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Assessment of Low Viscosity Oil Performance and Degradation in a Heavy Duty Engine Real-World Fleet Test

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Abstract

Low viscosity engine oils (LVO) are considered one of the most interesting solutions for improving fuel economy in internal combustion engines (ICE). There are different studies involving LVO and ICE, but currently limited data are available regarding “real-world” performance of LVO in a real service fleet. Included in a broadest study related with fuel consumption saving effects and performance of LVO in a real service fleet, the aim of this work is to present the results obtained in terms of comparative oil performance.
So, on this test, a comparative analysis using 39 buses was performed, based on a deep and extensive oil analysis program to assess those aspects above mentioned. Two engine technologies (Diesel and CNG) were considered and four different lubricants, two of them LVO and other two used as a reference baseline. The test duration comprised two oil drain intervals of 30000 km each one, totalizing more than 2 million of kilometers accumulated.
Results have shown that LVO presented an excellent performance along the oil drain interval (ODI), even improving some characteristics of the baseline oils with higher viscosity values. Results have shown that oil degradation is more dependent on engine technology, but in any case presented a penalization in terms of ODI reduction, a key indicator for end-users related with maintenance costs. In the case of CNG engines, higher oil degradation in terms of oil oxidation and nitration was observed.

Keywords
Low viscosity oils, Oil degradation, Fuel economy, Fleet test, Oil condition monitoring

1. Introduction

In recent years, an increasing concern about the environment and environmental health has been growing in the developed world. Being one of the main sources of pollutant emissions worldwide, ICE-powered vehicles have adopted a consistent trend of reduction of different emission types, spurred by government's legislation or OEM's initiatives. Furthermore, the regular evolution of fuel prices is always translated in a public interest for reducing fuel consumption of ICE, also related to emissions reduction.

Thus, a wide number of alternative options have appeared to improve ICE fuel economy: on one hand, improvements of different automobile systems (regenerative braking, start-stop, aerodynamics, etc.) and, on the other hand, significant improvements in terms of engine efficiency, focused on two different points of view: thermo-chemical processes involved in combustion and mechanical efficiency. Unfortunately, none singular contribution can reach final targets of fuel economy expected in a close future, and obviously an optimum combination of several alternatives will be required. In order to decide which one can be part of the solution, a previous analysis in terms of potential benefits versus implementation cost must be done. One of the solutions that presents a better ratio in terms of benefit versus implementation cost is the use of low viscosity oils[1], which directly affect in engine mechanical efficiency. It can be clearly noticed that the automotive industry has strongly bet for reducing the viscosity of oil; OEM's recommendations have shown a net reduction in SAE grades for service-fill oils[2]. Obviously, this situation has been accomplished by higher quality formulations, both improving base oils (including the evolution of base oils from API G-I to API G-III and G-IV) as well as the use of novel additives (partially obliged by the evolution of post-treatment technologies for some engines and stringent emission requirements)[3].

The basic physics of the application of LVO is based on the reduction of the thickness of the layer of lubricating oil which separates two surfaces in relative motion, according to the fundamentals of hydrodynamic lubrication. The fluid viscosity, the load carried by the two surfaces and the relative speed combine to determine the thickness of the fluid film. This, in turn determines the lubrication regime[4]. There are established four different lubrication regimes:

Hydrodynamic lubrication – two surfaces are separated by a fluid film.

Elastohydrodynamic lubrication – fluid-film lubrication in which hydrodynamic action is significantly enhanced by surface elastic deformation and lubricant viscosity increases due to high pressure[5].

Mixed lubrication – two surfaces are partly separated, partly in contact.

Boundary lubrication – two surfaces are mostly in contact with each other even though a fluid is present.

How these factors all affect the friction losses and how they correspond to the different regimes is shown on the Stribeck curve[6], in Figure 1.

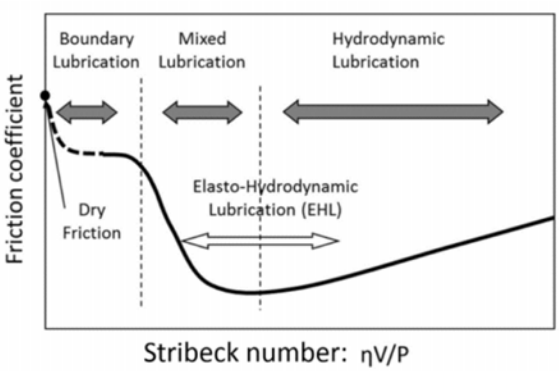

Figure 1. Stribeck curve and lubrication regimes associated.

Thus, the viscosity reduction has a very clear objective, diminishing viscous friction losses, but at the same time can lead to a non-desired consequences: changing the lubrication regime and therefore modifying lubricant's condition and performance[7]. Clearly in the quest for lubricant derived fuel economy it is essential to balance the need for reduced fuel consumption with the need to meet the most challenging OEM and industry specifications to maintain excellent engine durability[8]. Also, there is an interest of fleet operators and OEM's to extend oil drain intervals (ODI) without compromising engine future condition[9]. This performance can decisively influence engine life, because it can promote wear and other negative effects.

Thereby, in recent years different tests have been performed with engine oils with improved bases and additive packages in order to validate fuel economy and derived effects. There are different researches carried out in test rig[8,10–12] and in real fleet[13,14]. Engine wear and the most affected areas have also been measured in some test[15,16], but there are no studies on the performance of these LVO and their inherent properties variations throughout the oil drain interval.

The work presented on this paper is just a portion of a broader study, in order to verify and quantify fuel economy and potential derived effects of these low viscosity oils in real world conditions. Results obtained in terms of fuel economy presented clear benefit at all levels[17].

2. Degradation related to low viscosity oils

The implementation of new technologies to reduce emissions, such as the use of pilot injection or exhaust gas recirculation (EGR) have led to the emergence of new challenges to be met by the lubricant[18–20]. Also, the advancement of engine technology through downsizing and the introduction of new combustion strategies present a challenging environment for the engine oil. Not only do these hardware changes mean increased specific power density and higher lubricant temperatures, but also reduced lubricant volumes, representing that the lubricant resides in the piston zone for longer times and is exposed to combustion products at higher temperatures. All of these changes point towards faster oil degradation.

Moreover, the continuous evolution of environmental requirements and the emergence of different post-treatment systems have caused a revolution in the lubricants additive field, equivalent to the appearance of zinc dialkyldithiophosphate several decades ago[21,22]. The need to reduce the presence of sulphur and phosphorus in exhaust gases caused the evolution of the base oil and additives to formulations with less content of these ZDDP's, and with the presence of other chemical functional element -Calcium (Ca), Molybdenum (Mo), etc.- and consequently varying performance of these new lubricants[23].

Therefore, the emergence of new formulations is accompanied by a specific study of their performance and the possible effects on degradation and durability of these novel oils.

At the moment, there are whole tests series to evaluate oil performance; clearly marked on the ACEA, API, ILSAC and several OEM's specifications[24], but there is not a concise study focused on what happens during its use in real world conditions, specially related to degradation, including oxidation and nitration.

Oxidation is defined as a reaction involving oxygen and the typical final product of oxidation in common reactions of engine oils is an acid. Hydrocarbon oxidation to an acid involves complex steps where many different compounds are produced. On the other hand, nitration implies a similar phenomenon related with nitrogen oxides. These processes are the major source of oil degradation and its consequences are well-known: viscosity increase, varnish formation, sludge and sediment formation, additive depletion, base oil breakdown, filter plugging, loss of foam resistance, loss of demulsibility, acid number increase, rust and corrosion. Therefore, understanding and controlling them is a major concern for the lubricant formulator.

There are two main ways to evaluate degradation. Many laboratory tests are used to study the oxidation performance of new fluids, including ASTM D2272 (RPVOT), D4310 (sludging), D943 (TOST) and D6514 (UOT). On the other hand, there are several in-service oil tests including total base number (TBN), total acid number (TAN), wear metal analysis (including iron, lead and copper), RULER, and FT-IR spectroscopy, that have been used widely to study the effects of oil degradation during oil service life[25].

3. Oil analysis

In order to know thoroughly the phenomena that are taking place within the oil, there are a number of analytical techniques based on different physicochemical principles to detect the evolution of the lubricant and the emergence of several chemicals and disappearance of functional components.

3.1 Kinematic viscosity

Viscosity is a measure of flow resistance, and not only affects tribological performance, since it affects the sealing effect of oils and the rate of oil consumption. Oil viscosity is measured most commonly by kinematic viscosity, usually at 40 ºC and 100 ºC.

In this investigation the variation of this viscosity was studied along the ODI. Viscosity is a key factor regarding lubricant performance, and the list of root causes that can alter viscosity is quite extensive. A decrease in viscosity may occur when non-lubricants like water and diesel fuel accidently get into the lubricant. Another way the lubricant could be losing its viscosity is through the loss or shear down of the viscosity-index (VI) improver. Besides, typical oxidation processes result in higher viscous species, increasing the net viscosity of the lubricant.

3.2 Fourier Transform Infrared Spectroscopy (FT-IR)

FT-IR is one of the most widely used tools in oil analysis, due to its easiness of implementation, its capacity to detect oil condition variations and its quick response. FT-

IR is based on the fundamental principles of molecular spectroscopy, where different types of molecules absorb specific wavelengths, thus pointing their presence. The benefit is that different types of molecules such as the presents in additives, water, fuel and glycol have different functional groups. Therefore, it is possible to determine the presence of different molecules in the sample with FT-IR, simply by measuring the infrared absorption at different wavelengths. Industry standards present well-known FT-IR measurement procedures, including also water and soot contamination in used engine oils[26].

Among others, oil oxidation and nitration of lubricant represent some of the most important parameters in order to fully understand the degradation process in oil. There is recent research about its origins and its evolution along ODI, and there are some expectations to find more specific ways to detect oil deterioration point through this parameters[27–29].

On the other hand, FT-IR has been assessed recently as an analytical technique to detect presence of certain types of additives (due to the presence of characteristic molecular bonds), and some methodologies have been developed to quantify them[30]. In this study it has been used to quantify the aminic and antiwear additive depletion, using FT-IR spectra methodology measurement procedures based on ASTM D6810[31] and ASTM D6971[32].

In Table 1 a basic description of the FT-IR quantification measurement procedures is presented.

Table 1. Summary of FT-IR measurement methodologies. Adapted from Macián et al.[30] and ASTM E2412[26].

	Oxidation	Nitration	Soot	Aminic	Antiwear
Units	Abs/cm^{-1}	Abs/cm^{-1}	%	Abs/cm^{-1}	Abs/cm^{-1}
Measurement Test Method	Peak area	Peak area	Peak height	Peak area	Peak area
Frequency range (cm^{-1})	1725-1650	1650-1600	1999,86	1550-1490	1026-941
Baseline 1 (cm^{-1}) start to stop	2200-1900	2200-1900	2200-1900	2200-1900	1100-1098

Baseline 2 (cm^{-1}) start to stop	650-615	650-615	650-615	650-615	911-909
Correlation	-	-	Yes	-	-

3.3 Linear Sweep Voltammetry (Ruler)

Virtually every lubricant formulation contains antioxidants. These additives are designed to be sacrificial, meaning they oxidize before any other component of the lubricant, thereby protecting it. This oxidative protection is the only process saving the lubricant from premature failure. Based on the Linear Sweep Voltammetry principle[33], this technique is capable to detect different antioxidant additives presence in the lubricant, and its depletion along the ODI[34], due to the potential oxidation of the different additives present in the lubricant.

3.4 TAN/TBN

The total base number (TBN) describes the level of alkalinity reserve of oil, responsible for the neutralization of acidic contaminants coming from the engine. In some cases, judging the quality of engine oil solely on its TBN s may not be enough, since incomplete neutralization of acids will result in a more acidic environment in the engine, where corrosion can occur. Corrosion may negatively impact the wear levels of all critical engine components such as journal bearings, piston rings, cylinder liners and valve train components. So, in this case, measuring total acid number (TAN) offers complementary information about oil degradation[35]. In the present study TAN and TBN were measured using the potentiometric titration principle, according to ASTM D664[36] and D2896[37] standards.

4. Test design and settings

There are several conditions to be taken into consideration in order to develop a valuable and significant test: the selection of vehicles, oils and operating conditions. In order to represent common engine diversity of a typical heavy duty fleet, three different vehicles were selected including two different engine technologies: Diesel and Compressed Natural Gas (CNG). Other considerations assumed were the maximization of data obtained, since real world test include a lot of variability phenomena. But, in real world scenario, it was not possible to develop the test including all conditions desired, mainly due to fleet operator restrictions and ICE manufacturer specifications.

4.1 Bus fleet

A public transport fleet from the city of Valencia (Spain) was selected for this test. In order to broaden the range, different models of buses were chosen with two different heavy-duty engine technologies: Diesel and CNG. In addition, two different Diesel engines were used, certified with different emissions standards (Euro IV and Euro V) corresponding with most modern vehicles. The list of main characteristics related with vehicles and engines are presented in Brake mean effective pressure (bmep) is a relative engine performance indicator, obtained by dividing the work per cycle by the cylinder volume displaced per cycle38.

Table 2. It is important to state that all fuels used in this test were commercially available and they met European fuel requirements (UNE-EN 590 for Diesel fuel, and Commission Directive 2001/27/EC for CNG). Brake mean effective pressure (bmep) is a relative engine performance indicator, obtained by dividing the work per cycle by the cylinder volume displaced per cycle[38].

Table 2. Bus models considered in the test and main characteristics.

	Diesel Euro IV	Diesel Euro V	CNG
Year	2008	2010	2007
Vehicle length / width / height [m]	17.94/2.55/3	11.95/2.55/3	12/2.5/3,3
Engine displacement [cm^3]	11967	7200	11967
Emissions standard	EURO IV	EURO V	EEV
Cylinder configuration	6-in-line	6-in-line	6-in-line
Max. Effective power [kW]	220@2200 rpm	210@2200 rpm	180@2200 rpm

Max. Effective torque [Nm]	1600@1100rpm	1100@1100 rpm	880@1000 rpm
Oil fill volume [l]	31	29	33
bmep [bar]	16.8 @1100 rpm	19.55 @1100 rpm	9.24 @1000 rpm
Thermal loading* [W/mm^2]	2.85	3.97	2.33
Turbocharging	Turbo+Intercooler	Turbo+Intercooler	Turbo+Intercooler
EGR [-]	NO	NO	-
Valve train configuration	OHV Roller follower (hardened steel)	OHV Cam follower (steel)	OHV Cam follower (steel)
Piston-cylinder interface	Hardened steel sleeve	Liner	Hardened steel sleeve
Piston rings: Compression ring Scraper ring Oil control ring	Ceramic Chromium (3 mm) Chromium (3 mm) Ceramic Chromium (4 mm)	Ceramic Chromium (3,5 mm) Chromium (2,5 mm) Chromium (4 mm)	Ceramic Chromium (3,5 mm) Phosphated (3 mm) Chromium (4 mm)
Connecting rod bearings	-	Steel+Aluminium coating Steel+Bronze/Pb +Cu 3% coating	Steel+Bronze/Pb +Cu 6% coating
Main shaft bearings	Steel+Bronze/Pb + Cu 3% coating steel+Bronze/Pb + Cu sputter	Steel+Aluminium coating Steel+Bronze/Pb + Cu 6% coating	Steel+Bronze/Pb + Cu 3% coating

Camshaft bearings	Bronze/Pb	Steel+Bronze/Pb coating	Steel+Aluminium coating Steel+Bronze/Pb coating

* In terms of effective power per piston area.

4.2 Engine oils

As said before, the main purpose of this study was to assess the effect of the use of LVO in real conditions. Although the initial plan was to implement just two oils, considering one high viscosity SAE grade versus one low viscosity SAE grade, requirements derived from engine manufacturer (homologated products), fleet company (assurance warranty coverage) and oil supplier (commercially available products) led to change that previous assumption. Finally, four different commercial oils were chosen, two LVO considered as candidates, and two higher viscosity grade oils, considered as a reference baseline. Main characteristics of fresh oils can be found in Table 3.

Table 3. Fresh oil main characteristics.

	OIL A	OIL B	OIL C	OIL D
Type	Baseline Euro IV engine oil	Baseline Euro V/ CNG engine oil	Low viscosity candidate Euro IV/Euro V engine oil	Low viscosity candidate CNG engine oil
SAE grade	15W40	10W40	5W30	5W30
Density@15°C [g/cm^3]	0.887	0.859	0.861	0.855
API Base Oil	API G-I	API G-III	API G-III + G-IV	API G-III + G-IV
ACEA Oil Sequence	ACEA E7/E5	ACEA E6/E4	ACEA E7/E4	ACEA E6/E7/E9
Viscosity@40 °C [cSt]	108	96	71	68

Viscosity@100 ºC [cSt]	14.5	14.4	11.75	11.7
Viscosity Index [-]	>141	>145	>158	>169
HTHS Viscosity@150ºC [mPa·s]	4.082	3.853	3.594	3.577
TBN [mgKOH/g]	10	10	16	10
TAN [mgKOH/g]	2.5	2.7	2.1	2.1
Oxidation by FT-IR [Abs/cm^{-1}]	7.73	8.12	8.23	12.66
Nitration by FT-IR [Abs/cm^{-1}]	4.34	7.42	7.94	6.66
Calcium [ppm]	3350	1980	5200	2800
Boron [ppm]	4.5	195	300	6
Zinc [ppm]	1530	960	1340	930
Phosphorus [ppm]	1200	730	1160	800
Magnesium [ppm]	15	700	30	80
Molybdenum [ppm]	-	50	-	-

Due to the requirements mentioned above, lubricants and bus models were matched as shown in Table 4.

Table 4. Bus models selection and lubricants matching.

Bus model	Number of buses	Candidate Engine Oil (number of buses involved)	Baseline Engine Oil (number of buses involved)
Diesel Euro IV	9	C (4)	A (5)
Diesel Euro V	10	C (5)	B (4)
CNG	20	D (10)	B (10)

In order to improve the representativeness of the test, it was decided to divide the experiment into two phases, corresponding to two oil drain intervals of 30000 km each one. Oil sampling is an important issue in this type of tests, since the sample must be representative of the lube in the engine evaluated, setting proper sampling frequencies to fulfill study objectives. Sample frequency in this test it has been set each 3000 km. Oil sampling procedure was performed following ASTM D-4057 standard[39].

Some previous remarks should be taken into account. In order to better understanding the degradation process and its evolution, oil formulation is a key parameter and it is necessary to consider some statements regarding fresh oil characteristics, for future analysis and conclusions.

Base oils: From previous information managed it is clear that there are two levels of base oil quality. Baseline oils present API G-I and API G-III formulations, while in the low viscosity segment there are present a blend of API G-III and API G-IV base oils, increasing base oil quality and lubricant VI. This situation will lead to different degradation performance.

Sulphated Ash, Phosphorus and Sulphur (SAPS) content: As it has been mentioned above, in order to maintain engine manufacturer's recommendation it has been required to use different types of formulation. Additive package content presents also a difference between reference and LVO. Oil B and D are considered Low SAPS oils, so these formulations present lower content of Zn and P, characteristic of a reduced amount of ZDDP's. Thus, less presence of ZDDP (and its anti-wear and antioxidant properties) is overtaken by complementary additives, for example B and Mo based additives and organic friction modifiers.

Detergent selection and content: Based on oil elemental analysis obtained, there is a clear correlation between detergent content and TBN value on fresh oil, but just in oil B there is a high Mg-based detergent content, while Ca-based detergents are used in the other formulations.

5. Results and discussion

In the following section, the results of the test are presented.

5.1 Kinematic viscosity

In Figure 2, it can be observed data obtained for the both ODI for kinematic viscosity at 40 °C and in each figure each engine technology and both types of oils tested are represented.

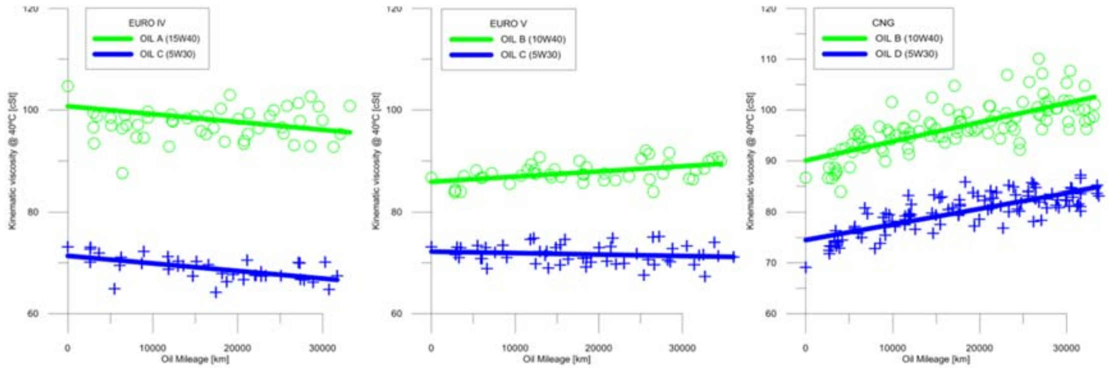

Figure 2. Kinematic viscosity at 40 °C along the ODI, for the oils used in Euro IV (left), Euro V (center) and CNG engines (right).

On the other hand, in Figure 3 the results for the same oil (Oil B and Oil C) applied in different technologies are depicted.

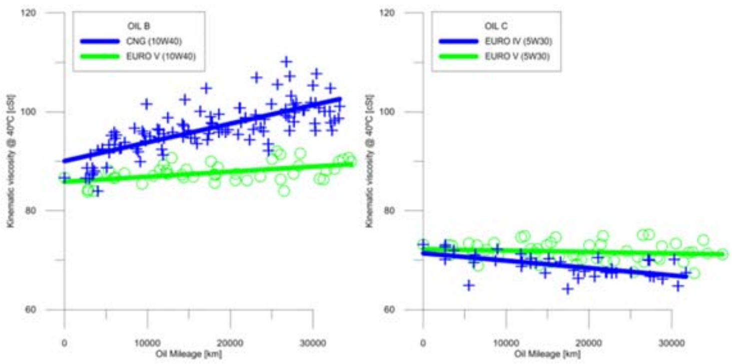

Figure 3. Kinematic viscosity at 40 °C along the ODI, for the Oil B (left), and Oil C (right).

Kinematic viscosity at 100 °C was also measured. In Figure 4, data obtained for the both ODI for KV@100 °C are presented, and in each figure is represented each engine technology.

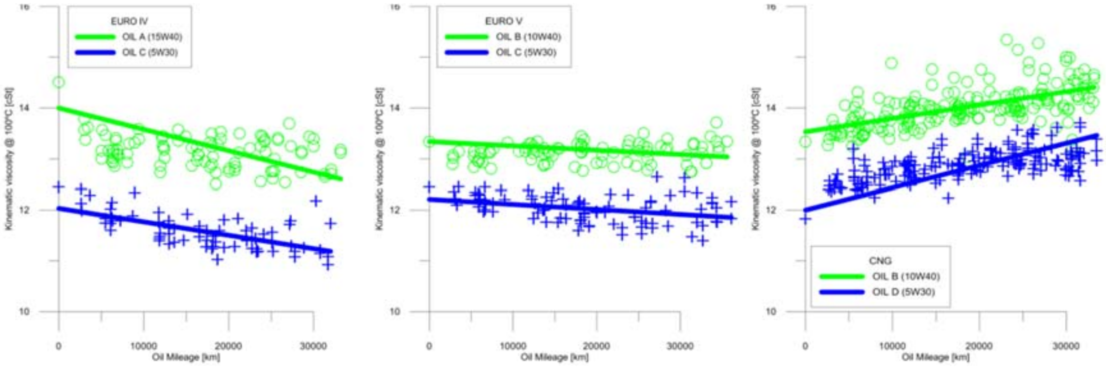

Figure 4. Kinematic viscosity at 100 °C along the ODI, for the oils used in Euro IV (left), Euro V (center) and CNG engines (right).

On the other hand, in Figure 5 the results for the same oil (Oil B and Oil C) applied in different technologies are depicted.

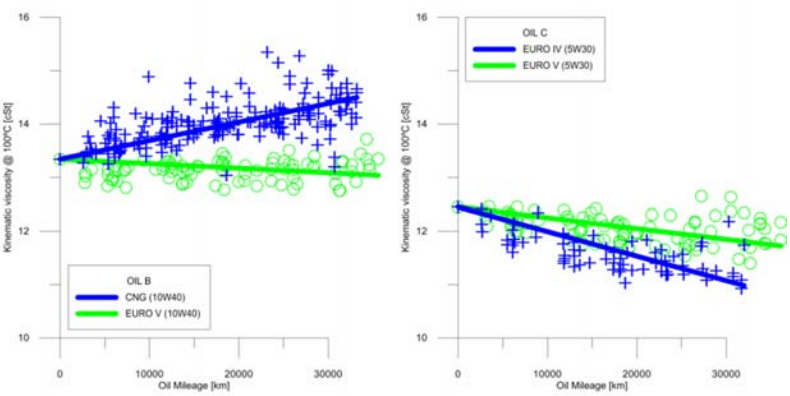

Figure 5. Kinematic viscosity at 100 °C along the ODI, for the Oil B (left), and Oil C (right).

Engine oil viscosity excursions have mainly two different causes leading to different responses: Viscosity Index Improver (VII) shearing that leads to a viscosity decrease and base oil oxidation leading to a viscosity increase. The prevalence of an effect upon other defines the viscosity variation along the ODI[40]. As can be observed on results depicted, in engines with comparative lower thermo-mechanical stress, VII shearing effects promotes a viscosity decrease, while if thermal stress is more important, base oil oxidation results in a net viscosity increase. As derived, CNG oils present a net increase in viscosity due to higher average combustion temperatures[41] and in Diesel technologies, Diesel Euro V engine is far more loaded than Diesel Euro IV engine, as pointed in the thermal loading parameter.

5.2 Antioxidant content (RULER)

In Figure 6, data obtained for the both ODI for antioxidant content by linear sweep voltammetry are presented, and in each figure is represented each engine technology.

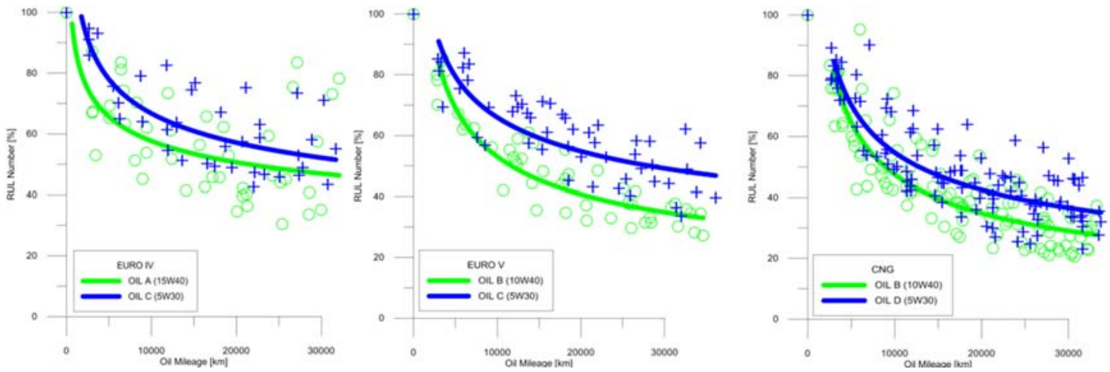

Figure 6. Antioxidant additive depletion along the ODI for oils used in Euro IV (left), Euro V (center) and CNG engines (right).

On the other hand, in Figure 7 the results for the same oil (Oil B and Oil C) applied in different technologies are presented.

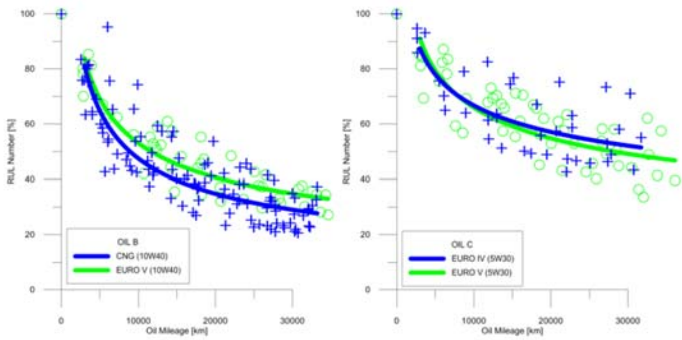

Figure 7. Antioxidant additive content along the ODI, for the Oil B (left), and Oil C (right).

Results obtained show expected performance: engines with higher thermo-mechanical stress present an antioxidant additive depletion rate higher than the engines less stressed and furthermore, higher quality oil formulations present a better response that less quality ones.

5.3 TAN/TBN

In Figure 8, data obtained for the both ODI for Total Acid Number (TAN) are depicted, and in each figure is represented each engine technology.

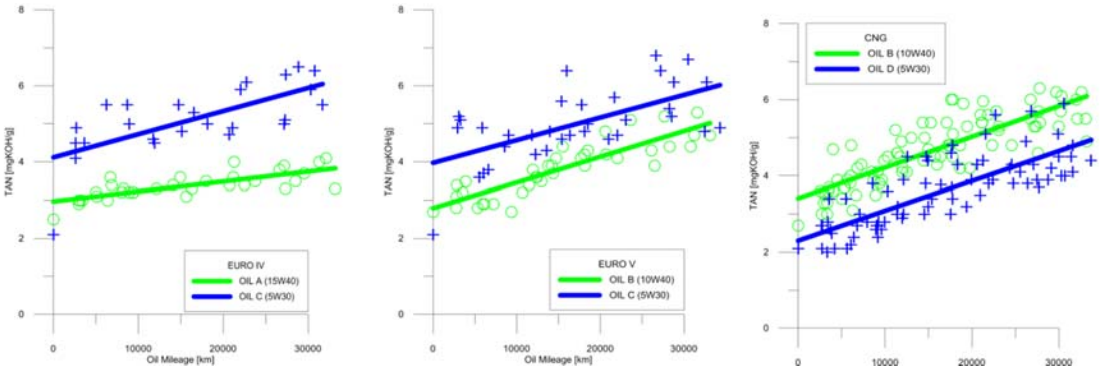

Figure 8. Total Acid Number (TAN) along the ODI, for the oils used in Euro IV (left), Euro V (center) and CNG engines (right).

On the other hand, in Figure 9 the results for the same oil (Oil B and Oil C) applied in different technologies are presented.

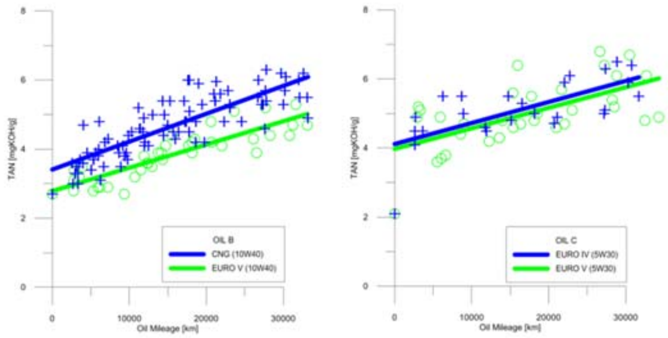

Figure 9. Total acid number (TAN) along the ODI, for the Oil B (left), and Oil C (right).

Also, Total Base Number (TBN) was measured. In Figure 10, data obtained for the both ODI are depicted, and in each figure each engine technology is represented.

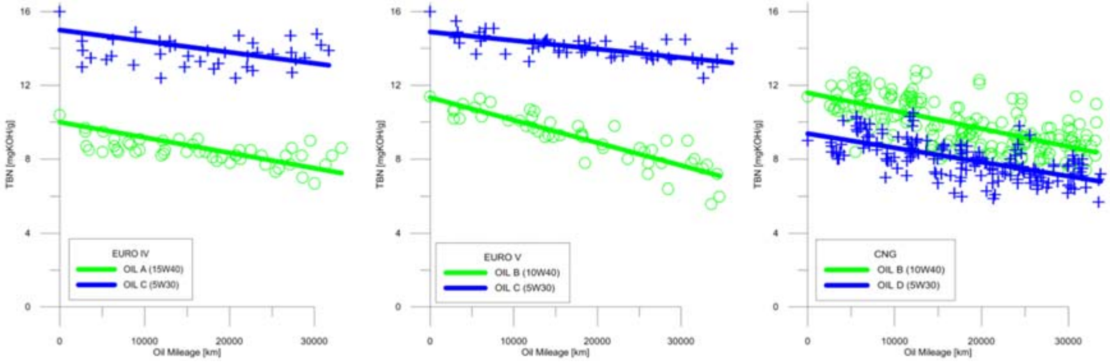

Figure 10. Total Base Number (TBN) along the ODI, for the oils used in Euro IV (left), Euro V (center) and CNG engines (right).

On the other hand, in Figure 11 the results for the same oil (Oil B and Oil C) applied in different technologies are presented.

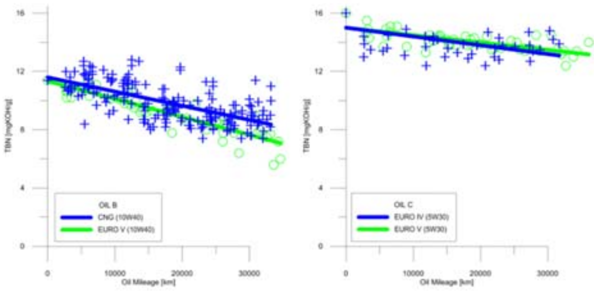

Figure 11. Total Base Number (TBN) along the ODI, for the Oil B (left), and Oil C (right).

Regarding to Total Acid Number (TAN), the main point is that a high level for TAN is reached for all oils, possibly influencing corrosive wear affecting lead and copper journal bearings. The case of Oil B is especially important since the use of a Mg-based detergent results in a higher increase of TAN, as seen in other studies[35].

TBN presented normal results, with Oil C presenting a greater TBN according to the higher content of Ca-based detergents. As in TAN data, results presented wide variation along the ODI, despite using low-sulphur fuel[42].

5.4 Oil Oxidation & Nitration

In Figure 12, data obtained for oil oxidation in each engine technology are presented.

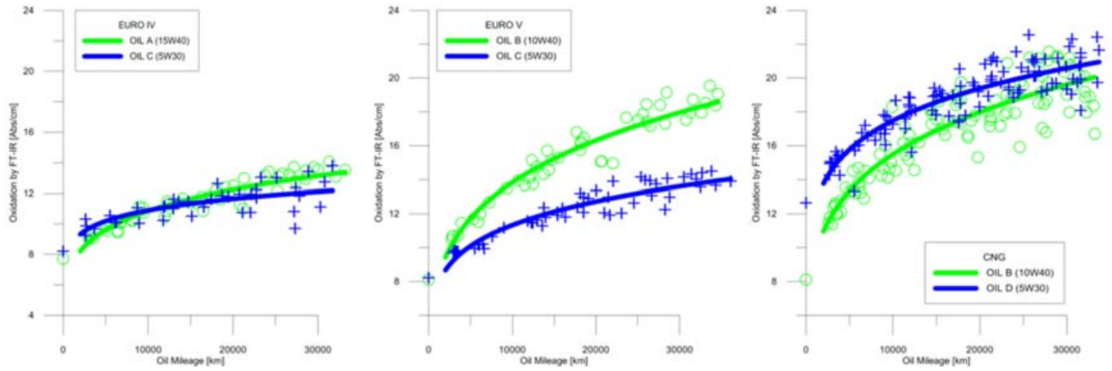

Figure 12. Oxidation along the ODI, for the oils used in Euro IV (left), Euro V (center) and CNG engines (right).

On the other hand, in Figure 13 the results for the same oil (Oil B and Oil C) applied in different technologies are presented.

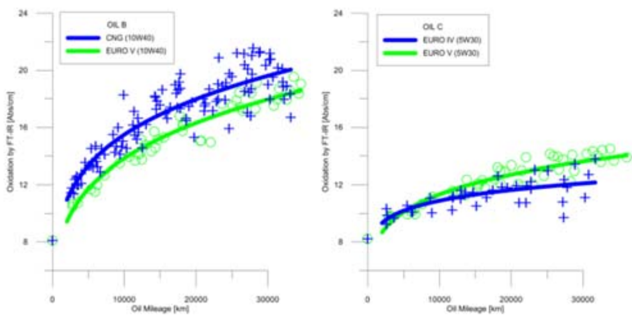

Figure 13. Oxidation along the ODI, for the Oil B (left), and Oil C (right).

Nitration was also measured. In Figure 14, data obtained for the both ODI for nitration are presented, and in each figure each engine technology is represented.

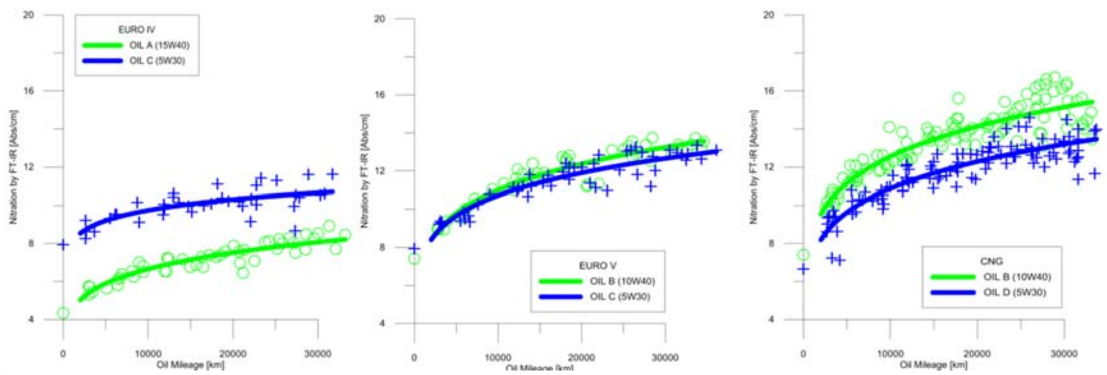

Figure 14. Nitration along the ODI, for the oils used in Euro IV (left), Euro V (center) and CNG engines (right).

On the other hand, in Figure 15 the results for the same oil (Oil B and Oil C) applied in different technologies are depicted.

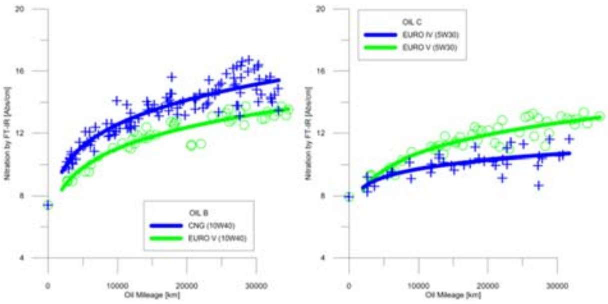

Figure 15. Nitration along the ODI, for the Oil B (left), and Oil C (right).

Regarding to all scenarios shown, oxidation increases as expected but values reached at the end of the ODI are different depending on each category. In Diesel Euro IV, oxidation levels are similar for both oils, but in Diesel Euro V, reference oil showed higher oxidation rate than the low viscosity candidate. In a comparative way, it can be clearly observed that oxidation level reached for Euro V diesel engines is quite higher than for Euro IV diesel engines. In CNG engines, both oils reached the highest levels of oxidation, probably as a consequence of higher thermal stress regarding to this technology compared versus Diesel engines. Additionally, for CNG engines, it has been observed that reference oil (15W40) performance is very similar compared with the low viscosity oil (5W30), even better can be assumed; but it has to be taken into account that initial point for fresh oils are quite different; a situation that has not been presented in other combinations. This situation can be completely understood when analyzing antioxidant content (related with aminic additives).

These results are closely related with the thermo-mechanical stress of each engine. Also, differences observed between each type of oil (reference versus candidate) can be attributable to different anti-oxidation additive package. For this case, low viscosity oil presents a better performance in terms of oxidation rate.

Nitration performance presented similar results to oxidation, but with less difference range between each technology. This could be linked with the difference in operating temperature in oil, that reduces the nitration effect as oil temperature exceeds certain level[27].

5.5 Aminic additives & Antiwear additives (ZDDP) by FT-IR

In Figure 16, data obtained for the both ODI for aminic additives are depicted, and in each figure each engine technology is represented.

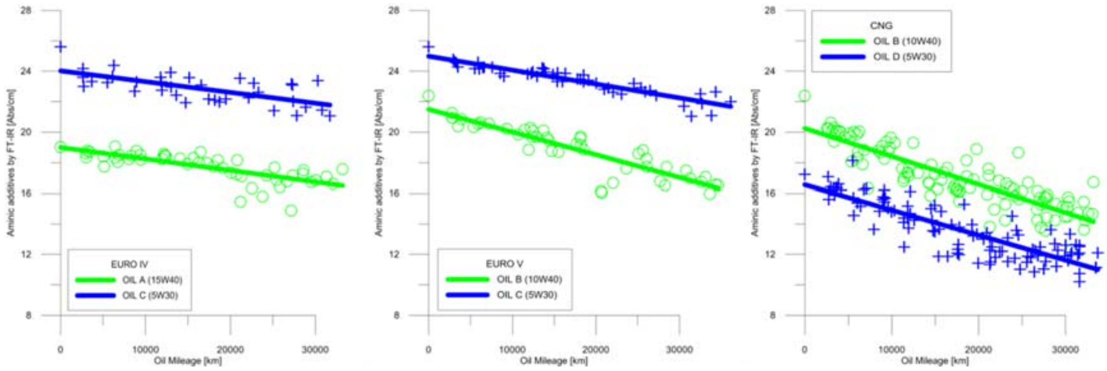

Figure 16. Aminic additives along the ODI, for the oils used in Euro IV (left), Euro V (center) and CNG engines (right)

On the other hand, in Figure 17 the results for the same oil (Oil B and Oil C) applied in different technologies are presented.

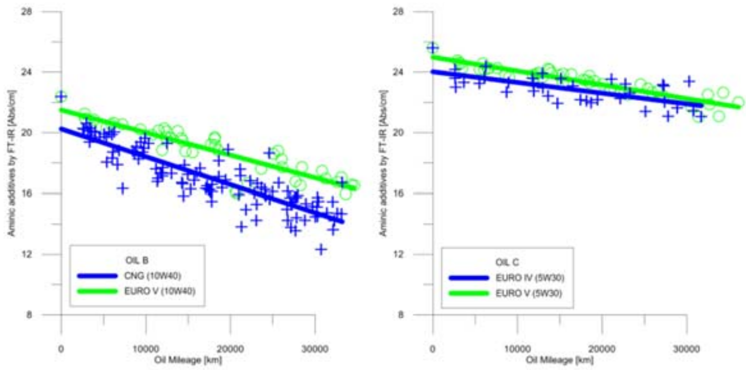

Figure 17. Aminic additives along the ODI, for the Oil B (left), and Oil C (right).

Antiwear additives content was also measured. In Figure 18, data obtained for the both ODI for antiwear additive content are presented, and in each figure each engine technology is depicted.

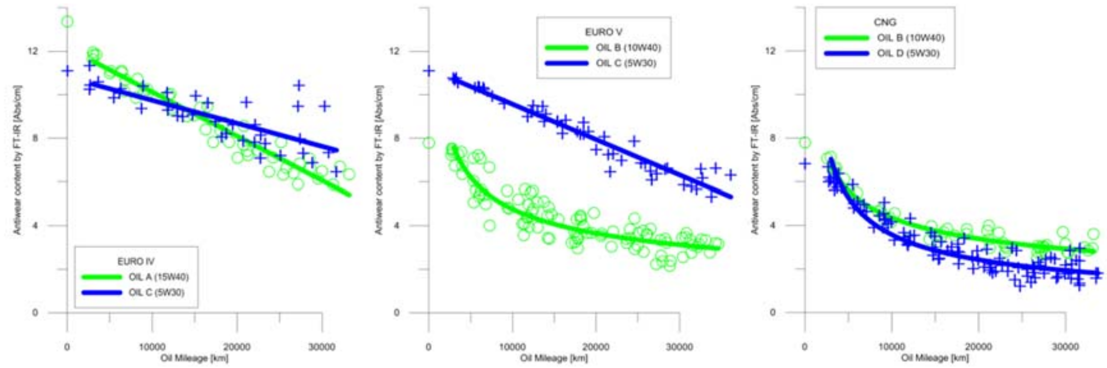

Figure 18. Antiwear additives along the ODI, for the oils used in Euro IV (left), Euro V (center) and CNG engines (right)

On the other hand, in Figure 19 the results for the same oil (Oil B and Oil C) applied in different technologies are presented.

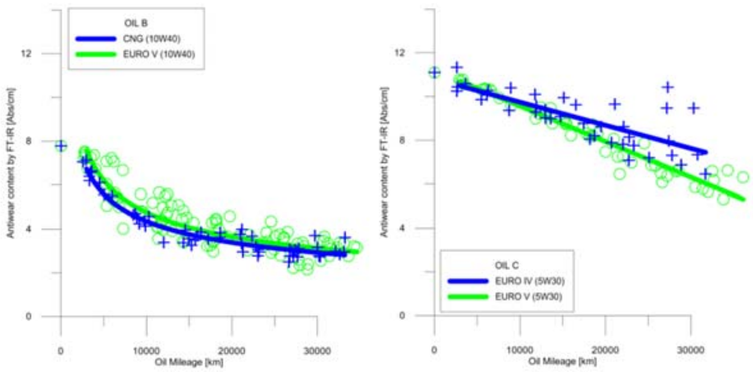

Figure 19. Antiwear additives along the ODI, for the Oil B (left), and Oil C (right).

Aminic additives, closely related with anti-oxidation characteristics, present linear depletion in all cases, depending on the initial content in fresh oil. It can be clearly observed that CNG engines present higher additive depletion rate as previously detected by RUL measurements.

In the case of Euro IV oils, there is a divergence between oxidation, RUL measurements and aminic additives measured trends. This can be justified due to the fact that RUL also includes phenolic antioxidants in its measurements, and there is a blend of aminic and phenolic antioxidants in engine oil formulations used.

Related to antiwear additives, results have shown that exists two different depletion trends, one linear and one power-based, probably as a consequence of different concentrations of ZDDP’s compounds used in each formulation, since Oil A and C contain less quantity due to the SAPS restriction. In the case of Oil B, trend presents stabilization at the end of the ODI signaling a complete depletion.

5.6 Soot

Lastly, in Figure 20, data obtained for the both ODI for soot are depicted, and in each figure each Diesel engine technology is represented.

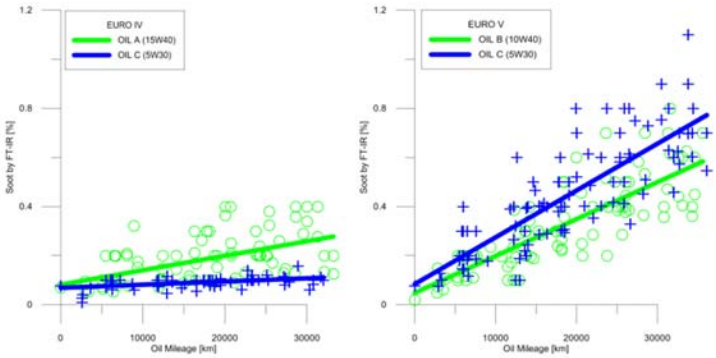

Figure 20. Soot along the ODI, for the oils used in Euro IV (left) and Euro V (right).

Soot presents a normal relative increase along the ODI. However, there is an interesting divergence between oils in the case of EURO IV engines, probably because of different soot-handling additives of different oils, while in the case of EURO V they present the same trend.

6. Conclusions

This study was conducted in order to evaluate LVO performance on typical heavy duty engines used on a severe environment such as urban transport service, especially focused on oil degradation.

First of all, main conclusion is that LVO tested presented an excellent performance along the ODI considered, even improving some characteristics of the baseline oils considered. These results are key information for end-users, because they need to know that no negative effects are derived as a consequence of using those LVO. For instance, a reduction in ODI as a consequence of a lower oil performance can be directly translated in higher maintenance cost, obviously an absolutely non desired effect. On the other hand, results obtained cannot justify an enlargement of ODI for this type of engine under authors' point of view, at least if similar engine reliability performance is desired.

In the case of alkalinity, there have been reported TBN and TAN variation values higher than 15 years ago, even with stringent legislation about sulphur content in fuel, probably because of the additives basic nature and their variations along the study. The oil oxidation and nitration variation relay basically on engine technology, presenting a higher increase in CNG technology, even showing less thermo-mechanical stress (related to bmep). The main hypothesis to explain this phenomenon is related to the higher thermal stress presented in this engine.

Relative to additive content, different measurements on additive depletion are strictly related to each oil formulation, with lower influence related with engine design.

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Notes

Abbreviation list

LVO	Low Viscosity Oil
ICE	Internal Combustion Engine
CNG	Compressed Natural Gas
ACEA	European Automobile Manufacturers' Association
ODI	Oil Drain Interval
OHV	Overhead valvetrain
SAE	Society of Automotive Engineers
OEM	Original Equipment Manufacturer
EGR	Exhaust Gas Recirculation
rpm	Revolutions per minute
FT-IR	Fourier Transform Infrared spectroscopy
API	American Petroleum Institute

ZDDP	Zinc Dialkyl Dithiophosphate
ILSAC	International Lubricants Standardization and Approval Committee
RPVOT	Rotary Pressure Vessel Oxidation Test
TOST	Turbine Oil Stability Test
UOT	Universal Oxidation Test
TAN	Total Acid Number
VI	Viscosity Index
VII	Viscosity Index Improver
SAPS	Sulphated Ash Phosphorus Sulphur
KV	Kinematic viscosity
TBN	Total Base Number
ASTM	American Society for Testing and Materials

References

1. Miller T. North American Fuel Economy Testing. In: *15th Annual Fuels & Lubes Asia Conference*. Singapore, 2009.
2. Covitch M, Brown M, May C, et al. Extending SAE J300 to Viscosity Grades below SAE 20. *SAE Technical Paper* 2010-01-2286; 2010, DOI: 10.4271/2010-01-2286.
3. Holmberg K, Andersson P, Erdemir A. Global energy consumption due to friction in passenger cars. *Tribol Int* 2012; 47: 221–234, DOI: 10.1016/j.triboint.2011.11.022.
4. Priest M, Taylor C. Automobile engine tribology—approaching the surface. *Wear* 2; 2000; 241: 193–203, DOI: 10.1016/S0043-1648(00)00375-6.
5. Larsson R, Höglund E. Elastohydrodynamic Lubrication at Impact Loading. *J Tribol* 4; 1994; 116: 770–776, DOI: 10.1115/1.2927331.
6. Payri F, Desantes JM. *Motores de Combustión Interna Alternativos*. Barcelona: Reverté, 2011.
7. Taylor CM. *Engine tribology*. Tribology . Amsterdam: Elsevier Science Publisher, 1993.

8. Van Dam W, Miller T, Parsons G. Optimizing Low Viscosity Lubricants for Improved Fuel Economy in Heavy Duty Diesel Engines. *SAE Technical Paper* 2011-01-1206; 2011, DOI: 10.4271/2011-01-1206.
9. Solomon L. Lifting the Cap on Drain Intervals. *Lubes'n'Greases*, July; 2011, pp. 38–45.
10. Macian V, Tormos B, Ruiz S, et al. In-Use Comparison Test to Evaluate the Effect of Low Viscosity Oils on Fuel Consumption of Diesel and CNG Public Buses. *SAE Technical Paper* 2014-01-2794; 2014, DOI: 10.4271/2014-01-2794.
11. Souza de Carvalho MJ, Rudolf Seidl P, Pereira Belchior CR, et al. Lubricant viscosity and viscosity improver additive effects on diesel fuel economy. *Tribol Int* 12; 2010; 43: 2298–2302, DOI: 10.1016/j.triboint.2010.07.014.
12. Manni M, Florio S. An Experimental Evaluation of the Impact of Ultra Low Viscosity Engine Oils on Fuel Economy and CO2 Emissions. *SAE Technical Paper* 2013-01-2566; 2013, DOI: 10.4271/2013-01-2566.
13. Browne D, Dewey M, Graham S, et al. Novel Fuel Efficiency Engine Lubricants for Urban Transit Applications. *SAE Technical Paper* 2014-01-2793; 2014, DOI: 10.4271/2014-01-2793.
14. Fontaras G, Vouitsis E, Samaras Z. Experimental Evaluation of the Fuel Consumption and Emissions Reduction Potential of Low Viscosity Lubricants. *SAE Technical Paper* 2009-01-1803; 2009, DOI: 10.4271/2009-01-1803.
15. Carden P, Pisani C, Andersson J, et al. The Effect of Low Viscosity Oil on the Wear, Friction and Fuel Consumption of a Heavy Duty Truck Engine. *SAE Technical Paper* 2013-01-0331; 2013; 6: 311–319, DOI: 10.4271/2013-01-0331.
16. Steinschütz K, Geringer B, Jech M, et al. Impact of Oil Aging on Wear of Piston Ring and Cylinder Liner System. *SAE Technical Paper* 2010-32-0124; 2010, DOI: 10.4271/2010-32-0124.
17. Macián V, Tormos B, Ruiz S, et al. Potential of low viscosity oils to reduce CO2 emissions and fuel consumption of urban buses fleets. *Transp Res Part D Transp Environ*; 39: 76–88, DOI: 10.1016/j.trd.2015.06.006.

18. Jang J, Lee Y-J, Kwon O, et al. The Effect of Engine Oil on Particulate Matter, Emissions and Fuel Economy in Gasoline and Diesel Vehicle. *SAE Technical Paper* 2014-01-2837; 2014, DOI: 10.4271/2014-01-2837.
19. Manni M, Gommellini C, Sabbioni G. Effect of physical characteristics of lubricating oils on emissions, fuel economy and oil consumption in a light duty diesel engine. *SAE Technical Paper* 952552; 1995, DOI: 10.4271/952552.
20. Green D a, Lewis R. The effects of soot-contaminated engine oil on wear and friction: a review. *Proc Inst Mech Eng Part D J Automob Eng* 9; 2008; 222: 1669–1689, DOI: 10.1243/09544070JAUTO468.
21. Rudnick LR. *Lubricant additives: chemistry and applications*. Boca Raton: CRC Press, 2009.
22. Spikes H. The history and mechanisms of ZDDP. *Tribol Lett* 3; 2004; 17: 469–489, DOI: 10.1023/B:TRIL.0000044495.26882.b5.
23. Rizvi SQA. *A Comprehensive Review of Lubricant Chemistry, Technology, Selection and Design*. West Conshohocken, PA: ASTM International, 2009.
24. Afton Chemical. *Specification Handbook*. New York: Afton Chemical, 2013.
25. Tormos B. Engine Condition Monitoring Based on Oil Analysis. In: Wiley (ed) *Encyclopedia of Tribology*. Boston, MA, 2013, pp. 970–977.
26. ASTM International. *ASTM E2412, Standard Practice for Condition Monitoring of Used Lubricants by Trend Analysis Using Fourier Transform Infrared (FT-IR) Spectrometry*. West Conshohocken, PA, 2010, DOI: 10.1520/E2412-10.2.
27. Coultas D. New insights into the ageing processes of engine oils. In: *UNITI Mineral Oil Technology Congress*. Stuttgart, 2015.
28. Macián V, Tormos B, Gómez Y a., et al. Proposal of an FTIR Methodology to Monitor Oxidation Level in Used Engine Oils: Effects of Thermal Degradation and Fuel Dilution. *Tribol Trans* 6; 2012; 55: 872–882, DOI: 10.1080/10402004.2012.721921.
29. Tormos B, Olmeda P, Gomez Y, et al. Monitoring and analysing oil condition to generate maintenance savings : a case study in a CNG engine powered urban transport fleet. *Insight* 2; 2013; 55: 84–87, DOI: 10.17841/insi.2012.55.2.84.

30. Macián V, Tormos B, Olmeda P, et al. Findings from a fleet test on the performance of two engine oil formulations in automotive CNG engines. *Lubr Sci* December 2013; 2015; 27: 15–28, DOI: 10.1002/ls.1248.
31. ASTM International. *ASTM D6810, Standard Test Method for Measurement of Hindered Phenolic Antioxidant Content in Non-Zinc Turbine Oils by Linear Sweep Voltammetry*. West Conshohocken, PA, 2013, DOI: 10.1520/D6810.
32. ASTM International. *ASTM D6971, Standard Test Method for Measurement of Hindered Phenolic and Aromatic Amine Antioxidant Content in Non-zinc Turbine Oils by Linear Sweep Voltammetry*. West Conshohocken, PA, 2014, DOI: 10.1520/D6971-09R14.
33. Fentress A, Sander J, Ameye J, et al. The Use of Linear Sweep Voltammetry in Condition Monitoring of Diesel Engine Oil. *J ASTM Int*; 8: 103442, DOI: 10.1520/JAI103442.
34. Livingstone G, Ameye J. Antioxidants monitoring as part of lubricant diagnostics. In: *OilDoc Conference*. Rosenheim, 2015.
35. Van Dam W. Measuring Reserve Alkalinity. *Pract Oil Anal* 2002; 7.
36. ASTM International. *ASTM D664, Standard Test Method for Acid Number of Petroleum Products by Potentiometric Titration*. West Conshohocken, PA, 2011, DOI: 10.1520/D0664-11A.
37. ASTM International. *ASTM D2896, Standard Test Method for Base Number of Petroleum Products by Potentiometric Perchloric Acid Titration*. West Conshohocken, PA, 2011, DOI: 10.1520/D2896-11.
38. Heywood JB. *Internal combustion engine fundamentals*. New York: McGraw-Hill.
39. ASTM International. *ASTM D4057, Standard Practice for Manual Sampling of Petroleum and Petroleum Products*. West Conshohocken, PA, 2012, DOI: 10.1520/D4057.
40. Van Dam W, Miller T, Parsons GM, et al. The Impact of Lubricant Viscosity and Additive Chemistry on Fuel Economy in Heavy Duty Diesel Engines. *SAE Technical Paper* 2011-01-2124; 2011, DOI: 10.4271/2011-01-2124.
41. Totten GE. *Handbook of Lubrication and Tribology: Volume I Application and Maintenance*. Boca Raton: CRC Press, 2006.

42. Macián V, Tormos B, Lerma J. Evaluation of Used Lubricant Behaviour in Industrial Vehicles Engines in the 1990s. *SAE Technical Paper* 2000-01-1824; 2000, DOI: 10.4271/2000-01-1824.