesel compared with diesel. This is justified by considering the most normal behavior of this fleet. In fact, their engines are usually subjected to higher velocities and lower loads, which correspond to the similar results obtained in the engine dynamometer tests, for this kind of engine operations.

It could also be referred that the consumption results reveal the considerations also suggested for the urban fleet. However for the extra-urban fleet, those contributions should not be sufficient to balance the energetic effect, but were enough to weaken that effect. The increase in fuel consumed is not proportional to the decrease in energetic content, as it is a little smaller. This was also revealed in the engine tests bench, probably resulting from the possible better air–fuel mixtures when engine operates at higher velocities and lower and medium loads.

In Portugal, B10 and B15 are already available in the market. Since the fuel prices present some considerable oscillations in time, the month of November 2010 was considered for the price reference for all the fuel cost analysis [38]. The relative difference between the prices of diverse blends does not vary significantly

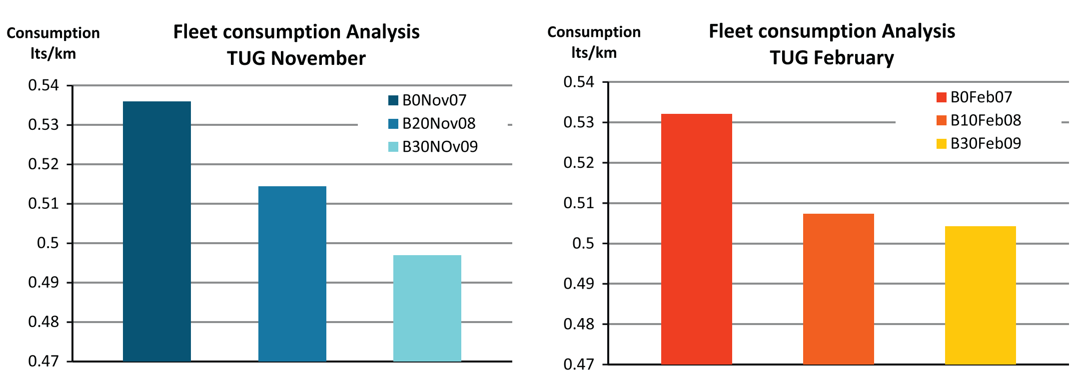

Fig. 5. Consumption results for TUG urban fleet.

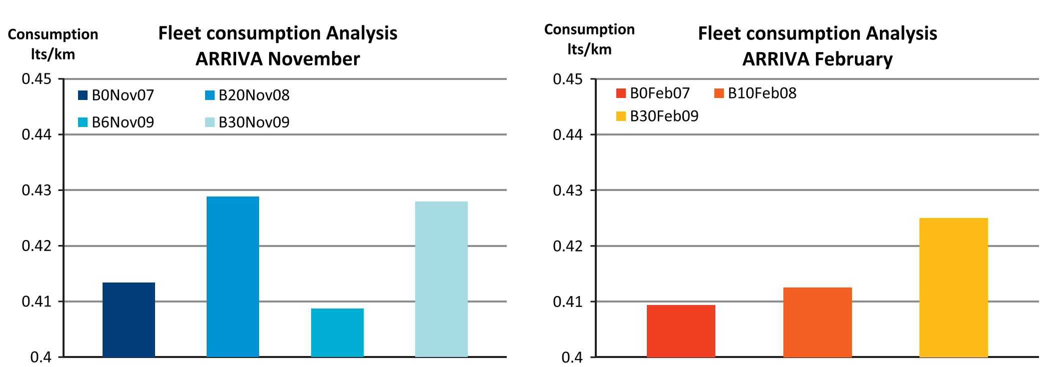

Fig. 6. Consumption results for ARRIVA extra-urban fleet.

Table 4
Economic fleet analysis about the use of divers fuels incorporating different amounts of biodiesel.

	Fuel prices (€ /lts)	Average consumption (lts/km)	Average cost (€/vehicle/month)	Global cost (€/month)	Overall variation (€)	Overall variation (%)
ARRIVA						
B0 Nov07	1.179	0.4134	1754.8	294800.1	0.0	0.0
B10 Fev08	1.134	0.4125	1684.1	282926.8	−11873.3	−4.0
B20 Nov08	1.12	0.4288	1729.0	290469.7	−4330.4	−1.6
B30 Fev08	1.106	0.4250	1692.2	284294.3	−10606.8	-3.6
B30 Nov09	1.106	0.4279	1703.7	288474.5	−6326.6	−2.1
B6 Nov09	1.179	0.4087	1734.6			
TUG						
B0 Nov07	1.179	0.5360	3159.5	104262.6	0.0	0.0
B10 Fev08	1.134	0.5073	2876.4	94920.0	−9342.6	−9.0
B20 Nov08	1.12	0.5144	2880.5	95055.9	−9206.6	−8.8
B30 Fev08	1.106	0.5043	2788.8	92028.8	−12233.8	−11.7
B30 Nov09	1.106	0.4969	2747.9	90680.7	−13681.8	−13.0

along time, but overall fuel prices suffer considerable changes. Considering the differences on B10 and B15 costs, it was possible to access the expected cost of B20 and B30, since it is expected a linear change in prices caused by the fuel taxes exemption attributed by the Portuguese government to biodiesel. The fuel prices are available in Table 4, corresponding to a reduction in the prices of 0.007€ for each 5% increase on the amount of biodiesel in the considered fuel.

The method used to get the economic analysis about the use of biodiesel in the fleets considers the same distance traveled for all the cases, which corresponds to a monthly average of 3600 km/vehicle for ARRIVA fleet and 5000 km/vehicle for TUG fleet.

It becomes clear that the use of biodiesel represents an increase in economic efficiency, which is visible by the decrease in the amount of monthly fuel costs for each of the situations, where the same quantity of biodiesel was used. In the TUG fleet, where the global fuel costs reduces from 9% to 13%, this kind of economic results was expected, since the prices of the blends are lower than the prices of B0 and the consumption was also lower. However, it is somewhat surprising that even considering the rise in consumption patent in the ARRIVA fleet, with the use of biodiesel, the lower prices of the fuel when it incorporates biodiesel, allows cutting the fleet costs on 2–4%, since the reduction in fuel costs prevails above the increase in consumption.

The obtained results, depicted in Table 4, provide important information to fleets owners and government decision makers to get the most profitable use of biodiesel, acquiring an economic sustainable energy alternative source for buses and other heavy-duty vehicles.

5. Summary and conclusions

The use of biodiesel has been imposed by the EU, with some fiscal support and with several measures to increase the rise of renewable energy integration in the transportation sector.

The presented methodology is established by the principle of comparing consumption results from dynamometer tests, representing the real world use of buses in urban and extra-urban routes, with data from a fleet of buses on normal road operation. This fleet was divided in two partial groups depending if the buses were used in urban or extra-urban circuits.

The followed methodology presented in this paper reveals that it is essential an adequate driving cycle for study fuel impacts on engine emissions and performance.

The several operation points chosen for the dynamometer tests of this work reveal that different engine operations represent diversified results. These tests reveal that analyze biodiesel incorporation regarding only a small number of operation points could generate erratic conclusions, mainly if those points do not represent the normal operation of an engine.

NO_x emissions obtained in dynamometer tests disclose that this combustion product is very sensitive to engine operating conditions, since the values change very much with different loads and speed demands. In general, the NO_x increases with biodiesel incorporated in fuel, by comparison with petroleum diesel; but it presents great amplitude of variation depending on the engine velocity and torque. The differences are higher for lower engine velocities and lower engine loads.

It is visible for B10, B15 and B20, that in certain operation regimes, the engine efficiency was improved with incorporation of biodiesel, since the engine may produce the same energy output (power) with lower available energy.

The fleet data study reveals that in an urban circulation, the introduction of biodiesel can give small reductions (4–6%) in consumption, even regarding the diminutive amount of energy available in biodiesel. The overall fleet consumption results, corresponding to long idling periods and with low velocity operation, agrees with the dynamometer results; that is, in this type of operation there is a lower fuel consumed probably due to an improvement on thermal efficiency. These results are a reflection of the type of engines that constitute this fleet, where the injection and atomization process were not very advanced. It is important to reproduce this kind of analysis with a fleet containing more Euro 4 and Euro 5 buses.

For the extra-urban fleet, it is obvious that the engine operation corresponds to a more stabilized action, traveling from medium to higher velocities which, once again is reflected in the dynamometer tests, revealing a faded advantage from biodiesel use, when the lower energetic content of that fuel becomes predominant.

The economic cost analysis reveals the potentiality to reduce the exploration costs of the fleets, reducing the amount of the fuel prices by the incorporation of biodiesel, considering the taxes exemption of this renewable fuel. This cost reduction represents 2–4% in extra-urban fleet and 10–12% in urban fleet.

The obtained results confirm the potentialities of this kind of approach and also introduce a new methodology that should now be improved to better simulate the engine operation condition and the circuit demands in engine dynamometers, allowing an even better correlation with the results obtained in real road conditions. This kind of approach implies the follow up of some vehicles with the same drivers, making the same circuits, in a more controlled comparative study on vehicles behaviors.

This work also reveals that since the petroleum diesel and biodiesel have similar cetane numbers, this cannot explain the results obtained, which means that it is the oxygen content in biodiesel that probably has strong implications on the increase of combustion efficiency, revealed in some of the engine operation regimes. This implies that this kind of studies should be more frequent in Europe, where the petroleum diesel base is very different from the one on United States, which concentrates a big part of studies on biodiesel use in fleets of vehicles, subjected to real world driving modes.

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