Simulation of an Urban Bus Fuelled with Several Biodiesel Blends
Advantages and Disadvantages on the Efficiency and Emissions

João P. Ribau[1] and Carla M. Silva[2]
[1]*IDMEC, LAETA, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal*
[2]*Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal*

Keywords: Biodiesel, Fuel Blends, Bus, Engine, Efficiency, Emissions.

Abstract: Nowadays, most anthropogenic emissions occur in urban regions, with significant local impacts on air quality and public health. Decision makers and governments have been introducing policies in the energy and transport sectors aiming to improve the efficiency of energy use, meeting climate change commitments, fostering fossil energy independency and promoting the use of biofuels in the transport sector.

This study aims to investigate the main advantages and disadvantages of introducing biodiesel into the Portuguese passenger road transport system. Biodiesel-diesel blends with a minimum of 7.5% and a maximum of 100% of biodiesel content (B7.5-B100) will be studied. An urban passenger bus is modelled in the vehicle simulation software AVL CRUISE in different driving conditions. The use of biodiesel blends are compared with the use of pure diesel concerning the engine efficiency and emissions. The trend is that the use of biodiesel has some advantages, from which the most agreed are the reduction of the pollutant emissions of HC, CO, and PM; however, with the main disadvantage of increasing the fuel consumption and NOx emissions.

1 INTRODUCTION

Worldwide governments have been introducing a large number of policies aiming to improve efficiency of energy use, foster fossil energy independency, and promote alternative fuels especially in the road transport sector. Some examples of a global trend to diminish emissions from the transportation sector are the Kyoto protocol, the 2003/30/EC European directive on biofuels for the transport sector, and the European 20-20-20 targets (EUR-Lex 2014).

The transport sector has an increasing and significant impact on energy use and on the greenhouse gas and pollutant emissions. Most anthropogenic emissions occur in urban regions, with significant local impacts on air quality and public health.

One of the approaches taken by the transport sector was the implementation of biofuels as a replacement or an additive to the fossil fuels used in road vehicles. The replacement of fossil fuels with renewable biofuels has been set as a target worldwide to reduce greenhouse effect and energy dependence as well as to improve agricultural economy. One of the goals stated by the European Parliament s that the transport fuels should contain 10% of renewable products (calculated on an energy basis) by 2020.

In particular, biodiesel blends have emerged in the last years as an alternative fuel for transportation. Nevertheless the use of biodiesel is not a contemporary idea. Several vegetable and animal oils were used in the first diesel engines by Rudolph Diesel himself, who envisioned that these oils could power diesel engines for agriculture in remote areas of the world, where petroleum was not available. Pioneering work on biodiesels was performed in South Africa between the great world wars, since this country has not oil reserves. (Martins 2013) Nevertheless, only in the past 20-30 years biofuels have gain attention due to the world increasing concern about the energy security of supply, and climate change.

Biodiesel has been produced on an industrial scale in the European Union since 1992, largely in response to positive signals from the EU institutions.

Today, there are approximately 120 plants in the EU producing up to 6,100,000 tons of biodiesel annually. These plants are mainly located in Germany, Netherlands, France, Italy, Austria, and Sweden. (EBB 2017) Today in Europe, rapeseed is still the main feedstock for biodiesel production. Up-

Ribau, J. and Silva, C.
Simulation of an Urban Bus Fuelled with Several Biodiesel Blends - Advantages and Disadvantages on the Efficiency and Emissions.
DOI: 10.5220/0006386103920399
In *Proceedings of the 3rd International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 2017)*, pages 392-399
ISBN: 978-989-758-242-4

to-date information and statistics on biodiesel production in Europe is available from the European Biodiesel Board (EBB 2017)

Biodiesel is most commonly obtained from a chemical reaction between an acid and an alcohol – esterification. Maybe the most well-known method is the transesterification, from which triglycerides react with an alcohol with the presence of a catalyst, producing ester and glycerol. These esters can be obtained from different vegetable oils and animal oils, and are known as FAME – fatty acid methyl ester. Other processes are available to produce biodiesel, e.g. using biotechnology, hydrotreatment of vegetable oils. (Edwards et al. 2011)

Although biodiesel is a promising solution there are some market penetration issues which delays its further use in the transport sector, mainly concerning the fuel quality standards (which are crucial for the aimed engine operation, fuel storage and handling), air quality impact, and engine components durability.

This study aims to investigate the main direct advantages and disadvantages of introducing biodiesel into the Portuguese passenger road transport system, namely the impact in the developed power, pollutant emissions, and energy efficiency. Biodiesel-diesel blends with a minimum of 7.5% and a maximum of 100% of biodiesel content (B7.5-B100) will be studied. An urban passenger bus is modelled in the vehicle simulation software AVL CRUISE in different driving conditions.

In section 2 some of the main properties of the biodiesel as an automotive fuel are highlighted. In section 3 the vehicle simulation procedure and data are presented. In section 4 the results are discussed followed by the conclusions in section 5.

2 BIODIESEL AS AUTOMOTIVE FUEL

As referred in the previous section, the biodiesel use in the transport sector has been widely investigated due to its renewability, comparable properties to fossil diesel, and the reduction in main emission products.

Biodiesel can be used in internal combustion engines (compression ignited, which are known as diesel engines) in pure form, or blended with fossil diesel. It can be used in engines with little or no modifications, depending on the biodiesel blend. Biodiesel blends are referred to as Bxx. The ‘xx’ indicates the amount of biodiesel by volume in the blend of biodiesel and fossil-diesel. For example, B80 refers to a blend of 80% biodiesel and 20% fossil-diesel by volume.

Automotive engine manufacturers in the European Union have been performing tests on biodiesel blends with fossil diesel from 5-10 % to 100 % pure. These have resulted in guarantees for each type of use and blend. Modifications (seals, piping, and injection) are required for use at 100 % pure biodiesel. The use of biodiesel as a low-blend component in transport fuel (up to 7 percent in Europe for the time being according to EN 590) does not require any changes in the distribution system, therefore avoiding expensive infrastructure changes. (EBB 2017)

The blended fuel becomes interesting since the use of biodiesel has its pros and cons, and a blend may balance the fuel properties towards the most beneficial use possible. Several studies have been analyzing the potential of biodiesel as an automotive fuel. In (Datta & Mandal 2016; Xue et al. 2011) detailed reviews of different biodiesels are presented, concerning their properties, feedstock, and experimental results on engines; and the overall outcome is that the higher is the content of biodiesel in the fuel most likely is the engine to emit less pollutants (with exception of nitrogen oxides - NOx), although the fuel economy and power decreases. Nevertheless there are exceptions, which depend mostly on the fuel properties, engine control systems, pollutant treatment systems, and operation of the engine.

Most studies indicate that using biodiesel there is a decrease on CO (carbon monoxide), HC (hydrocarbons), and PM (particulate matter) emissions. On the other hand, there is an increase on NOx emissions, and increase of the fuel consumption. In (Wu et al. 2009) pure biodiesel fuels were tested in heavy-duty engines relating these previous conclusions with the different fuel properties. With the same purpose and conclusions (Karavalakis et al. 2016; Rakopoulos et al. 2011; Buyukkaya 2010) analyzed and compared several blends of biodiesel with fossil diesel as fuel.

The creation of combustion models and emissions prediction is extremely difficult since these events depend on many variables and may change for different engine operation points as demonstrated in (Lešnik et al. 2014)

2.1 Properties and Outcomes of Biodiesel as Fuel

The combustion, energy efficiency, and resultant emissions of any biodiesel fueled engine depend on the composition and thermophysical properties of the biodiesel used.

Since biodiesels can have several different feedstocks (e.g. corn, colza, sunflower seeds, cotton, waste oils, animal oils, vegetable oils,… the final fuel can also have different characteristics. Some of those characteristics are advantageous and other disadvantageous comparatively to diesel. (Sadeghinezhad et al. 2013; Alleman et al. 2016) Table 1 is a compilation of different biodiesel properties from different feedstocks, and compares them with diesel.

In order for biodiesel to be legally used in internal combustion engines and road vehicles in Europe, two sets of standards establish the specifications for biodiesel fuels in the European Union:

• EN 14214 includes specifications for fatty acid methyl ester (FAME) fuel for diesel engines. B100 that meets this standard could be used unblended in a diesel engine (if the engine has been adapted to operate on B100) or blended with petroleum diesel fuel.

• EN 590, the European diesel fuel specification, is also applicable to biodiesel blends up to 7% of FAME.

2.1.1 Viscosity and Compressibility

Although some studies claim that higher viscosity of biodiesel may enhance fuel spray penetration, improving air–fuel mixing, it also may lead to inefficient fuel injection atomization decreasing combustion efficiency.

Concerning the fuel compressibility, it is lower in biodiesel than in fossil, meaning that injection may be performed faster (i.e. the ignition may also occur faster supported by the increased cetane index). In this case the pressure and temperatures become higher enhancing the combustion.

2.1.2 Cetane Number

The number of cetane represents how easy a fuel can auto-ignite. Higher cetane numbers help ensure good cold start properties and minimize the formation of white smoke.

The higher cetane number in biodiesel compared with fossil diesel, enhances the ignition of the fuel and promotes the temperature and pressure increase during combustion, i.e. the developed power. This may lead to the improvement of the combustion itself (higher combustion efficiency), lowering the CO and HC emissions, but increasing NO_x.

2.1.3 Heating Value and Oxygen Content

The heating value of any fuel is an important measure of its energy content that potentially could be released to produce work. The lower heating value (LHV) is the energy content accounting with the latent heat of the water content vaporization.

The LHV together with the volumetric density of a fuel are very important since they determine the fuel consumption required to deliver a specific amount of energy into a specific volume (for storage or inside an engine cylinder). It should be noted that the fuel-air stoichiometric mixture LHV is the most important, since that it is the fuel-air mixture that promotes the engine combustion.

Since biodiesel is composed with more oxygen atoms, its energy content (LHV) is lower than fossil diesel, leading to a reduction on the developed power and torque. For the same reason its stoichiometric relation is also lower meaning that less air is needed. The higher oxygen content is also responsible for the increase of NO_x emissions.

2.1.4 Cloud and Flash Point

The flash point is the lowest temperature at a given ambient pressure for which the fuel vapor and air mixture are stoichiometric and is easily ignited. It aims to show the fuel flammability (Martins 2013). A very low flash point suggests a less secure fuel (to store and handle), i.e. minimum flash point for diesel fuel is required for fire safety. The cloud point is the temperature at which wax crystals begin to form, and usually defines the minimum working temperature of the fuel. In very cold climates, this cloud point may be problematic.

2.1.5 Hygroscopy and Impurities

The water content in biodiesel can come from poor drying techniques during manufacturing, or from its hygroscopic properties, absorbing water from atmospheric moisture and when in contact with excessive water during transport or storage. Excess water can lead to corrosion and provides an environment for microorganisms growth. Moreover it may decrease the net released heat of combustion.

2.1.6 Sulphur Content

Sulphur is released to the atmosphere as sulphur dioxide during the combustion of biodiesel, degrading the exhaust catalyst systems, causing acid pollutant emissions which have significant environmental and health issues. Generally, biodiesel

Table 1: A compilation of several biodiesels properties (ρ - density @ 15ºC (kg/m^3), LHV (MJ/kg), ν- kinematic viscosity @ 40ºC (mm^2/s), CI - cetane index, FP - flash point (ºC)) (Sadeghinezhad et al. 2013; Wu et al. 2009; Rakopoulos et al. 2011; Lešnik et al. 2014; Merkisz et al. 2016; Rakopoulos et al. 2008; Ozcanli et al. 2013).

	Diesel			**Sunflower**			**Cotton seed**			**Rapessed**			**Palm**			**Soybean**			**Corn**			**Waste fried oil**			**EN14214**	
	Min	**Max**	**Av.**	Min	Max	Av.	Min	Max	Av.	Min	Max	Av.	Min	Max	Av.	Min	Max	Av.	Min	Max	Av.	Min	Max	Av.	**Min**	**Max**
ρ	**820**	**860**	840	860	920	885	850	910	880	872	885	879	870	878	875	873	914	889	884	915	895	870	884	877	**860**	**900**
LHV	**42**	**44**	43	37	39	38	37	42	39	37	40	39	37	40	39	37	40	39	36	40	38	40	40	40	--	
ν	**2.4**	**5.9**	3.4	4.0	34.0	10.2	3.7	34.0	10.6	4.6	11.0	6.5	4.5	7.1	5.3	4.0	39.5	13.5	4.2	32.0	13.5	4.9	6.9	5.6	**3.5**	**5**
CI	**45**	**55**	50	37	52	48	38	54	49	37	56	50	50	64	58	37	60	50	39	61	52	55	56	56	**> 51**	
FP	**66**	**75**	70	110	183	147	75	75	75	139	275	185	173	173	173	69	163	124	167	192	180	148	167	158	**> 101**	

contains lower sulphur than fossil diesel. The diversity of biodiesel feedstocks also makes the final fuel sulphur content diverse and sometimes above the one in the fossil diesel. (He et al. 2009)

2.2 General Known Advantages and Disadvantages

Using a certain biodiesel in a compression ignition engine (diesel engine), may result in some advantages comparatively to diesel, but it may also brig some disadvantages. From several studies it was clear that some benefits promoted by specific properties were not found in other studies performing the same experiments. This is often due to different injection control, engine operation, ambient conditions, and even fuel physicochemical properties. However, some of the following major advantages and disadvantages of biodiesel comparatively to fossil diesel should be expected:

Advantages

High cetane number, which increase the possibility of achieving high engine speeds and injection delays. Better ignition, and higher pressure and temperature during combustion;

- And then, reduction of some pollutant emissions (CO, HC, PM, as well as the smoke level) due to more efficient combustion;
- Low sulfur content, i.e. less sulfur related emissions;
- Good lubrication properties;
- Little toxicity and irritation to human body;
- Reduced engine noise;
- Relatively high ignition temperature (flash point), i.e. safety in operation and storage;
- It is an alternative (and renewable, from certain perspectives) fuel to fossil energy.

Disadvantages

- Lower energy content, then higher fuel consumption and possibly lower power and torque;
- Possible increased emission of NO_x , due to more oxygen content in the fuel and more complete combustion;
- Increased emission of aldehydes;
- Higher viscosity, which may have negative impact on the fuel atomization;
- Lower cloud point, i.e. worse low-temperature properties (difficult engine start and fuel pump issues);
- Shorter oil change interval due to deposit precipitation;
- Increased corrosion, which reduces durability of components made from elastomers, rubbers, and certain alloys made from copper, steel, aluminum, zinc and lead;
- Intense hygroscopy, since the fuel is able of bonding 40 times more water than diesel fuel, which may lead to greater susceptibility to microbiological contamination;

3 VEHICLE MODELLING

A passenger bus was modelled using the vehicle simulation software AVL CRUISE, developed by AVL (AVL 2017). The simulated vehicle has the characteristics as presented in Table 2 and Figure 1:

Table 2: Vehicle specifications.

Vehicle body	
Curb weight (kg)	12080
Gross weight (kg)	14300
Width / Length	2.55 / 12
Wheel base (m)	6120
Engine	
Number of cylinders	6
Displacement (cm^3)	7800
Max. power (kW) @ rpm	210 @ 2000 rpm
Max. torque (N.m) @ rpm	1080 @ 1200-1800 rpm

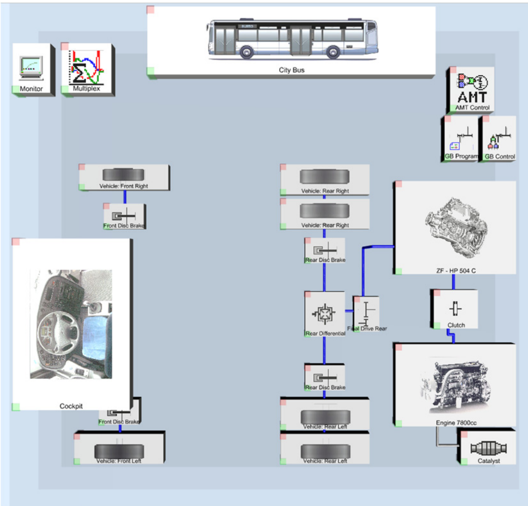

Figure 1: AVL CRUISE model.

Four driving cycles were considered for the bus simulation (Figure 1): ETC, UDDS, Lisbon_cyc, and Porto_cyc. The EPA (United States Environmental Protection Agency) Urban Dynamometer Driving Schedule (UDDS) has been developed for chassis dynamometer testing of heavy-duty vehicles; and the ETC cycle was developed by the former FIGE Institute, Aachen, Germany, based on real road cycle measurements of heavy duty vehicles (DieselNet 2017). The Lisbon_cyc and Porto_cyc are real measured bus routes performed in Lisbon and Oporto cities, Portugal.

Table 3: Driving cycles specifications.

Driving cycles	ETC	UDDS	Lisbon_cyc	Porto_cyc
Time (s)	1799	1060	5240	2138
Distance (km)	29.48	8.90	23.04	7.67
Av. speed (km/h)	58.97	30.4	15.82	12.91
Max. Speed (km/h)	91.1	93.3	65.5	54
Av. grade (%)	--	--	-2.1/2.3	-3.8/3.2

The first approach taken was to simulate the bus using pure diesel as fuel performing the four driving cycles with the full passenger capacity, i.e. using the gross weight. Then, the objective is to shown the engine emissions, and efficiency, for different biodiesel blends with fossil diesel (5%, 10%, 20% 40%, 60% 80%, 100%). Since the variation of the results is very sensitive to fuel properties (and biodiesel properties may vary depending on the fuel feedstock, and production processes), engine operation and ambient conditions, data from several studies were analyzed

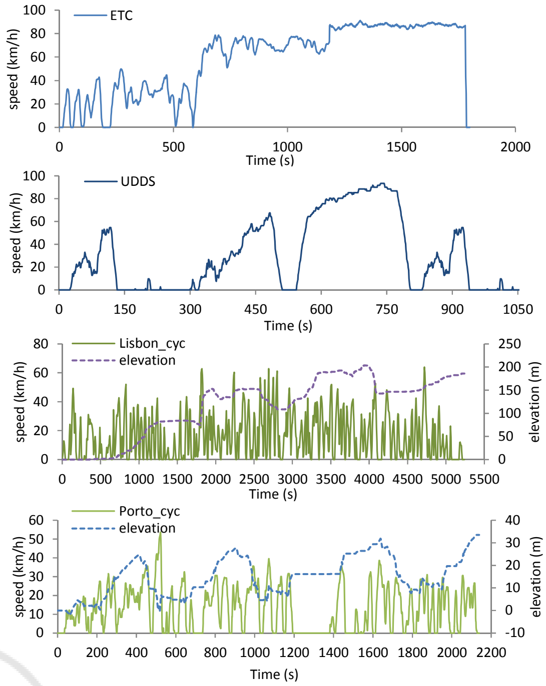

Figure 2: Driving cycles profile.

and implemented in the results as a simple sensitive analysis. Moreover, in order to avoid pollutant treatment system influence, the emissions results are from the engine exhaust.
Therefore, the results presented in section 4, contain the simulation results and present also some data based on this studies concerning the biodiesel blend influence in this kind of heavy-duty engines (Table 4), including data from different biodiesel sources.

Table 4: Studies used in sensitivity data.

blends	efficiency	Emissions	feedstock	Reference
B0-100	yes	NOx, CO, HC, PM	animal vegetal	(EPA 2017)
B5, 20, 70, 100	yes	NOx, CO, HC	rapeseed	(Buyukkaya 2010)
B10, 20	yes	NOx, CO, HC, PM	sunflower, cottonseed	(Rakopoulos et al. 2008)
B100	--	NOx, CO, HC, PM	cottonseed soybean rapeseed palm oil cooking oil	(Wu et al. 2009)
B100	--	NOx, CO, HC, PM	rapeseed	(Merkisz et al. 2016)
B100	--	NOx, CO, HC, PM	rapeseed	(Zhang et al. 2009)

4 SIMULATION OF ENGINE PERFORMANCE USING BIODIESEL

In this section we present the main results obtained from the vehicle simulation (Figure 3 to Figure 7).

As expected the real driving cycles, Porto_cyc and Lisbon_cyc, are the most demanding, i.e. the fuel consumption is higher. Following the same trend the PM and HC emissions are also higher in real cycles.

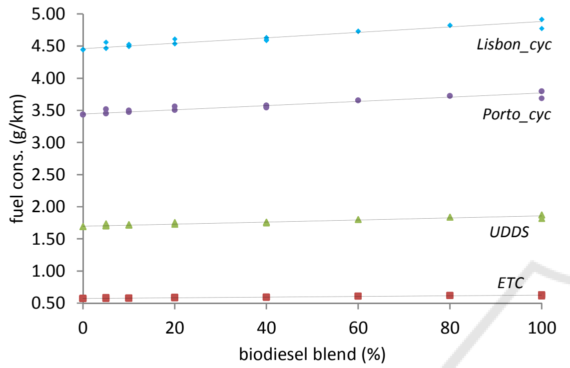

Figure 3: Engine fuel consumption function of the biodiesel blend for the four simulated driving cycles.

The increase of biodiesel in the fuel mixture causes a reduction of fuel calorific value, increases fuel density and kinematic viscosity. This leads to the increase of the fuel mass in the engine. Although higher combustion efficiency is expected, the fact is that the lower caloric value of biodiesel leads to higher specific consumption rates, and usually to a reduction of the maximum torque and power.

Many studies have been studying the effect of the biodiesel engine performance and emissions (e.g. the studies cited in this paper). The dissimilarities of the results may rely on several variables as highlighted in section 2, like fuel properties and feedstock, engine, etc. Differences in chemical composition properties of diesel and biodiesel fuel influence on different mass fraction of the elements C, H, S and O in the biodiesel fuel mixtures. Nevertheless, most of the authors generally agree that biodiesel increases the combustion efficiency, and temperature.

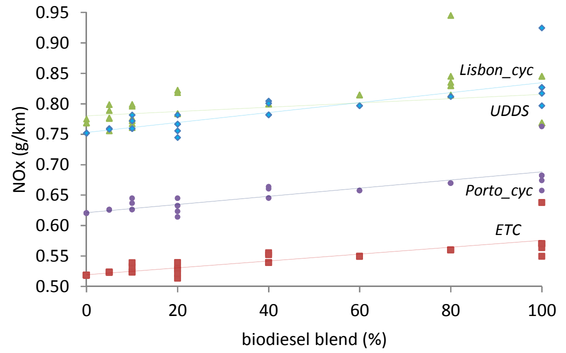

Figure 4: Engine NOx emissions function of the biodiesel blend for the four simulated driving cycles.

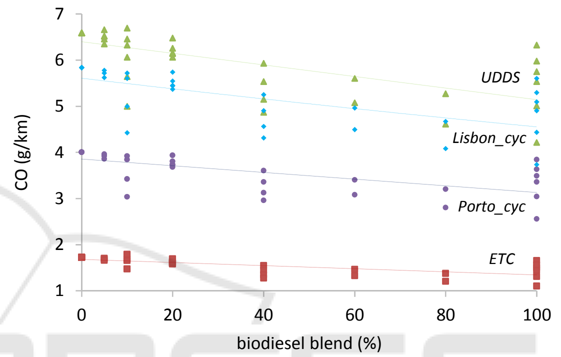

Figure 5: Engine CO emissions function of the biodiesel blend for the four simulated driving cycles.

The oxygen weight content of biodiesel is higher than that of diesel.

The oxygenated compounds of the biodiesel together with the combustion mixture in-cylinder remaining time due to the higher cetane number improve the fuel oxidation i.e. the combustion process is more complete. For this reason there will be less unburned fuel and HC emissions.

The oxygen contained in fuel contributes to an increase of the local oxygen–fuel ratio during combustion enabling a more complete combustion even in fuel-rich regions of the combustion chamber, contradicting the mechanism of PM and soot formation. The particulate emission reduction and specifically the reduction in soot emissions become one of the most important advantages of biodiesel.

As the oxygen content increases with the biofuel blend, larger fractions of the fuel carbon are converted to CO in the rich premixed region, rather than soot formation. Nevertheless CO emissions are also reduced. However the improved combustion efficiency is able to enable a more complete combustion.

Nevertheless, the higher temperature of combustion and higher oxygen content in the mixture, and also the increased stoichiometric burning (less rich) for biodiesel blends have disadvantages, for instance the increased formation of NOx emissions.

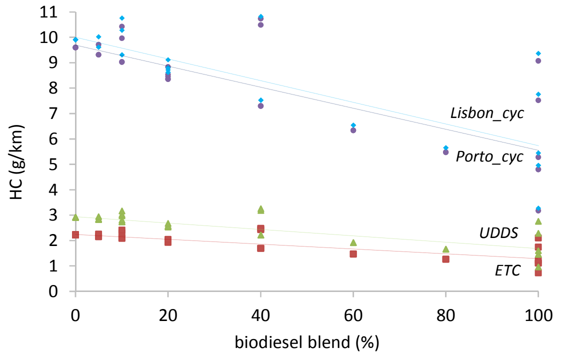

Figure 6: Engine HC emissions function of the biodiesel blend for the four simulated driving cycles.

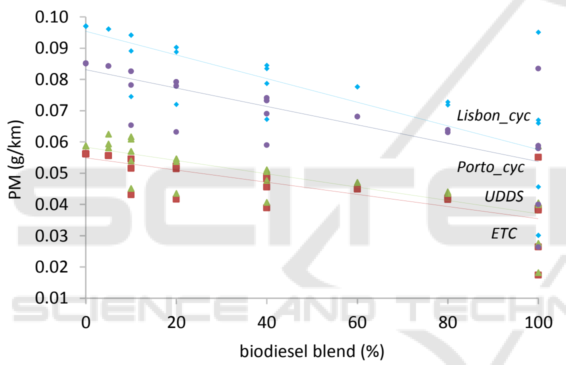

Figure 7: Engine PM emissions function of the biodiesel blend for the four simulated driving cycles.

5 CONCLUSIONS

An urban bus was simulated performing four different driving cycles, from which two were real measured driving cycles. Using biodiesel instead of the conventional fossil diesel in road vehicles has some advantages, from which the most agreed are the reduction of the pollutant emissions of HC, CO, and PM. Nevertheless, the use of such “renewable” fuel, in pure form or blended, has some disadvantages – the higher fuel consumption and higher NOx emissions. Although this seems to be the trend, it is also true that the fuel feedstock, fuel properties, and engine operation, may produce varied results. Therefore it is important to specify the fuel provenience, and from a global perspective, its advantages should be accounted at a life cycle level analyzing the impact at the engine and from its production.

The impact of using biodiesel in the engine is also be supported by exhaust treatment systems, like EGR (Exhaust gas recirculation for NOx reduction), DFP (diesel particulate filters), which may increase the potential local advantages of using biodiesel.

Finally, the costs of using biodiesel should also be addressed in future work. The increased consumption should be balanced by a competitive price comparatively to diesel. And, the vehicle investment costs should also be considered. The inherent properties of biodiesel may lead to the increase of maintenance or some modifications to the fuel system (engine included), especially for biodiesel blends above 10%.

ACKNOWLEDGEMENTS

This work was supported by the FCT (Fundação para a Ciência e a Tecnologia, Ministério da Educação e Ciência, Portugal) the Post-Doctoral grant SFRH/BPD/101090/2014, and the Program Investigator FCT IF/00181/2012. The authors would like to ackouwledge AVL troughout the AVL AST University Partnership Program (UPP). This work was supported by FCT, through IDMEC, under LAETA-UID/EMS/50022/2013; and by IDL under UID/GEO/50019/2013.

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