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SERVICE MILEAGE ASSESSMENT OF LUBRICANT CHARGE USED IN ENGINES FUELED WITH BIODIESEL B100

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Abstract. Degradation of the lubricant due to its use in engines fueled with biodiesel B100 was studied in a fleet of buses, which serves for urban public transportation in the city of Curitiba, Southern Brazil. For this purpose, samples of engine lubricant were collected and analyzed along 18 months. In order to confer statistical representativeness to collected data, a fleet of 7 vehicles was considered, four of these fueled with biodiesel B100, while the other 3 operated fed with commercial diesel fuel, thus the latter group served as a reference for comparisons. The following parameters of the lubricant oil were measured and analyzed: viscosity, basicity, acidity, oxidation, contamination by soot, contamination by nitrogenous substances, contamination by water, as well as contents of iron, lead, aluminum, copper, chrome, silicon and molybdenum, which are elements typically originated from the wear of metallic components. Collected data allowed pointing out the viscosity as the parameter of the lubricant that is the most sensitive one to concomitant use of the lubricant with biodiesel B100 fuel. In addition, the analysis showed that the service mileage of the lubricant charge can be extended from 7500 up to 9500 km in the case of bi-articulated buses, and from 10000 up to 11300 km in the case of mono-articulated ones.

Keywords: Biodiesel B100; Lubricant degradation in diesel engines; Analysis of lubricant performance in engines; Service mileage of engine lubricant.

1. INTRODUCTION

The increasing levels of pollution in urban centers have induced the adoption of mitigating measures in order to reduce negative impacts produced by automotive transport. In Curitiba, Southern Brazil, the office that regulates urban passenger transport in the city has promoted the use of pure biodiesel (B100) as a fuel for a fleet made of 34 buses. However, as this measure was put into practice, concerns related to a possible reduction of engine service life were

raised, thus forcing the vehicles-owner companies to adopt a conservative maintenance plan, which doubled the frequency of lubricant oil replacement. Nevertheless, a more frequent replacement of lubricant oil implies an increase in the environmental impact produced by the use of biodiesel, which may, if not eliminate, at least reduce significantly the benefits stemming from less-pollutant engine emissions. This was the opportunity for the present study, which was conducted with the goal of defining on a consistent basis the frequency of lubricant oil replacement in engines fueled with biodiesel B100.

In Brazil, the addition of biodiesel to diesel fuel became mandatory in 2008 and was gradually incremented from the initial value of 2% (in volume) up to the current 8%, reached in March of 2017 (BRASIL, 2014). This stimulation caused by the legislation led to an increased use of automotive biodiesel, and the consequent increase in Brazilian production, which rose from 0.07 million m³ in 2006 to 3.80 million m³ in 2016 (ANP, 2016).

Several raw materials are used in the production of biodiesel, such as vegetable oils, animal fats and used frying oil. According to ANP (2016) the produced in Brazil biodiesel is derived from soybean oil (76.4%), animal fat (19.8%), cottonseed oil (2.2%), and other vegetable oils such as palm, sunflower and castor (1.6%). Besides being renewable, biodiesel is also biodegradable; non-toxic; virtually free of sulfur and aromatic compounds; and may be produced with simple technology (FETRANSPOR, 2011). Additionally, biodiesel exhibits a higher lubricity than mineral diesel (Farias et al., 2010), thus allowing reduced wearing of fuel injection components (Knothe et al, 2006; de Sá Parente, 2003). According to Fontana (2011), the addition of 2% of biodiesel into the diesel fuel increases at twice the lubricity of the fuel. Biodiesel has other advantages over mineral diesel, such as a higher cetane number (CN), thus allowing a better control of the combustion start due to its reduced ignition delays; and a higher flash-point, then making safer its manipulation (Rakopoulos et al., 2006; Knothe et al., 2006). Soybean biodiesel has a CN ranging from 48 to 52 (Knothe et al., 2006), which is a value greater than that of petroleum diesel (typically about 40). According to Van Gerpen (1996) CN generally depends on the composition of the fuel and can affect the engine startability; noise; and emissions of exhaust gases. The latter is considered the largest biodiesel advantage, which lies on the fact of allowing a cleaner burning, resulting in lower pollutant emission levels when compared to mineral diesel.

On the other hand, Rakopoulos et al. (2006) highlight as disadvantages of using this biofuel its higher viscosity, lower heating value and lower volatility. In addition, biodiesel can attack some elastomers found in hoses and seals in the vehicle fuel system (Van Gerpen et al., 1997). Over time, this process is intensified and leads to deterioration of rubber connections and causes dryness of the hoses (Fontana, 2011; Hinrichs and Kleinbach, 2003). This effect is most noticeable after 100000 km usage and could be avoided by replacing rubber components by fluor-carbon elastomers. However, addition of up to 20% of biodiesel (B-20) is practically non-corrosive to rubber (Fontana, 2011). Another limitation of biodiesel is that it is less energetic than diesel. The lower heating value of soybean biodiesel is 37.2 MJ/kg while that of mineral diesel is 42.6 MJ/kg. Then, for the same volume of injected fuel the power loss would be of the order of 8.5% (Knothe et al., 2006). However, due to the higher viscosity of biodiesel, which reduces leakages losses in the injection system and increases the injected volume of fuel, the actual loss is just about 5% power, torque and efficiency when compared to diesel.

There are few studies in the literature about the effects that the use of biodiesel B100 causes on the lubricant. Perhaps the main reason for this shortage is the fact that results of such studies are strongly influenced by engine usage conditions. This in turn explains why in general such studies address fleets with well-established operating conditions. Schumacher et al. (2001) studied along 10 years a fleet of twelve trucks equipped with engines of 5.9 liters and fueled with blends of biodiesel and diesel containing 1, 2, 20, 50 and 100% of biodiesel (by volume). The engine lubricant of these trucks was periodically analyzed, having its contents of aluminum, iron, chromium, lead, copper and silicon measured. The results of these analyses indicated that the rate of wear of engines fueled with biodiesel was not worse than that of engines fueled with mineral diesel. Agarwal et al. (2003) analyzed samples of lubricant oil extracted from two engines, in order to determine contents of wear metals (Fe, Cu, Zn, Cr, Mg, Co and Pb). These engines were fed, respectively, with biodiesel B20 made of linseed oil methyl ester (LOME) and mineral diesel. Contents of metallic wear particles were found to be 30% smaller for the engine operated with biodiesel. Rakopoulos et al. (2006) noticed that the use of biodiesel leads to an increase of dilution and polymerization of the engine lubricant oil, thus requiring more frequent oil replacement. Manienyan et al. (2015) compared lubricant samples extracted from an engine powered either with biodiesel B20 or with pure diesel. Debris of cobalt, copper, iron, magnesium, lead and zinc in the lubricant were evaluated and it was reported that the amount of wear metals was lower when the engine was operated with B20.

Previous studies conducted in Brazil about the effects of using biodiesel fuel in fleets are restricted to B20 blends (FETRANSPOR, 2011; Lastres, 2011). Such studies reported alterations in physical and chemical characteristics of the lubricant oil and in the amounts of metallic traces resulting from the wearing of engine components. Fontana (2011) cites a series of experiments conducted in the city of Curitiba, in the context of a partnership held between Paraná Institute of Technology (TECPAR) and the Federal University of Paraná (UFPR). During these experiments the wear of cylinders, pistons and piston rings of a VW Golf vehicle equipped with a 1.9 liter engine was evaluated. This vehicle ran 160000 kilometers fueled with biodiesel B20. The wear of this engine was compared with the one of an engine that was used in similar conditions, but fueled with conventional diesel fuel. The comparison showed that the wear was lower in the engine fueled with B20.

2. METHODOLOGY

In order to assess the lubricant performance in engines fueled with biodiesel B100, a fleet of seven buses operating in the urban passenger transport of the city of Curitiba was analyzed during a period of 18 months. These vehicles are owned by *Auto Viação Redentor*, a licensee of public transportation of the metropolitan area of Curitiba in the state of Parana, Brazil. All vehicles in this fleet are of the model Volvo B12M and were equipped with engines DH12D340. Three of these vehicles are bi-articulated (capacity for 250 passengers, transmission ZF 6HP604C) and the other four are articulated (capacity for 170 passengers, transmission Voith DIWA 864-5E). Table 1 shows vehicles denomination, the fuel used in each of them, the manufacturing year and the respective mileage when the first sample of lubricant oil was collected. All the three bi-articulated buses were running in the trajectory called *Linha Verde*, while the articulated vehicles were running in the line called *Circular Sul*. It is worth mentioning, however, that the monthly trajectory of all the seven vehicles was around 6000 km.

Table 1. Main data of the studied fleet.

Vehicle code	Fuel	Manufacturing year	Mileage, km
Bi-articulated			
HE 700	Diesel B S10	2011	210759
HE 701	B100	2011	196131
HE 702	B100	2011	179734
Articulated			
HR 041	B100	2008	299558
HR 042	B100	2008	330221
HR 043	Diesel B S10	2008	281017
HR 044	Diesel B S10	2008	279901

As can be seen in Table 1, one vehicle of the bi-articulated group and two of the articulated group ran fueled with commercial diesel fuel (Diesel B S10) and these were adopted as the baseline for comparisons. In the case of the vehicle HE 700, which was running fueled with biodiesel B100 previously to the start of this study, a preparatory stage was necessary to change it into commercial diesel fuel. So, this vehicle had the fuel tank emptied and carefully cleaned to remove any traces of biodiesel. Afterwards, the fuel filters were replaced with new ones and the vehicle was then stocked with commercial diesel fuel.

Table 2: Characterization of the biodiesel B100 used in this study.

Characteristic	Unity	Limit ANP 45/2014	B100
Density (20°C)	kg/m ³	850 to 900	881,8
Kinematic viscosity (40°C)	mm ² /s	3,0 to 6,0	4,139
Water content, max.	mg/kg	200,0	174
Total contamination, max.	mg/kg	24	14,3
Flashpoint, min.	°C	100	113
Ester content, min.	% mass	96,5	98,3
Sulfated ash, max.	% mass	0,020	< 0,005
Total sulfur, max.	mg/kg	10	< 1,0
Sodium + Potassium, max.	mg/kg	5	< 1,0
Calcium + Magnesium	mg/kg	5	< 1,0
Phosphorus, max.	mg/kg	10	< 0,05
Acidity, max.	mg KOH/g	0,80	0,46
Free glycerol, max.	% mass	0,02	0,013
Total glycerol, max.	% mass	0,25	0,190
Monoacylglycerol, max.	% mass	0,7	0,598
Diacylglycerol, max.	% mass	0,20	0,108
Triacylglycerol, max.	% mass	0,20	< 0,0009
Methanol max.	% mass	0,20	0,09
Iodine index	g/100g	Take notes	129
Stability to oxidation at 110°C, min.	h	6	9,3

Table 3: Characteristics of the commercial fuel Diesel B S10.

Characteristic	Units	ANP specification	Found values
Aspect	--	Clear and clean	Clear and clean
Color	--	--	Yellowish
Density (20°C)	kg/m ³	815.0 – 853.0	840.0
Flash point, min.	°C	38	67
Electrical conductivity, min.	pS/m	25	80

Table 2 shows the characterization of the biodiesel B100 used during this study, which is the soy methyl ester. Limiting values, as specified by the Brazilian regulatory agency for fuels (ANP) are also shown in this table. The commercial diesel fuel (Diesel B S10), which has a maximum content of 10 mg of sulfur per kg of fuel, meets the ANP legislation for captive fleets operating in the urban transport (ANP, 2008). At the time when this study was started, in September 2014, this fuel included 5% of biodiesel by volume (B5). After July 2014 the commercial diesel fuel became mixed with 6% of biodiesel (B6), and in November 2014, the addition of biodiesel reached 7% (B7). These contents of biodiesel in the commercial diesel fuel were specified by the Brazilian Law 13033 (BRASIL, 2014). Table 3 shows the characteristics of the commercial diesel fuel as described in the bulletin of compliance emitted by the fuel vendor company.

The lubricant oil used in the engines of the tested vehicles was the Texaco Ursa Premium TDX SAE 15W40, which has a performance degree API CI-4/ACEA E7. This lubricant oil also meets the specifications of the engine manufacturer (Volvo VDS-3 application). Some characteristic data of a brand new oil sample are shown in Table 4.

Table 4: Main data of a new, unused lubricant oil sample (Ursa Premium TDX 15W-40).

Characteristic	Testing method	Value
Water (%)	ASTM D95	0,0
Glycol (%)	ASTM E2412	0,0
Carbon black (%)	ASTM E2412	0,0
Viscosity at 40°C, cSt	ASTM D445	108,6
Viscosity at 100°C, cSt	ASTM D445	14,65
TBN, mg KOH/g	ASTM D2896	9,75
TAN, mg KOH/g	ASTM D664	2,43
Oxidation (Abs/cm)	ASTM E2412	0,0
Nitration (Abs/cm)	ASTM E2412	0,0
Sulfation (Abs/cm)	ASTM E2412	0,0
Metals (ppm)	ASTM D 6595	
		B=0 Cr=0 Cu=0
		Fe=4 Mo=0 Na=2
		Ni= 0 P=1600 Pb=0
		Si=5 Sn=0 Ag=0
		Al=2 Ba=0 Ca=2650
		Mg=11 Zn=1369

The service mileage of the lubricant charge for vehicles fueled with biodiesel B100 was initially fixed as a half of that for vehicles fueled with commercial diesel. This choice was held for the initial 12 months of this study, but was changed for the last 6 months, when an extended lubricant service mileage was adopted for B100 fueled vehicles. Samples of lubricant oil were collected for analysis at two different moments during the service life of the lubricant charge. The first one was collected when the lubricant is still utilizable (approximately at 2/3 of its total service mileage) while the second sample corresponds to the lubricant that is being discarded at the end of the adopted service mileage. The first sample is called here as Sample A or, alternatively, Sample AE for the case of extended service mileage of the lubricant charge. Analogously, the second sample is called Sample D or Sample DE. Table 5 shows the elapsed service mileage of the lubricant charge at the moment when the samples were collected. The total number of samples of the same kind collected throughout this study is also shown in this table (as a number enclosed within parenthesis).

Table 5: Service mileage of the lubricant sample and number of analyzed samples.

Vehicle code	Fuel	Service mileage, km (number of samples)			
		Sample A	Sample D	Sample AE	Sample DE
Bi-articulated					
HE 700	Diesel B S10	10000 (8)	15000 (10)		
HE 701	B100	5000 (8)	7500 (10)	7500 (4)	10000 (3)
HE 702	B100	5000 (11)	7500 (13)	7500 (3)	10000 (3)
Articulated					
HR 041	B100	6500 (7)	10000 (8)	10000 (2)	13000 (2)
HR 042	B100	6500 (10)	10000 (9)	10000 (2)	13000 (2)
HR 043	Diesel B S10	13000 (6)	20000 (7)		
HR 044	Diesel B S10	13000 (5)	20000 (5)		

The samples were analyzed in order to monitor the condition of the lubricant oil and to evaluate the effects of the fuel on the lubricant. The following tests were performed for each collected sample:

- Measurement of viscosity at 40°C and 100°C (ASTM D445);
- Determination of total acid number (TAN) (ASTM D664);
- Determination of total base number (TBN) (ASTM D2896);
- Measurement of water content (ASTM D95);
- Condition monitoring in regard to carbonation, oxidation, nitration and sulfation (ASTM E2412);
- Measurement of wear metals content (ASTM D6595).

3. RESULTS AND DISCUSSION

3.1 Analysis of lubricant samples

Figure 1 shows the average values of measured viscosities at 100°C. It can be seen in this figure that the lubricant viscosity of the samples is lesser than the value corresponding to the new unused lubricant (14,65 cSt), thus indicating a dilution by the fuel. However, for all vehicles of the studied fleet the average values of viscosity remained above the minimum acceptable, which was set by the engine manufacturer as 12,5cSt.

Averaged oxidation values are shown in Fig. 2. It can be seen in this figure that deterioration was more severe in vehicles fueled with biodiesel B100. A similar result was found by Kovac et al. (2013), who concluded that increased concentration of biodiesel (5%, 10% and 20%) accelerates lubricant oxidation. It is worth mentioning that the engine of vehicle HE701, which ran fueled with biodiesel B100, was disassembled at the end of the study and by visual inspection it was established that there were no deposit formation, therefore, it was concluded that the higher values found for the lubricant oxidation stemmed from its dilution with biodiesel.

Averaged values of total base number (TBN) as measured during the first 12 months of this study are shown in Fig. 3. In comparison to the value corresponding to the new unused lubricant (9.45 mg KOH/g), there was a decrease in TBN values for all monitored vehicles. However, this decrease was more severe in vehicles fueled with commercial diesel fuel.

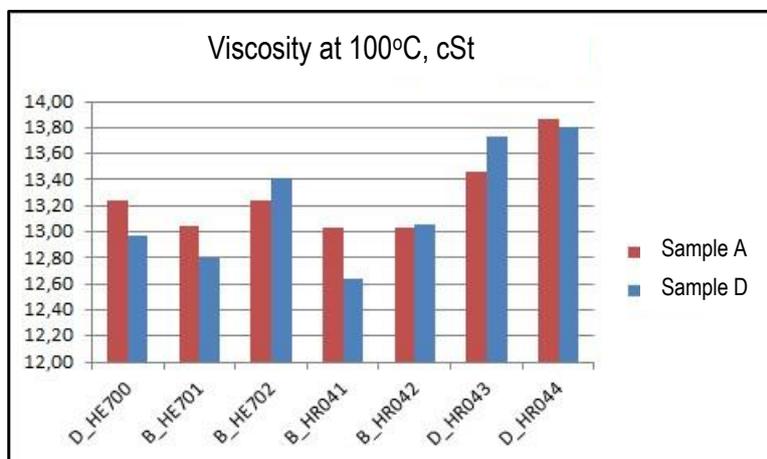


Figure 1: Average values of viscosities at 100°C measured along the first year of this study.

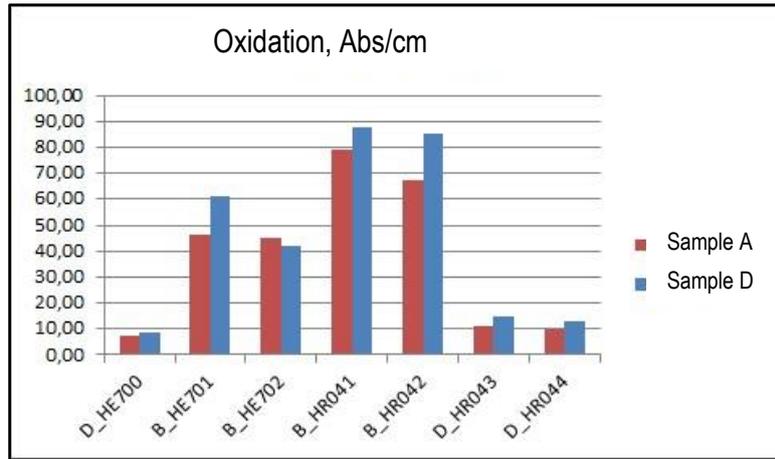


Figure 2: Average values of oxidation measured along the first year of this study.

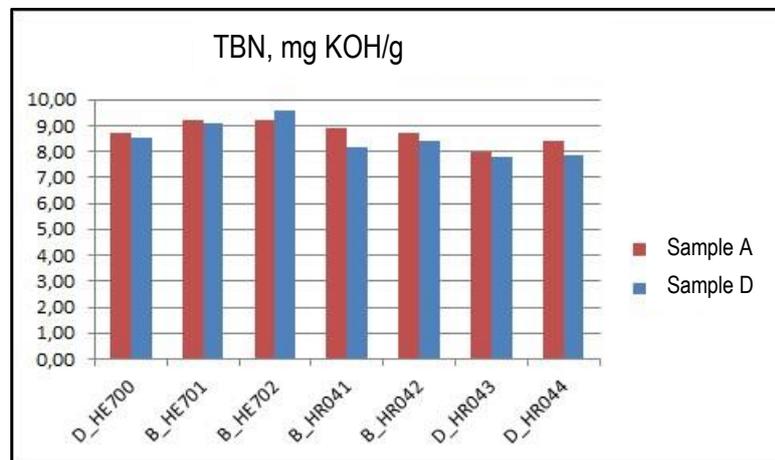


Figure 3: Average values of total base number (TBN) measured along the first year of this study.

The concentrations of wear metals in the lubricant, as measured throughout the first 12 months of this study, are shown in Figures 4 and 5. It can be seen in the left part of Figure 4 that concentration of iron debris in the lubricant is smaller for vehicles fueled with biodiesel B100, which indicates that the wearing was less severe in these vehicles. It is worth noting that the iron found in lubricant samples is due to wearing of the cylinder liner, the valve guide, piston rings, camshaft and crankshaft. The right part of Fig. 4 displays the concentration of copper in the lubricant, which was noticeably lower for articulated vehicles and even lower for the buses fueled with B100 belonging to this group. In the group of bi-articulated vehicles, wearing was lower for those fueled with biodiesel. This indicates less wear on bushings, oil cooler, bearings of the connecting rods and main bearings.

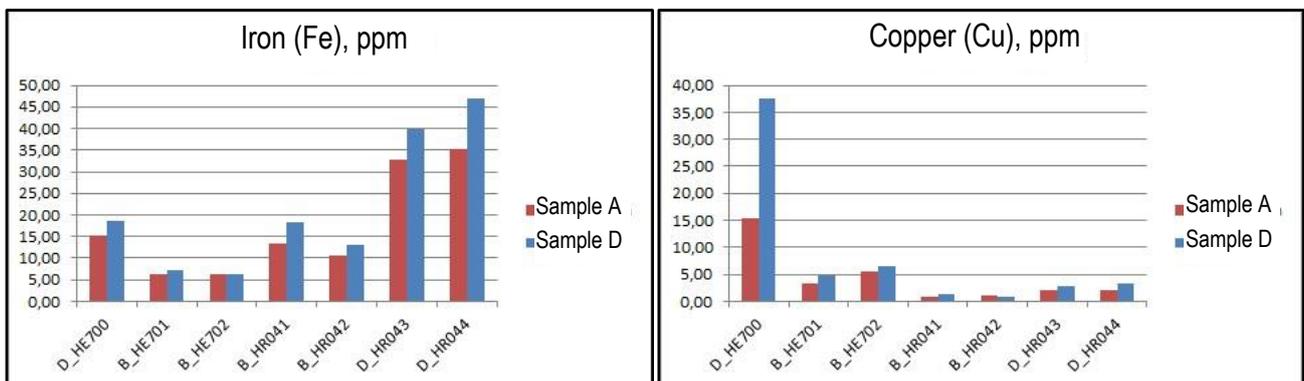


Figure 4: Average content of iron and copper, measured along the first year of this study.

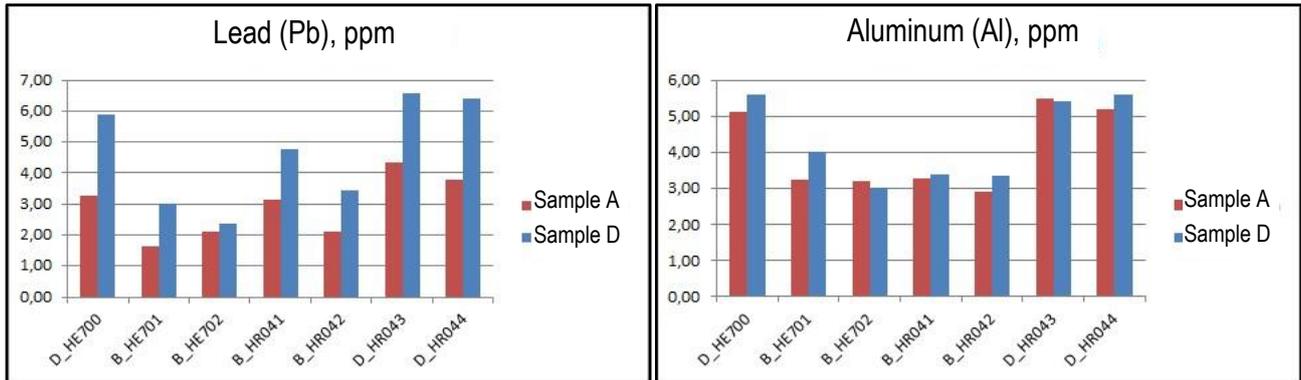


Figure 5: Average content of lead and aluminum, as measured along the first year of this study.

Left part of Fig. 5 shows that concentration of lead in the lubricant samples was lower for vehicles fueled with B100. This clearly indicates that the erosion from sources such as connecting rod bearings and main bearings was smaller in these vehicles in comparison to those fueled with commercial diesel. The concentration levels of aluminum in the lubricant samples can be seen in the right part of Fig. 5. It is clear that these concentrations are smaller in vehicles fueled with biodiesel B100, thus indicating that the wearing and erosion of components such as pistons and intercooler was lesser in these vehicles than in those fueled with commercial diesel.

Similar results were found in the analysis of samples collected during the last 6 months of this study, when an extended service mileage of the lubricant charge was adopted. These results showed that, as expected, a longer service mileage of the lubricant charge leads to an increase of the fuel dilution in the lubricant, thus further intensifying the reduction of both lubricant viscosity and TBN, as well as the increase of lubricant oxidation. In addition, since wearing and erosion are prolonged, the concentration of metal debris at the end of the lubricant service life also increases. However, all these lubricant characteristics but viscosity remained within the limits established by the engine manufacturer, shown in Table 6.

Table 6: Limiting values of some lubricant oil characteristics (Caines and Haycock, 2004).

Lubricant characteristic	Limiting value	
	Critical level	Volvo specification
Viscosity @ 100°C, [cSt] (min)	-	12.50
TBN, [mg KOH/g] (min)	-	4
Iron (Fe), ppm (max)	100	100
Copper (Cu), ppm (max)	50	20
Lead (Pb), ppm (max)	50	20
Aluminum (Al), ppm (max)	25	15

3.2 Assessment of lubricant service life

Taking into account the limiting values reported in Table 6 an evaluation was made of the maximal mileage for lubricant charge replacement, at which the averaged lubricant characteristics still remained acceptable. Since the differences in vehicle configuration, in maximal number of transported passengers and in traveling trajectory characterize different usage conditions, this evaluation was carried out separately for mono and bi-articulated vehicles. For this, it was initially observed that TBN and concentration of wearing metals remained far away from their limiting values for both groups of vehicles, while viscosity at 100°C was the lubricant characteristic that more rapidly approached to its minimum acceptable value. Thus, this parameter was taken as the more sensitive one to the use of biodiesel B100 as a fuel.

Throughout the present study, lubricant viscosity data for bi-articulated vehicles were obtained for mileages 0; 5000; 7500 and 10000 km, while for mono-articulated vehicles, the measurements were performed at 0; 6500; 10000 and 13000 km. Figures 6 and 7 show the available viscosity data, as well as a linear fitting of these. Linear fittings indicated that the minimum acceptable viscosity at 100°C (12.5 cSt) would be achieved with a lubricant charge service life corresponding to 9500 km for bi-articulated vehicles and 11300 km for the mono-articulated ones. Note that these values are smaller than the extended service mileage of the lubricant charge adopted in the final part of this study (10000 km and 13000 km, respectively, for bi-articulated and mono-articulated vehicles), but greater than the initially practiced values (7500 and 10000 km, respectively).

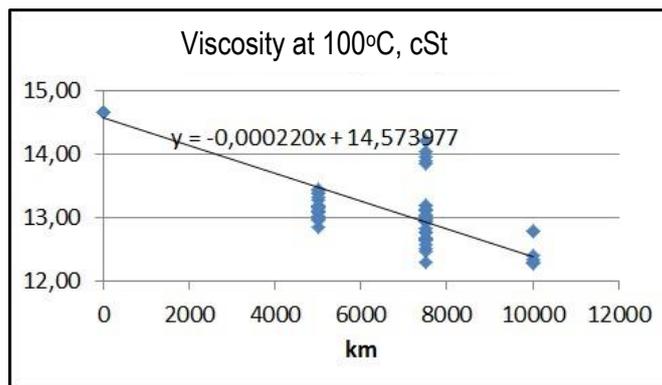


Figure 6: Viscosity data for bi-articulated vehicles fueled with biodiesel B100.

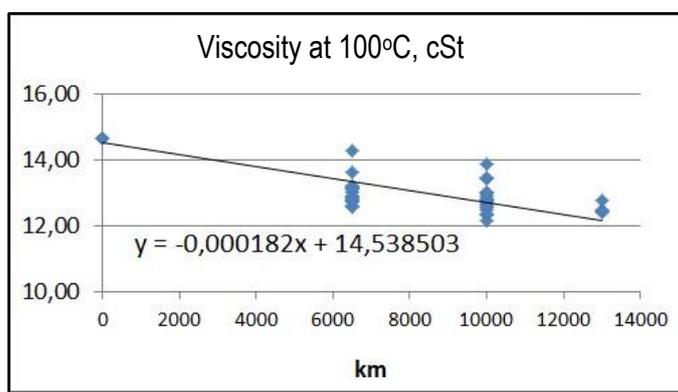


Figure 7: Viscosity data for mono-articulated vehicles fueled with biodiesel B100.

4. CONCLUSIONS

From the results drawn in this study it can be concluded that the use of biodiesel B100 as a fuel intensifies the effects of lubricant dilution by fuel. This way, the reduction of both lubricant viscosity and lubricant alkaline reserve (TBN), as well as the increase of lubricant oxidation (TAN), which are consequences of lubricant dilution, are more severe in vehicles fueled with biodiesel B100 than in those fueled with commercial diesel fuel. On the other hand, wearing and erosion are lesser in vehicles fed with biodiesel B100, which is probably a consequence of the higher lubricity of biodiesel B100 as compared to commercial diesel fuel. By this reason, vehicles fueled with biodiesel B100 exhibited smaller concentrations of metal debris produced during the wearing process. Finally, the viscosity was identified as the lubricant characteristic that is more sensitive to the use of biodiesel B100 as a substitute to commercial diesel. Adjusting a linear tendency function to the measured values of lubricant viscosity it was possible to establish that the service mileage of the lubricant charge can be extended from 7500 up to 9500 km in the case of bi-articulated buses, and from 10000 up to 11300 km in the case of mono-articulated ones.

5. ACKNOWLEDGMENTS

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7. RESPONSIBILITY NOTICE

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