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IMPROVED FLEET OPERATION AND MAINTENANCE THROUGH THE USE OF LOW VISCOSITY ENGINE OILS: FUEL ECONOMY AND OIL PERFORMANCE

POPRAWA EFEKTYWNOŚCI EKSPLOATACJI FLOTY DZIĘKI ZASTOSOWANIU OLEJÓW SILNIKOWYCH O NISKIEJ LEPKOŚCI: OSZCZĘDNOŚĆ PALIWA I WYDAJNOŚĆ OLEJU

For heavy-duty vehicles and road transportation, fuel consumption and associated CO_2 emissions have been of great concern, which has led to the development and implementation of technologies to reduce their impact on the environment. Low viscosity engine oils have arisen as one proven cost-effective solution to increase the engine efficiency; however, for the heavy-duty vehicle segment, engine protection against wear is a priority for end-users, and therefore there is some reluctance to the use of that new oil formulations. In this study, eight lubricant oils, representative of the HTHS viscosity reduction that heavy-duty oils have been undergoing and new API CK-4 and FA-4 categories, were evaluated for fuel economy, oil performance and engine wear, in a long-term test involving a fleet of 49 heavy-duty vehicles of four different engine technologies, some of them with diesel fuel and others with compressed natural gas. Results of fuel economy were positive for most of the buses' models. Regarding oil performance and wear, most of the formulations were found to be suitable for extended oil drain intervals (ODI); and although no alarming results were found, overall performance of the formulations of the fourth stage could lead to significant wear if the oil drain interval is extended. In this study, it should be noted that some of the information has been presented by the authors in other publications, here they are presented with the purpose of complementing the new results and summarize the entire test.

Keywords: *low viscosity engine oils, fuel economy, real working conditions, oil performance, engine wear.*

W przypadku pojazdów o dużej ładowności, i transportu drogowego w ogóle, ważny problem stanowi zużycie paliwa i związana z nim emisja CO2, które wymagają opracowywania i wdrażania technologii zmniejszających ich wpływ na środowisko. Jednym ze sprawdzonych i finansowo korzystnych rozwiązań w tym zakresie są oleje silnikowe o niskiej lepkości, które zwiększają wydajność silnika. Jednak w segmencie pojazdów ciężkich, priorytetem dla użytkowników końcowych jest ochrona silnika przed zużyciem, co pociąga za sobą niechęć do stosowania tych nowych preparatów olejowych. W pracy, przedstawiono badania ośmiu olejów smarowych o obniżonej lepkości wysokotemperaturowej HTHS reprezentatywnych dla produkowanych obecnie kategorii olejów do pojazdów ciężkich, z uwzględnieniem nowych kategorii oleju API CK-4 i FA-4. Oleje oceniano pod kątem oszczędności paliwa, wydajności oleju i zużycia silnika w badaniu długoterminowym obejmującym flotę 49 autobusów o silnikach opartych na różnych technologiach, z których część była zasilana olejem napędowym a część sprzężonym gazem ziemnym. Wyniki dotyczące oszczędności zużycia paliwa były pozytywne dla większości modeli badanych autobusów. Jeśli chodzi o wydajność oleju i zużycie silnika, większość preparatów okazała się być przystosowana do dłuższych okresów wymiany oleju; chociaż nie zaobserwowano niepokojących wyników, to jednak ogólna wydajność preparatów w czwartym etapie testu, mogłaby prowadzić do znacznego zużycia silnika przy wydłużeniu okresu wymiany oleju. Część przedstawionych danych publikowaliśmy już w innych pracach. Niniejszy artykuł stanowi uzupełnienie poprzednich wyników oraz podsumowanie całego badania.

Słowa kluczowe: *oleje silnikowe o niskiej lepkości, oszczędność paliwa, rzeczywiste warunki pracy, wydajność oleju, zużycie silnika.*

1. Introduction

Reduction of engine oils' viscosity has been one of the main cost-effective alternatives to reduce fuel consumption of internal combustion engines [19, 3] and therefore to reduce CO_2 emissions to levels required by standards and governments' laws [18, 6, 31, 35]. The evolution of the oil formulations has been accompanied by developments in the engine that also seek to improve the engine efficiency and reduce emissions; however, many of these solutions are either harmful to the lubricant oil or require it to work under more severe working conditions and contamination [22, 13, 38, 8]. In this way, new oil formulations are aimed to reduce the engine parasitic losses, associated with friction, but also ensure proper lubrication of the engine and wear protection.

In the last years, standards that classify the engine oils for the heavy-duty vehicles (HDVs) segment have been updated to account for changes in the working conditions of the vehicles and to comply with the environmental regulations. In this regard, the American Petroleum Institute (API) launched two new oil categories at the end of 2016 to define oils for fuel economy; these are API CK-4 with an unchanged HTHS viscosity limit above 3.5 cP, and API FA-4 category with a reduced viscosity between 2.9 and 3.2 cP [20]. The Society of Automotive Engineers (SAE) on the other hand, has released new oil viscosity grades for the HDVs and light-duty vehicles (LDVs) since 2013, the SAE 16 with HTHS viscosity of 2.3 cP, followed by SAE 12 and 8, released in 2015, with viscosity limits of 2 and 1.7 cP, respectively [25].

From the lubrication theory, these reduced viscosity values can help to decrease friction mechanical losses when the working conditions promote the appearance of hydrodynamic lubrication, and therefore friction is only determined by the shearing of the oil [22, 30]. Nonetheless, internal combustion engines comprise complex tribological pairs working under the different regimes of lubrication during one cycle. The piston-cylinder assembly, journal bearings and valve train, are therefore the main contributors to friction losses [30, 10, 24, 29]. In this way, reducing the oil viscosity comes with the risk of not being able to create a fluid film of lubricant, due to lower film thicknesses, and therefore promote mixed and boundary lubrication, where there is direct contact between the surfaces [21].

Wear of the engine components is a direct consequence of mixed and boundary lubrication, determining the performance and lifetime of the engine. Taking into account that HDVs usually work under low-medium speeds and high loads, an optimum balance between lubricant oil viscosity and wear protection must be found if fuel economy and greenhouse gas (GHG) emissions reduction is the goal, accompanied with the enhancement of maintenance practices, reduction of operation and maintenance costs and unscheduled downtimes. A recent work developed in a LDV, by instance, demonstrated that very low HTHS viscosity values are no longer able to significantly reduce fuel consumption and even increased the engine wear [26].

Low viscosity engine oils (LVEOs) have been extensively evaluated for fuel economy and performance, especially for LDVs under stationary and real working conditions [16, 11, 27, 26, 5]. For the HDVs segment, on the other hand, studies are more limited [35, 36, 32, 33] due to requirements and costs inherent to the vehicles operation. The study presented here aims to develop an exhaustive analysis of the effect of different engine oil formulations over fuel economy, performance and engine wear, under real working conditions of a public service HDVs fleet; and in this way highlight the importance of choosing the correct oil formulation, which in turn has a direct impact on the operation and maintenance of the fleet [23]. Attending to advances in the development of lubricant oils, with ever lower HTHS viscosity and the new API categories, a long-term test was developed, divided in four stages with a duration of one oil drain interval (ODI) each one, adding up more than 5 million km travelled. Taking into account that the oil performance varies with the engine design and working conditions, four different engine technologies were included in the test, three with diesel fuel and one with compressed natural gas (CNG). Regarding the oil formulations, they were evaluated a total of eight engine oils representative of the HTHS viscosity reduction that HDVs oils have been undergoing and different additives packages. Results demonstrated that reduction of HTHS viscosity and implementation of the new API CK-4 y FA-4 categories give positive results in fuel consumption reduction for three of the four buses' models. In terms of oil performance and engine wear, although no alarming results were found, it is possible to conclude that for new oil formulations, of the fourth stage, extending the ODI could lead to significant engine wear.

2. Methodology and materials

With the aim of developing a complete and comprehensive study of the effect of LVEOs in the HDVs segment, the work presented here comprises two sections. The first one to evaluate the effect of LVEOs over fuel consumption, and the second to assess the oil performance, degradation and engine wear, and consequently the potential effect on ODI (enlarging or decreasing) and thus in maintenance costs. Due to the multiple variables that accompany a real world test, such as environmental conditions, driving behavior, characteristics of the road (rolling resistance, elevation profile, traffic), number of passengers, that have an effect over fuel consumption, but that cannot be controlled, it was decided to develop a long-term test divided in stages (see Figure 1) of one ODI each one (30.000 km with a duration of about one year), completing a total of four stages. This test definition allowed obtaining a considerable amount of data with statistically significant results. Furthermore, the test definition, regarding oil formulation and buses distribution, was developed for each stage once results of the previous one were collected and analyzed. This was done with the aim of selecting the appropriate oil formulations for each bus model and prevent any possible engine damage.

Table 1. Characteristics of the bus models

Bus model	Diesel I	Diesel II	CNG	Diesel III
Model year	2008	2010	2007	2010
Length/width/height [m]	17.94/2.55/3	11.95/2.55/3	12/2.5/3.3	12/2.55/3.15
Vehicle approximate weight [tons]	17.5	12.7	12.1	11
Passenger capacity seated/stand	45/95	25/60	30/63	25/66
Engine displacement [cm^3]	11967	7200	11967	9300
Cylinders	6	6	6	5
Emissions certification level	Euro IV	Euro V	EEV	EEV
Power [kW]	220@2200 rpm	210@2200 rpm	180@2200 rpm	170@1900 rpm
Torque [Nm]	1600@1100 rpm	1100@1100 rpm	880@1000 rpm	1050@1500 rpm
Thermal loading [W/mm^2]	2.85	3.97	2.33	2.56
Oil sump volume [l]	31	29	33	31
EGR	NO	NO	NO	YES
Valve train configuration	OHV Roller follower (hardened steel)	OHV Cam follower (steel)	OHV Cam follower (steel)	OHV Cam follower (steel)
Engine oil specification recommended by manufacturer	API CJ-4 ACEA E4/E6/E7/E9			

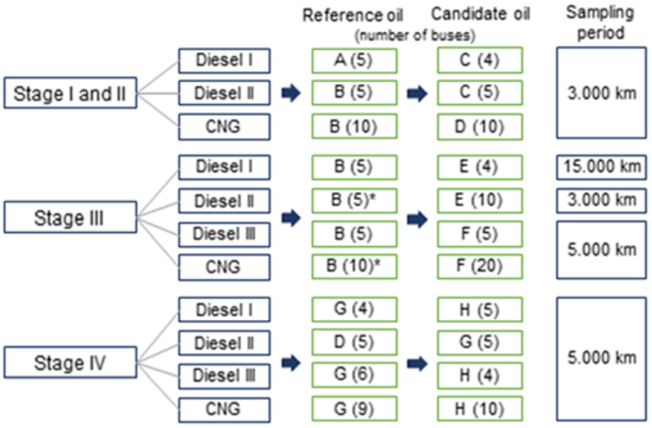

*Fig. 1. Distribution of the buses and oils for the four stages of the test. *Results of stages I and II were used as reference oil*

2.1. Fuel consumption test definition

Four engine models were selected for the test, three of them employing diesel fuel and one with CNG. Diesel I, Diesel II and Diesel III buses comply with the Euro IV, Euro V and EEV (Enhanced Environmentally friendly Vehicles) emissions certification level, respectively, while CNG buses comply with EEV. The main characteristics of the buses are presented in Table 1. In order to evaluate the LVEOs effect over fuel consumption, data of refueling and distance traveled by each bus was collected and recorded, in a daily basis, through GPS and information from the Computerized Maintenance Management System (CMMS) of the EMT of Valencia. Fuel consumption data was then calculated from these two parameters and averaged over the entire ODI period. In addition, average ambient temperature was recorded daily, as it has a significant effect on fuel consumption given, by instance, the use of A/C systems during summer season.

As it is shown in Figure 1, for the first and second stage of the test, 39 buses were employed, Diesel I, Diesel II and CNG. Following the recommendations of the buses OEMs it was decided to start with four formulations commercially available, splitting the group of buses in two, one using reference oil, and the other with an oil of lower viscosity. For the third stage, 10 Diesel III buses were included in the test and they were selected two oil formulations, as candidate oils, with HTHS viscosity values below the European Automobile Manufacturers' Association (ACEA) specifications for HDVs. Furthermore, data from the previous two stages were used for the analysis of results, that is, during the third stage, Diesel II and CNG buses only used candidate oil and results were compared with that of the reference oils used during the first and second stages. Given the novelty of the new API CK-4 and FA-4 oil categories, thought to improve fuel economy, it was decided to include two oil formulations complying with these API categories for the fourth stage of the test. In this way, except for Diesel II buses that continued to use a commercially available lubricant as reference oil, the rest of the bus models used API CK-4 oil as reference and API FA-4 as candidate.

Regarding the fuel used during tests, diesel fuel met the requirements of the standard UNE-EN 590 [4], while CNG fuel followed the requirements of the Commission Directive 2001/27/EC [7].

For each stage and once the ODI was completed, data recorded was submitted to Analysis of Variance (ANOVA). This is a statistical tool that allows evaluating the significance of the variables included in the analysis; these are daily temperature, oil mileage, month, oil formulation, service route and oil refill volume. As it was mentioned in Section 2, there exists variables inherent to the operation of the bus fleet that cannot be controlled and thus, the tests could not be randomized. The ANOVA analysis was therefore applied to each bus model separately avoiding the effect of different engine technologies, service routes, etc. on fuel consumption. Results of the ANOVA are percentage differences of the average fuel consumption between reference and candidate oil and their statistical significance with a 95% confidence.

2.2. Oil performance and degradation test definition

Oil formulations employed along the test are presented in Table 2 along with their main characteristics. Oils A, B, C and D are commercially available, while the rest of them are non-commercial new formulations for testing. Oil samples were collected following the

Table 2. Main properties of the oil formulations

Oil	A	B	C	D	E	F	G	H
SAE grade	15W40	10W40	5W30	5W30	5W30	5W30	5W30	5W30
API category	CI-4	CJ-4		CJ-4			CK-4	FA-4
API base oil group	I	III	III+IV	III+IV	III+IV	III+IV	III+IV	III+IV
kV@40°C [cSt]	108	96	71	68	55	54	68	55
kV@100°C [cSt]	14.5	14.4	12.5	11.7	9.8	9.4	12.6	10.5
HTHS@150°C [cP]	4.08	3.85	3.59	3.58	3.05	3.05	3.57	3.10
VI	>141	>145	>158	<169	>158	<169	168	165
TBN [mgKOH/g]	10	10	16	10	16	9	11	12
SAPS level	High	Mid	High	Mid	High	Mid	Mid	Mid
Calcium (Ca) [ppm]	1980	3357	5241	2329	3965	2282	1248	1312
Magnesium (Mg) [ppm]	704	15	27	100	25	61	847	895
Sodium (Na) [ppm]	nd	nd	nd	2.93	nd	nd	3.68	3.83
Barium (Ba) [ppm]	nd	nd	nd	10.03	nd	0.02	0.94	0.79
Phosphorus (P) [ppm]	731	1219	1064	712	960	712	715	764
Zinc (Zn) [ppm]	966	1534	1371	749	1132	827	784	835
Boron (B) [ppm]	195.10	4.50	301.95	3.63	897.82	12.36	311.85	333.69
Molybdenum (Mo) [ppm]	nd	nd	nd	nd	nd	nd	42.32	45.13
Used on stages	1,2	1,2,3	1,2	1,2,4	3	3	4	4

Table 3. Analytical techniques

Group	Parameter	Technique	Standard	Device
Degradation	Kinematic viscosity @100°C	Capillary viscometer	ASTM D-445	Cannon-Fenske opaque capillary viscometers
	TAN	Automatic potentiometric titrator	ASTM D-664	Thermo Scientific Orion 950 ROSS® FAST QC™ Titrator
	TBN		ASTM D-2896 (Fresh oil)	
			ASTM D-4739 (Used oil)	
	Oxidation	FT-IR Spectrometer	CMT-0080-11	iPal FTIR spectrophotometer, A2 Technologies
	Nitration			
	Aminic and antiwear additives		CMT-0120-12	
Wear	Wear metals and additives	ICP-OES Spectrometer	ASTM D-5185	iCap 7000 Series ICP Spectrometer

procedure depicted in ASTM D-4057 [1], with an interval between samples shown in Figure 1.

In order to evaluate the performance of the oil formulation and its condition along the ODI, a broad range of parameters were monitored. They are presented in Table 3 along with the technique, device employed and the standards that regularize their measurement procedure. These parameters have also been classified according to their purpose, that is, oil degradation and wear. Oxidation of the oil, aminic and antiwear additives were measured by FT-IR spectroscopy following an "in-house" methodology [17], based on ASTM D-7214. For the analysis of engine wear, inductively coupled plasma - optical emission spectrometry (ICP-OES) technique was employed, allowing to monitor the presence of wear metals and also those from the additive package in the oil formulation.

3. Results and discussion

3.1. Fuel consumption

Results of fuel consumption reduction due to the use of using LVEOs are presented here by bus model and for the four stages of the test. Results of stages I and II have been presented elsewhere in reference [15], where it was found that formulations with lower HTHS viscosity had significant benefits on fuel economy for the Diesel I, Diesel II and CNG buses, and that this potential is closely related with the engine's thermal load. Results of stage III, on the other hand, have been previously addressed in [32]; here LVEOs continued to prove their fuel economy potential, however, it was also concluded that for Diesel II buses, of higher thermal load, the use of formulations with HTHS lower than 3.5 cP, leads to the increase of fuel consumption.

In the bar plots presented in this section, bars with diagonal cross pattern represent the reference oil, while solid pattern is used for candidate formulations. Furthermore, fuel consumption difference between the reference and candidate oil is presented as percentage difference, therefore values with negative sign represent fuel saving, while positive sign means fuel consumption increase.

3.1.1. Diesel I buses

Six different oil formulations were tested in this bus model, being candidate oils E and H the ones with the lowest HTHS viscosity, 3.05 and 3.10 cP, respectively. Average fuel consumption at the end of each stage of the test is illustrated in Figure 2 along with the deviation of the measurements. Results of the ANOVA analysis are summarized in Table 4 with absolute and percentage differences in fuel consumption. Fuel savings were achieved for all the stages using a candidate oil of lower HTHS viscosity, although it is larger during the fourth stage. If HTHS viscosity values are compared between reference and candidate oil in the same stage, it can be seen that the smaller difference occurs in stage IV, suggesting that another parameter is helping to reduce fuel consumption, which would be the additives of the API FA-4 category.

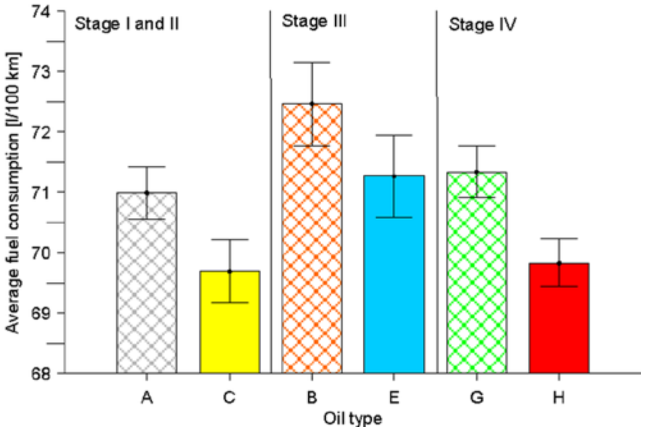

Fig. 2. Average fuel consumption and error bars for Diesel I buses along the test

Table 4. Fuel consumption for Diesel I buses

Reference - candidate oil	Absolute difference [l/100km]	Percentage difference [%]
A - C	1.30	-1.83
B - E	1.20	-1.65
G - H	1.51	-2.11

3.1.2. Diesel II buses

Average fuel consumption with the five oil formulations tested with this bus model are illustrated in Figure 3 and absolute and percentage differences in fuel consumption are in Table 5. For stages I and II candidate oil C gave non statistically significant fuel savings, less than 1%; therefore, and having analyzed the results of oil performance and degradation, it was decided to employ a formulation with a lower HTHS viscosity for stage III. Results with candidate oil E, which were compared with reference oil B of stages I and II, however, showed to greatly increase the fuel consumed by the buses in almost 6%. This result could be explained from the significant reduction of HTHS viscosity and the thermal load of this type of engine (Table 1); as the working conditions of a public service bus consist mostly of high loads and low engine speed, the appearance of mixed and boundary lubrication is likely to occur.

For stage IV on the other hand, it was decided to maintain HTHS viscosity in about 3.5 cP for the test oils D and G, the last one belonging to the new API CK-4 category. Results of fuel consumption gave an increase of 0.27% but its significance could not be proved statistically. Given that there is no difference in HTHS viscosity and the similarities in the rest of the oils' properties (see Table 2), this small fuel increase could be attributed to deviations in the measurements.

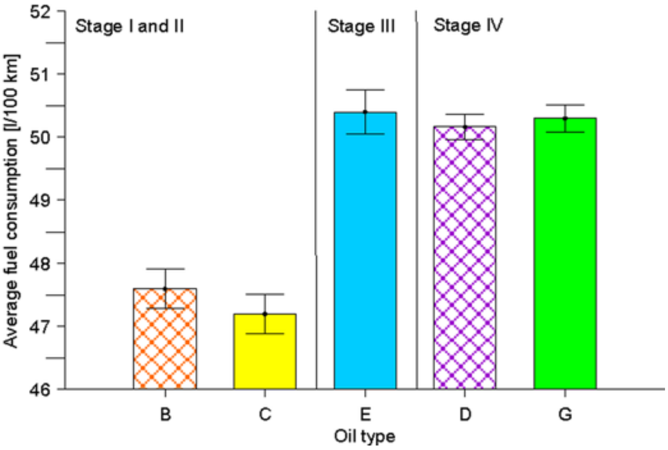

Fig. 3. Average fuel consumption and error bars for Diesel II buses along the test

Table 5. Fuel consumption differences for Diesel II buses

Reference - candidate oil	Absolute difference [l/100km]	Percentage difference [%]
B - C	0.43	-0.90 N.S
B - E	2.84	5.97
D - G	0.14	0.27 N.S

3.1.3. Diesel III buses

Diesel III buses were included in the test for stage III and IV. The average fuel consumption of the four oils tested in these buses is shown in Figure 4 and the differences in fuel consumption at the end of each stage are summarized in Table 6. As for Diesel I buses, fuel consumption savings gave greater results in stage IV than in stage III, even though the difference in HTHS viscosity values between reference and candidate oil are smaller. Results of both stages demonstrate that for this bus model it is possible to continue lowering the HTHS viscosity below 3 cP, however, it is also important to highlight the contribution of the additives of the API FA-4 category to fuel economy.

3.1.4. CNG buses

Average fuel consumption of the six oil formulations tested in CNG buses at the end of each stage are shown in Figure 5, while comparisons of fuel consumption reduction between reference and candidate oil are summarized in Table 7. For stages I, II and III, candidate oils gave the greatest fuel savings among all bus models, demonstrating the potential of LVEOs, especially when HTHS viscosity is reduced to 3.05 cP (oil F); a maximum fuel consumption reduction of 4.5% was achieved with this formulation. Furthermore it can also be seen, in stage I, that a small difference in HTHS viscosity can even give positive results for fuel economy. In stage IV, the percentage of fuel economy was reduced, although it is in the range of results obtained with Diesel I and III when comparing candidate oils G and H.

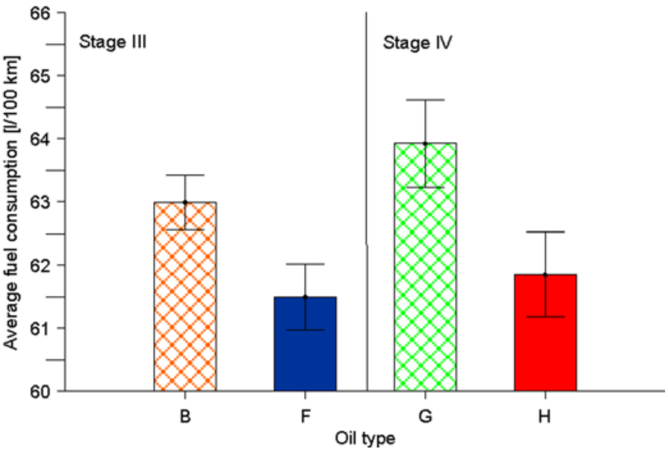

Fig. 4. Average fuel consumption and error bars for Diesel III buses along the test

Table 6. Fuel consumption differences for Diesel III buses

Reference - candidate oil	Absolute difference [l/100km]	Percentage difference [%]
B - F	1.48	-2.35
G - H	2.07	-3.24

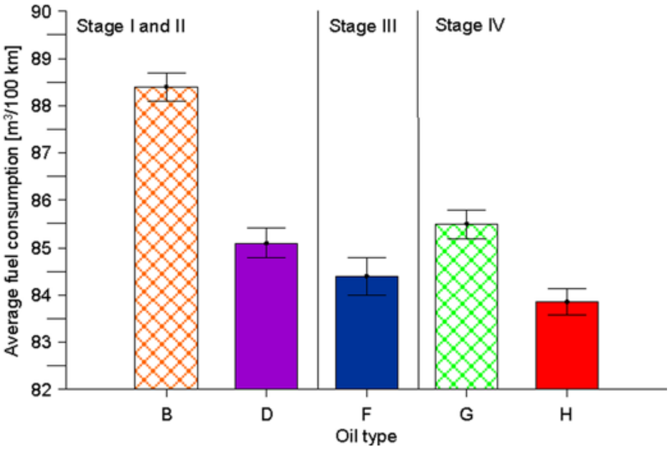

Fig. 5. Average fuel consumption and error bars for CNG buses along the test

Table 7. Fuel consumption differences for CNG buses

Reference - candidate oil	Absolute difference [l/100km]	Percentage difference [%]
B - D	3.30	-3.73
B - F	4.00	-4.52
G - H	1.64	-1.92

3.1.5. Fuel economy and thermal load

This section has been aimed to show the relation between the thermal load of the engine and the fuel economy potential of the different engine oil formulations. For this analysis, it is important to bear in mind that it is not possible to make a direct comparison between oils and engine technologies of different stages of the test, due to variables that cannot be controlled, such as ambient temperature and load (number of passengers), that may vary along the stages.

In Figure 6 it has been plotted the thermal load of the buses' engines (Table 1), defined as the maximum effective power over the piston area, against the fuel economy in percentage given by the candidate oil formulations. Here it can be seen that these parameters are strongly linked; for greater values of thermal load, the fuel economy potential of LVEOs tends to decrease, and even transform into fuel increase.

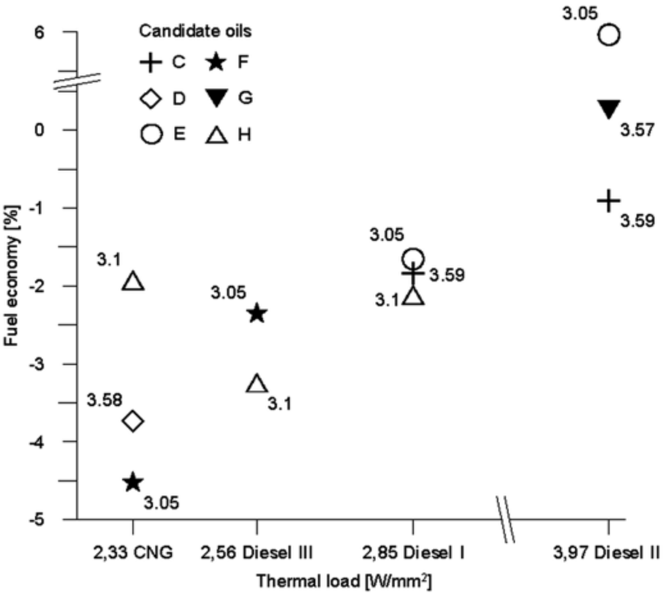

Fig. 6. Thermal load and fuel economy relationship

3.2. Oil performance and degradation

In this section are presented the most important results of oil performance, degradation and engine wear, obtained along the four stages of the test. Results of the parameters summarized in Table 3 are illustrated by engine model. Results of stages I and II have been previously presented in [14], and those of stage III in [33].

3.2.1. Kinematic viscosity

Kinematic viscosity was measured at 100ºC. Variations in this parameter have two main causes, one related with oxidation of the base oil [28], which in turn depends on the thermal load of the engine, and the other with the viscosity index improver (VII) added to the formulation. The effect of VII polymers consists in increasing the oil viscosity at elevated temperatures while keeping low resistance to flow in cold; however, this effect decreases with oil aging and is also affected by the high shear conditions presented in the normal engine operation [34, 37]. Results of kinematic viscosity at 100ºC are shown in Figure 7.

For Diesel I buses, oils A, B and C present a decrease in the kinematic viscosity along the ODI, suggesting shearing of the VII as the predominant factor of viscosity variation. On the other hand, oils G and H of the fourth stage and oil E of the third one, present an increase in the kinematic viscosity, as a result of its oxidation rates (see Figure 8). For oil E and H, a combination of the effect given by the VII shearing and base oil oxidation, resulted in a slighter increase of viscosity than oil G, which could have lower VII shearing.

For Diesel II buses and oils B and C, kinematic viscosity has a slight decrease along the ODI, as a result of the VII shearing that reduces the viscosity, accompanied by the opposite effect given by the oil oxidation. For the oil E the oxidation rate shown in Figure 8, was higher than C and its effect can be seen in the slighter variation of its kinematic viscosity.

For Diesel III and CNG buses, Figure 7 shows the prevalence of base oil oxidation for all the oil formulations. Stands out the results of oil F in Diesel III buses, its oxidations change along the ODI is lower than the other formulations, but the increase of its viscosity is higher. This situation suggests the presence of contaminants in the oil, such as soot.

In this study, the oxidation effect over the increase of kinematic viscosity was analyzed, however, there are another factors that also have an effect on this performance, such as external contaminants and combustion by-products.

3.2.2. Oxidation and aminic additives

Lubricant oils can oxidize when they are in contact with oxidizing atmospheres, as a consequence of blow-by by instance [9], and especially at elevated temperatures causing the oil molecules to break, rearrange and react [12]. This reaction causes oil thickening and thus loss of fluidity [2]; which in turn has a strong effect on the life of the oil. Furthermore, oxidation of the oil is affected by the presence of metals, such as iron and copper, which can be in contact with the oil if there are engine components with these metals, and in the form of wear debris [28]. Figure 8 shows the results of the oils' oxidation, by engine model, as a percentage change taking the fresh oil measurement as reference. As expected, this oil parameter increased along the ODI for all the oil formulations, and especially for oil B with a

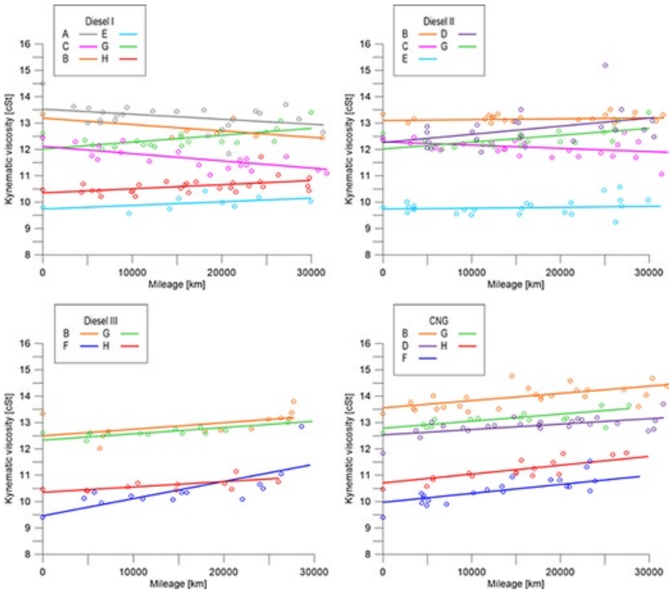

Fig. 7. Kinematic viscosity by engine model at 100ºC

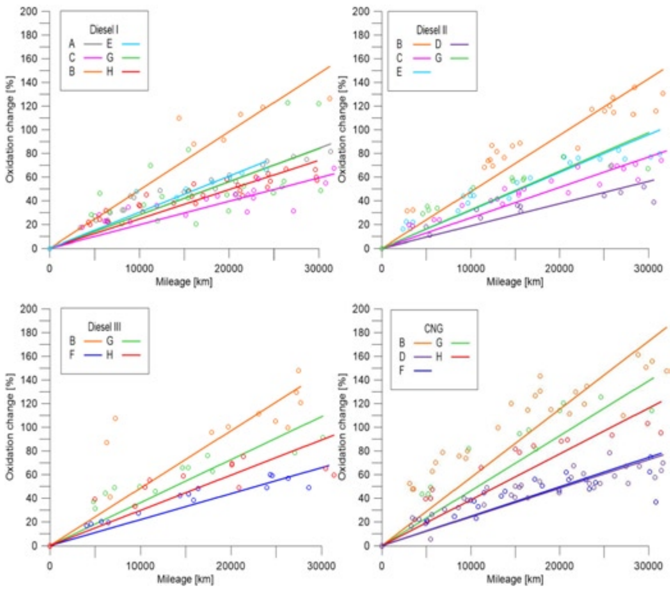

Fig. 8. Oxidation percentage change by engine model

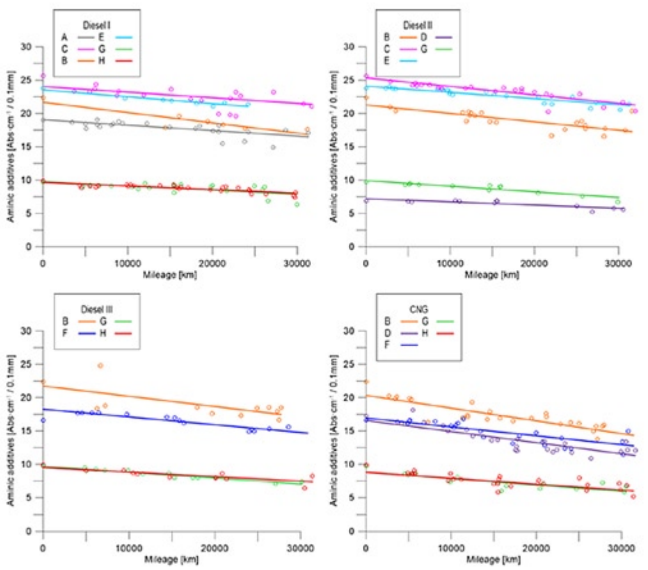

Fig. 9. Aminic additives by engine model

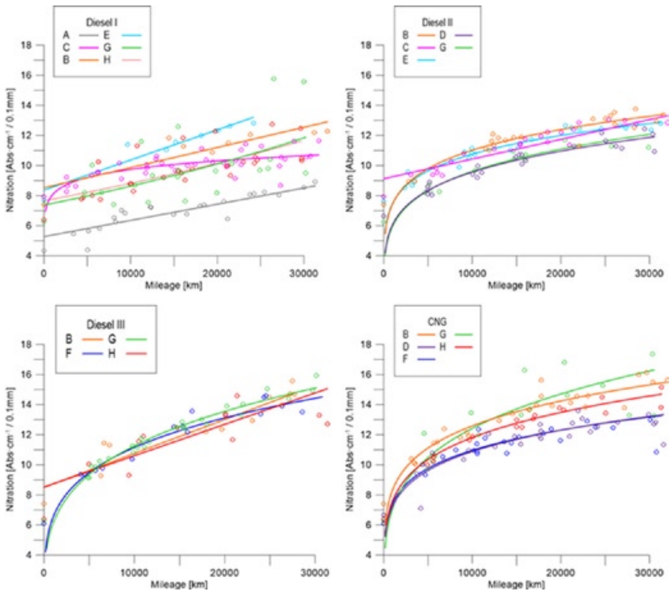

Fig. 10. Nitration by engine model

steeper slope in all the bus models. It can also be seen that the rate of oxidation was higher for the CNG buses because of the higher average combustion temperatures that they experience. For the Diesel III buses, the oxidation levels are also significant, possibly because of the use of EGR, which recirculates exhaust gases at elevated temperatures [13]. Oils G and H (API CK-4 and FA-4 oils) of the last stage present significant oxidation for all the bus models, especially if it is compared to previous formulations of lower oxidation resistance. This situation could be a consequence of the smaller quantity of aminic additive present in these formulations (shown in Figure 9), and the variation of the antiwear additive, as explained in Section 3.2.4.

In the following Figure 9, they are illustrated the results of aminic additives present in the oil formulations. Engine oils usually contain this additive along with ZDDP (zinc dithiophosphate) in order to delay the oxidation of the oil; its depletion along the ODI is clearly reflected in the oxidation rates of the oil. From these results, it can bee seen that the new API CK-4 and FA-4 oils contain smaller quantities of the additive, compared to the other formulations, but their depletion tendency is similar to some previous categories. Regarding oil B in Diesel I buses, the depletion of the aminic additive is more marked than the other formulations, which had an impact on its oxidation tendency.

3.2.3. Nitration

Nitration appears as a consequence of nitrogen dioxide (NOx) emissions from combustion reacting with the oil, it is closely related with oil oxidation in terms of its effects over the oil performance, that is, oil acidity, increase of viscosity and corrosive wear. This parameter was monitored by FT-IR spectrometer and results have been illustrated in Figure 10. Nitration along the ODI presented similar results to those of oxidation, although with smaller differences between the oil formulations. CNG and Diesel III buses presented the higher rates of nitration; for the former, the high temperatures reached during combustion, compared to diesel engines, promote the increase of NOx levels; while for the Diesel III engines, the use of EGR also introduces NOx compounds in the oil through the recirculated gases.

3.2.4. Antiwear additives

The antiwear additive used in the oil formulations, ZDDP, was monitored using a FT-IR spectrometer. The wavenumber range used for the measurements was between 1025 and 960 cm^{-1}, with two baseline points, one from 2200 to 1900 cm^{-1}, and the other from 650 to 550 cm^{-1}; results of antiwear additive are the measured area. Results of the content of this additive along the ODI are illustrated in Figure 11. Here, the depletion of the additive is marked for all the oil formulations; however for candidate oils of the fourth stage, G and H, the depletion of ZDDP is very significant; it can be seen that oils ran out of this additive before reaching the middle of the ODI for all the engine models, although it is more evident for CNG buses. Given that ZDDP is also used as anti-oxidant additive, the effect of its depletion can be observed on the oxidation rates of the oils, and in turn on the increase of TAN and wear of soft metals, such as copper and lead.

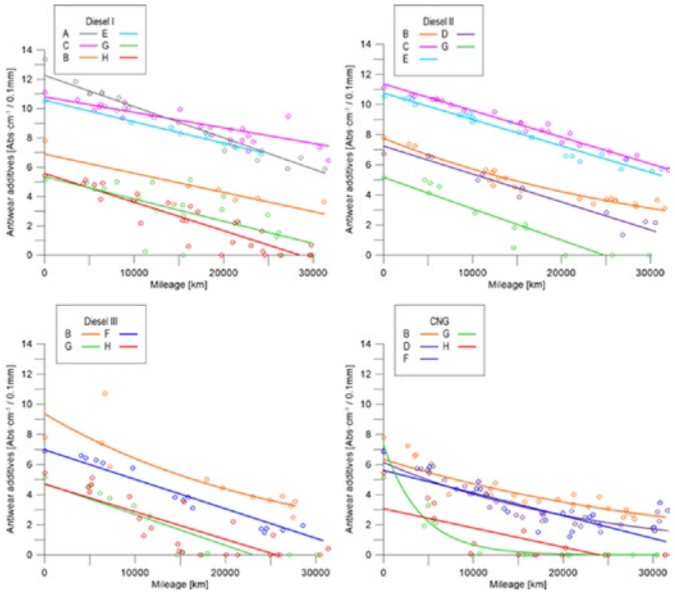

Fig. 11. Antiwear additives (ZDDP) by engine model

3.2.5. Total acid number (TAN) and total base number (TBN)

Results of TAN and TBN have been illustrated in Figure 12 and 13, respectively. It can be observed that the increase of acidic matter in the oil is significant for all the formulations and engine models. All the oil formulations presented marked decreases of TBN, and specifically for candidate oils of the fourth stage, G and H, TBN at the end of the ODI was about 50% lower than its initial value. In Figure 13, it can be noted that oils C and E have higher values of TBN from the

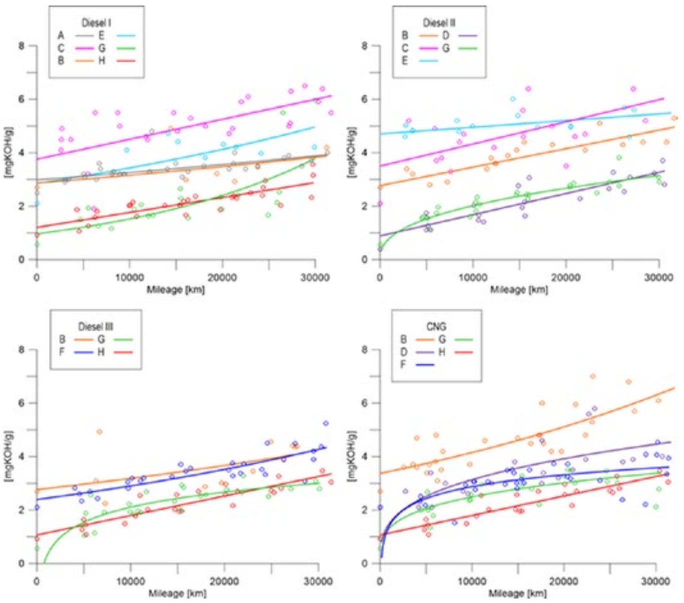

Fig. 12. TAN by engine model

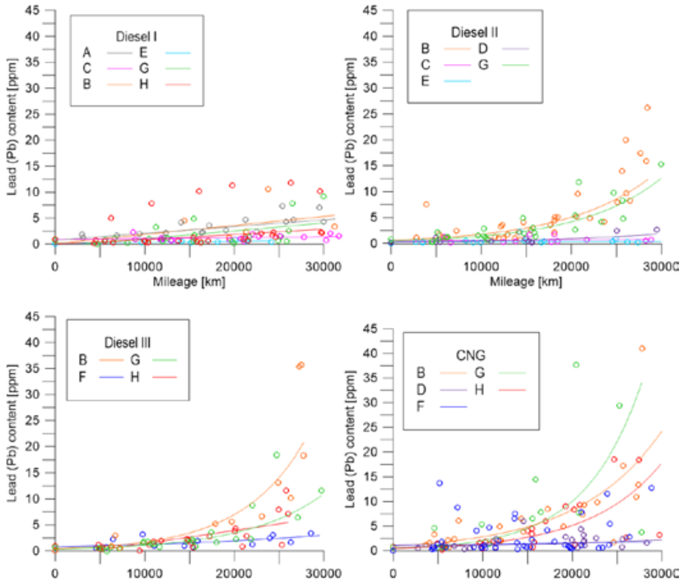

Fig. 14. Lead concentration by engine model

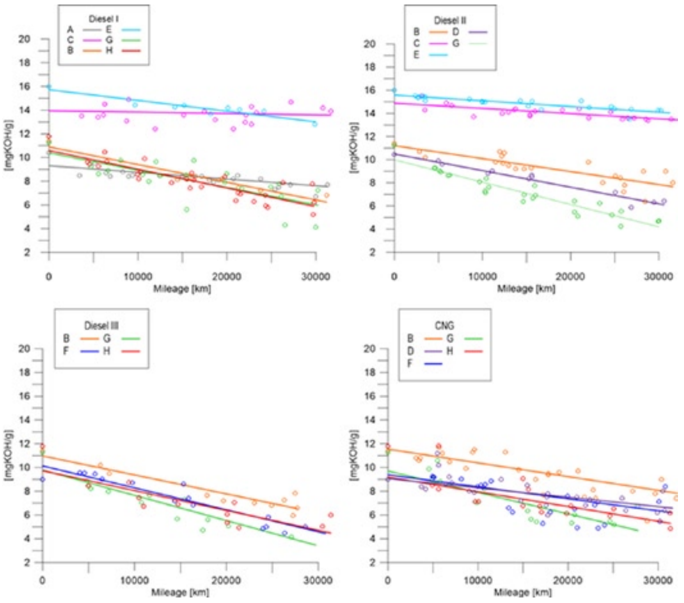

Fig. 13. TBN by engine model

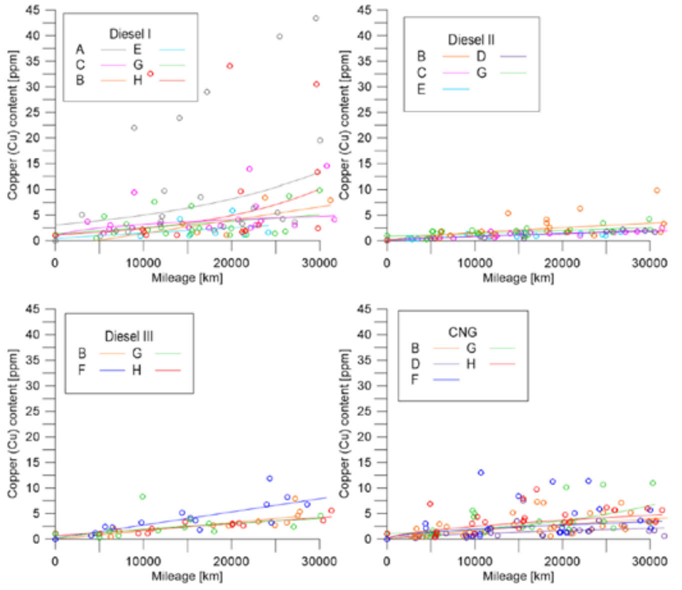

Fig. 15. Copper concentration by engine model

beginning of the test; this is due to the Ca-based detergent employed in these formulations (Table 2).

Results of this section, with high variations in the TAN measurements and the decrease of TBN, suggest the presence of corrosive wear [13] affecting lead (Pb) and copper (Cu), usually found in journal bearings and prone to corrosion [28]. The following Figures 14 and 15 show the concentrations of Pb and Cu, respectively, measured by ICP-OES spectrometer. Furthermore, in Table 8 and 9 are presented the mean and standard deviation (STD) of Pb and Cu concentrations, at the end of the ODI.

Regarding Pb concentration, its increase is significant for three of the engine models, Diesel II, Diesel III and CNG, and especially for oils B, G and H. Their increase can also be associated with the depletion of the antiwear additives, even before reaching 15.000 km, in some cases. Overall, the Cu content does not present abnormal results and the increasing rates are very similar between oil formulations. For Diesel I buses, oils A and H present some peak points however, given

Table 8. Mean and standard deviation of the Pb concentration at the end of the ODI

	Mean Pb concentration ± STD at 30.000 km[ppm]			
Oil formulation	Diesel I	Diesel II	CNG	Diesel III
A	4,3 ± 2,0			
B	3,4 ± 0,0	21,0 ± 13,5	21,8 ± 11,1	24,9 ± 11,0
C	1,3 ± 0,6	0,9 ± 0,5		
D		3,0 ± 1,7	3,0 ± 3,0	
E	0,6 ± 0,2	0,4 ± 0,2		
F			8,6 ± 10,5	3,9 ± 1,4
G	3,6 ± 3,6	8,7 ± 4,0	27,9 ±17,2	14,4 ± 7,9
H	6,6 ± 4,4		16,9 ± 10,8	7,1 ± 5,3

Table 9. Mean and standard deviation of the Cu concentration at the end of the ODI

	Mean Cu concentration ± STD at 30.000 km [ppm]			
Oil formulation	Diesel I	Diesel II	CNG	Diesel III
A	17,6 ± 14,0			
B	8,2 ± 0,3	4,4 ± 2,0	5,2 ± 3,6	5,3 ± 1,7
C	6,2 ± 4,6	2,0 ± 0,6		
D		2,0 ± 0,5	2,1 ± 1,3	
E	2,9 ± 2,1	1,9 ± 0,5		
F			4,5 ± 2,7	8,0 ± 2,6
G	5,5 ± 3,9	2,5 ± 1,0	6,4 ± 3,8	3,5 ± 0,9
H	20,3 ± 13,1		5,0 ± 1,1	4,0 ± 0,9

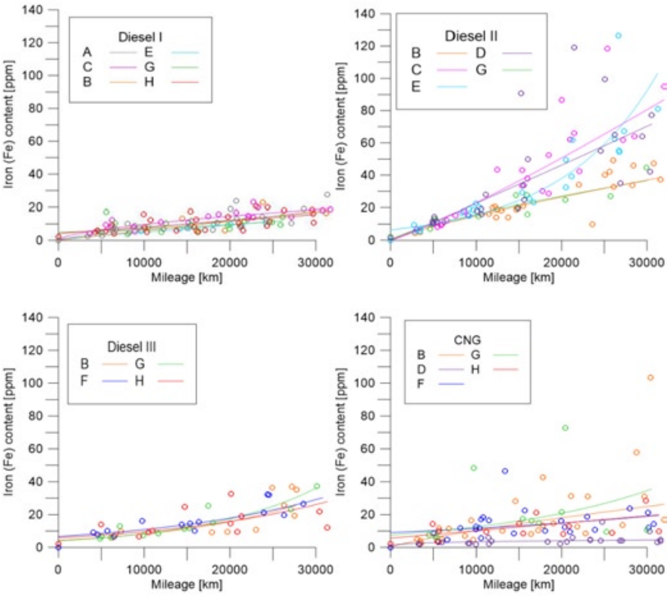

Fig. 16. Iron concentration by engine model

that the other wear metals, Pb and iron (Fe) (depicted in the following Section 3.2.6.), do not present high concentration values, its presence in the engine oil could be due to causes other than wear, such as external contamination.

3.2.6. Engine wear

To evaluate wear of the engine, the concentration of Fe in the oil was monitored by ICP-OES, and it can be seen in Figure 16 by engine model throughout the ODI. In the Table 10 are shown the results of Fe content in terms of wear ratio [ppm/10000 km] evaluated at the end of the ODI for all the bus models and their corresponding oil formulations. It stands out the significant increase of Fe content for the Diesel II buses and all the oil formulations, compared to the other bus models. This situation in the Diesel II buses arises from the combination of two main factors, their high thermomechanical stress, and the configuration of the valve train, which consists of steel OHV (over head valve) cam follower, leading to the increase of Fe debris in the oil. Overall, oil formulations of the fourth stage, G and H, showed to have a better performance in terms of Fe content than lubricants of previous stages, possibly due to the higher quality of the formulation.

Table 10. Wear ratio evaluated at the end of the ODI

	Wear ratio [Fe ppm/10000 km]			
Oil formulation	Diesel I	Diesel II	CNG	Diesel III
A	5.84	-	-	-
B	5.61	15.13	5.05	10.41
C	6.28	29.52	-	-
D	-	26.83	3.92	-
E	4.58	26.93	-	-
F	-	-	6.98	10.25
G	3.70	12.77	11.84	9.80
H	5.21	-	6.40	8.13

4. Conclusions

a) The use of LVEOs in HDVs continues to be a proven alternative to reduce fuel consumption and therefore the carbon footprint of internal combustion engines. Four engine technologies were involved in the test where eight different oil formulations were evaluated. Results showed fuel consumption reduction for three of the four buses' models, demonstrating that the potential of LVEOs is closely linked to the mechanical and thermal stress of the engine. For the Diesel II buses, for instance, it is clear that the optimum HTHS viscosity value has a limit in about 3.5 cP, a lower viscosity results in a significant fuel consumption increase of about 6%. The use of the new formulations G and H that belong to the latest API CK-4 and FA-4 categories gave greater values of fuel economy for the Diesel I and Diesel III vehicles, than in the previous stages of the test. This could be a consequence of lower HTHS viscosity, for oil H, and the additives used in the new API categories.

b) Overall, from the oil analysis, it can be observed that the performance of LVEOs was as expected with no significant effects on engine wear. Regarding oil degradation, formulations with lower HTHS viscosity presented higher variations in measurements of TBN and TAN and in kinematic viscosity, which can be attributed to the increased demands placed on the lubricating oil due to lower oil film thickness.

c) For oils G and H, it is important to highlight the significant depletion of the antiwear additives, even before reaching 15.000 km. Given that the SAPS level of the formulations is low and the fuel used by the vehicles has low content in sulfur, the marked increase of TAN can be associated with other factors, such as oxidation. These previously mentioned conditions can lead to limit any possible extension of the ODI. Results of Fe content in these oils, however, showed to be lower than most of the previous formulations, possibly due to the additives and higher quality of these new formulations.

d) Results presented here, obtained from a public service HDVs fleet, show the importance of a comprehensive analysis of the oil formulations used in the vehicles, as it gives valuable information to make well-informed decisions on the maintenance program of the vehicles, reduce costs, both of maintenance and operation, and to reduce downtimes and repairs.

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