Low viscosity engine oils: Study of wear effects and oil key parameters in a Heavy Duty engine Fleet Test

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Abstract

Low viscosity engine oils (LVO) are considered key contributor for improving fuel economy in internal combustion engines (ICE). Attending that the use of LVO could imply a variation in tribological states found in ICE, this work's aim is to test LVO in real fleet, with emphasis on engine wear and oil key performance indicators.

This test comprised 39 buses, two engine technologies and four different lubricants. For each sample, the elemental composition of the wear debris by ICP-AES and HTHS viscosity of the oil were measured among other properties.

The results showed that, with a correct oil formulation, there is no significant difference when using LVO in terms of engine wear, HTHS viscosity variation and oil consumption.

Abbreviation list

LVO	Low Viscosity Oil
ICE	Internal Combustion Engine
CNG	Compressed Natural Gas
ICP-AES	Atomic emission spectrometry by Inductively coupled plasma
HTHS	High temperature – High Shear
SIE	Spark Ignited Engine
CIE	Compression Ignited Engine
ACEA	European Automobile Manufacturers' Association
HDV	Heavy Duty vehicles
ODI	Oil Drain Interval
OHC	Overhead camshaft
SAE	Society of Automotive Engineers
OEM	Original Equipment Manufacturer
DoE	Design of Experiments
EGR	Exhaust Gas Recirculation
rpm	Revolutions per minute
TBN	Total Base Number
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
FT-IR	Fourier Transform Infrared Spectroscopy

1. Introduction

During the development of alternative internal combustion engine (ICE), one of the most studied topics has been the improvement of engine efficiency; in the early beginnings, to improve its performance, and more recently, to minimize fuel consumption and reducing the negative impact of the exhaust gases to the environment. This development work has been carried out from two different points of view[1]; first, based on optimizing the thermo-dynamic and fluid mechanic processes to increase the indicated power (i.e. the rate of work transfer from the gas within the cylinder to the piston[2]), and the second one, based on increasing the engine mechanical efficiency by reducing mechanical losses.

Broadly, for a heavy-duty vehicle working under normal conditions, the percentage of energy transmitted from the potential in the fuel to the wheels of is only about 15% to 20%[3], as seen in Figure 1.

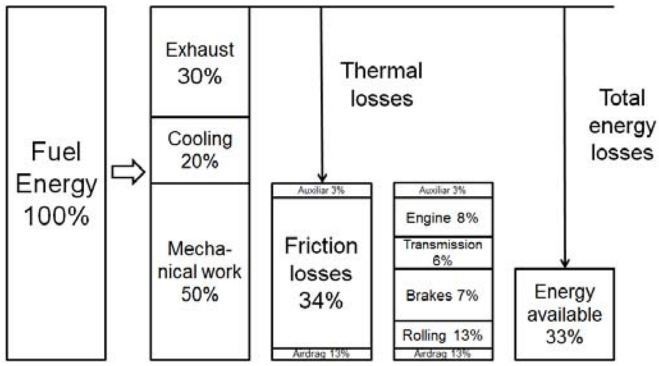

Figure 1. Diagram of typical energy distribution in an averaged heavy-duty vehicle. Adapted from [3].

Taking into account that the internal engine friction can be as high as 50% of the mechanical losses in internal combustion engines [4], this is a target area for a potential contribution to increase fuel economy. A broadly set of strategies has been defined focused in reducing ICE mechanical losses, within which can be listed: the design and manufacture of lighter parts and use of non-metallic materials [5], improvements in surface coatings and related technology [6], engine downsizing [7], and the use of low viscosity oils, among others [8], [9].

The use of low viscosity oils began more than 40 years ago [10] to reduce friction losses, and since then, several studies have been conducted both in spark ignition engines (SIE) and compression ignition engines (CIE). The average reduction in fuel consumption in test rig studies ranged between 1% and 4% depending on different factors such as engine operating points, oil formulations used (specially viscosity grades considered and additive packages) and oil temperatures, etc. [11], [12]. All this knowledge resulted in a consistent trend on reducing the average viscosity of lubricants, as seen in Covitch et al. [13].

Since the main objective of these investigations was to reduce fuel consumption and consequently minimize the level of emissions in order to fulfill stringent requirements, the vast majority of this research has been applied to light duty engines. Since today, the Association of European Automobile Manufacturers (ACEA), the organization that defines European automotive industry standards, has not yet defined any evidence of fuel economy for diesel oils for heavy-duty vehicles (HDV) [14], although this situation is expected to change in a close future following similar trends in other markets worldwide. Since fuel economy has been demonstrated as a consistent trend and expecting future restrictions on fuel consumption for vehicles of medium and heavy duty segment, low viscosity lubricating oils represent an irresistible opportunity because the good relation in terms of cost of implementation-estimated savings [10], which can contribute to a considerable proportion of the final percentages stipulated in regulations. Since there is a little information of the performance of low viscosity oils in HDV [15], and mainly studied in test rig [16], a full-scale test was addressed to ensure and validate all the hypothesis launched in test rig experiments.

On the other hand, there is a counterpart regarding the use of low viscosity oils in ICE. A direct consequence of the viscosity reduction at the whole range of temperature implies a direct reduction in film thickness [17], and this can lead to increased friction at some contacts, and even locally to increased wear rates if the oil film thickness becomes so thin that permits local asperity contacts. This situation could lead also to a reduction in engine life, thus an increasing in maintenance actions and a reduction in the tribological performance and potential fuel economy of the ICE. For all those reasons, this study was conducted also to assess the potential effects that the use of low viscosity lubricating oils may have on the wear phenomena on those engines, and investigate the effects on oil performance along its oil drain interval (ODI).

The work presented in this articles is part of a broader study, which main goal was to verify and quantify fuel economy of these low viscosity oils in real world conditions. After a concise and structured work, the results presented clear benefits in terms of fuel economy, as found in [18].

2. Tribology and wear related to low-viscosity oils

Engine tribology has been always an important subject of study in the automotive industry. Since the very beginning [19], an important understanding of tribology was necessary to deal with all the mechanical requirements in ICE. The main tribological systems present in an ICE comprise three main areas: piston ring pack system, journal bearings and valve train system [2]. Developed in 1902, the Stribeck curve explains fluid film lubrication, and defines the main lubrication regimes that are present in the tribological systems presented above. Stribeck curve, defined by the Hersey parameter that takes into account lubricant viscosity, velocity and contact normal pressure, is shown in Figure 2 focused on previously mentioned engine tribological pairs.

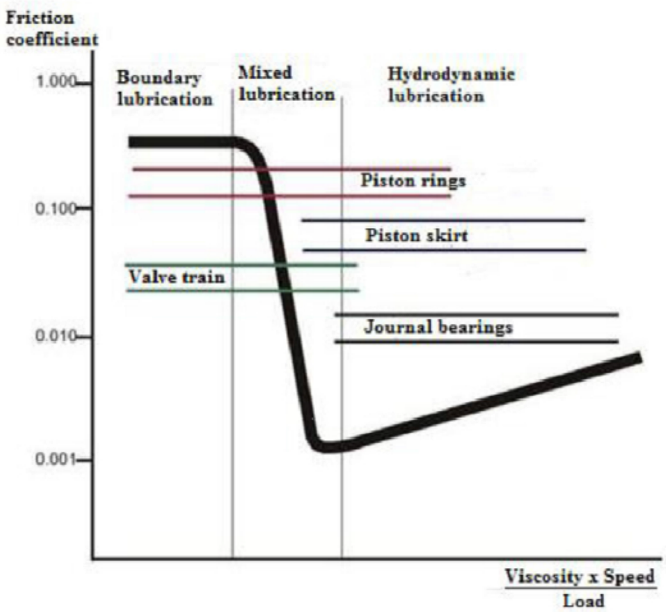

Figure 2. Stribeck curve and typical lubrication regimes on main tribological engine pairs. Adapted from [1].

Each of the ICE tribological pairs operates in different ranges, as shown in the figure above. The main tribological system, and the most studied [20], comprises the friction between liner and ring-pack, and shows the most varied and stringent boundary conditions; the different operating parameters during the whole cycle, provoke that this system broadly covers the vast majority of the Stribeck curve each cycle, as shown in the work by Ting [21], among others. Also, lubricating film is restored in each cycle, thus this could be considered a lubrication open-cycle, where the film is completely extinct and oil is constantly renewed [22]. On the other hand, since journal bearings tribological operation range is more restrained, they are specially designed to perform in the hydrodynamic range, with reduced friction coefficient and wear response [23], [24]. Since journal bearings tribology is one of the most advanced research topic in this area, the application of the elastohydrodynamic theory is presenting more accurate results to predict bearings friction and wear[25], [26].

Lastly, valve train system represents a completely opposite tribological performance from the other pairs, with the predominance of mixed and boundary lubrication [10], [27]. The technical developments in valve trains, e.g. the overhead camshaft (OHC), has made the lubrication of this tribological contact a difficult issue [28]–[30]. The relative distance and the contact morphology present specific characteristics which results in a less important role of lubricant viscosity [31] . Also, recent developments have been achieved in order to reduce these phenomena, with the application of roller follower system [32], and with the development of oil formulations with specially dedicated additives [33], [34] .

But the appearance of LVO changed this entire scenario. Along with other solutions mentioned above, the philosophy and the use of LVO has pushed off engine manufacturers and oil and additive formulators to improve their products in order to meet stringent emissions and fuel economy requirements.

Although the usage of LVO in order to improve engine's fuel economy is not a new trend [35], in recent years it has been accepted as a necessary and consistent solution contribution. In the 90's, oils classified as SAE 10W40 and 15W40 were mostly used, but they were gradually displaced by SAE 10W30 and 5W30 in recent years. Nowadays, most OEM's require service-fill oil classified as SAE 5W30 in light-duty segment. In the first decade of this century very low viscosity oils appeared, and it is common in the Japanese market to find cars that use SAE 5W20. According to that, SAE has been redefining its Engine Oil Viscosity Classification [36], in order to meet this trend including in the last two years three new SAE grades with lower viscosity, and allowing some engine manufacturers, especially Asians, the implementation of these regulations to meet fuel consumption restrictions [37], [38].

Some investigations have been carried out to fully define LVO usage consequences, especially regarding to the effect of viscosity reduction in film thickness at engine tribo-contacts. Traditionally, kinematic viscosity of engine oils was measured at standard temperatures of 40ºC and 100ºC and atmospheric pressure, but this measurement is not representative of the inner behavior of lubricant in engine. Since modern multigrade lubricants present a non-Newtonian fluid performance, where shear stress and local temperatures affect directly to viscosity, a different dynamic viscosity measurement at 150 °C and 10^{-6} s^{-1} was defined, called High Temperature-High Shear viscosity (HTHS) [39]. This parameter has been addressed as a key parameter to correlate more exactly the fuel economy effect by LVO in ICE [15], [40], but also has been used to characterize wear phenomena when using LVO [16], [41]–[43].

Reduced information is available about the real world performance of LVO, especially in heavy duty engines. Another important point concerning the usage of low viscosity oils is related with oil consumption effects in engine. Oil consumption has two main origins, blow-by effect [44] and cylinder liner-piston rings dynamics [45], since the lubricant is the responsible for sealing the combustion chamber in the expansion cycle. A variation in this viscosity could result in an increase in oil consumption, as studied by Carden et al. [16].

Since heavy duty engines represent a differentiated engine segment, with different wear patterns and configurations [46], it was necessary to develop a fleet test in real world conditions in order to assess the real contribution of LVO usage to engine wear and potential effects on derived durability, and also help formulators and OEM to fully understand the implications of this solution to the own engine oil and to the engine.

3. Test design and settings

In order to develop a complete and valuable test, a previous full-scale design of experiments (DoE) was defined, including the selection of vehicles, oils and operating conditions. However, all the variety included in the DoE was not possible to be developed in real conditions, due to fleet operator restrictions and ICE manufacturer specifications. Despite this fact, the test was designed with two complementing criteria: it was mandatory to have as much data as it was possible, since real world test include a lot of variability phenomena. And on the other hand, taking into account the common engine diversity of a typical heavy duty fleet, three different vehicles were selected including two different fuels: Diesel and CNG. In the next sections each different parameter will be detailed.

3.1 Bus fleet

For the purpose of this test, part of an urban transport fleet was required. In order to broaden the range of the test, different models of buses were chosen with two different engine technologies: Diesel and Compressed Natural Gas (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 Table 1. It is important to state that all fuels used in this test were commercially available and they meet national fuel requirements (UNE-EN 590 for Diesel fuel, and Commission Directive 2001/27/EC for CNG). To provide more accurate information, some configuration and coating materials of each tribological pair is also presented.

Table 1. 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 [litres]	12	7.2	12
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
Crankcase oil volume [l]	31	29	33
bmep [bar]	16,8 @1100 rpm	19,55 @1100 rpm	9,24 @1000 rpm
Thermal loading* [W/mm2]	2.85	3.97	2.33

Turbo-charging	Turbo+Intercooler	Turbo+Intercooler	Turbo+Intercooler
EGR [-]	NO	NO	-
Valve train configuration	OHV Roller follower (hardened steel)	OHV Tappet follower (steel)	OHV Tappet 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.

3.2 Engine oils

The main purpose of this study has been to assess the effect of the use of LVO on engine wear in real conditions. Four different commercial oils were chosen, due to OEM requirements: two low viscosity grade oils, considered as candidates, and two higher viscosity grade oils, considered as a reference baseline. The main characteristics of the oils as-received are found in Table 2.

Table 2. Fresh oils 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/cm3]	0.887	0.859	0.861	0.855
Viscosity@40°C [cSt]	108	96	71	68
Viscosity@100ºC [cSt]	14.5	14.4	11.75	11.7
Viscosity Index [-]	>141	>145	>158	<169
HTHS Viscosity@150ºC	4.082	3.853	3.594	3.577

[mPa·s]				
TBN [mgKOH/g]	10	10	16	10
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

Finally, lubricants and bus models were matched as shown in Table 3.

Table 3. 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)

3.3 Oil analysis program and sampling

The HTHS dynamic viscosity is one of the key parameters regarding to LVO usage. HTHS viscosity can be measured by three different methods, corresponding to three different standards [47]–[49]. The main difference in each method is related with the shear-stress originating element. In this test a high pressure capillary viscometer was used, according to ASTM D 5481 [49].

Although there are several different analysis to perform in order to monitor engine wear, elemental spectrometry by ICP-AES (Atomic Emission Spectrometry by Inductively Coupled Plasma) [50] is one of the most reliable and used nowadays. In this case, a methodology of wear and additive elements monitoring was used following the ASTM D 5185 [51] standard.

Lastly, engine oil consumption was computed attending the oil topping up quantity performed over the engine during the complete oil drain interval, added by an intermediate tank present in each vehicle and obtained from Computerized Maintenance Management System of fleet operator.

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. This can be done, not only by assuring a correct and systematic sampling procedure, but also by setting proper sampling frequencies to fulfill study objectives. Sample frequency in this test it has been set each 3000 km.

The sampling procedure defined includes sampling location, sampling method, and material requirements. If sampling was made along with oil drain operation, a new 125 ml plastic bottle was filled with the oil drained from the crankcase. Initially, the crankcase screw was released, and the oil was left to drain for 3 seconds period. Afterwards, the bottle was filled approximately with 100 ml; so later the sample could be well shaken previous to analysis, in order to homogenize the content.

If the sample was taken during oil service period, a different methodology was used. A handheld pump, new piping and a new plastic bottle were used for each bus. Every engine was turned on for several minutes in order to homogenize the crankcase oil. After that period, the pipe was introduced through the oil dipstick path until it reached the crankcase. Then, the oil sample, approximately 100ml, was pumped to the plastic bottle, and then it was labeled and stored for analysis.

4. Results & discussion

4.1 HTHS viscosity

An important issue to bear in mind in this test was the initial HTHS viscosity value in fresh candidate oils. Although SAE J300 standard introduces a lower limit in SAE 30 grade of 2.9 cP for HTHS viscosity, ACEA specifications limit this value to a minimum of 3.5 cP[14], corresponding to the lower limit defined in SAE J300 for SAE 40, which is the main reason for the proximity between HTHS viscosity values on fresh candidate and baseline oils.

In this section, HTHS viscosity evolution of each combination of engine type and oils used are presented. In Figure 3, Figure 4 and Figure 5 HTHS viscosity measurements for the entire test (60000 km) are depicted, according to each engine type. In the upper part of the figure baseline oil is presented, and in the lower part the candidate oil.

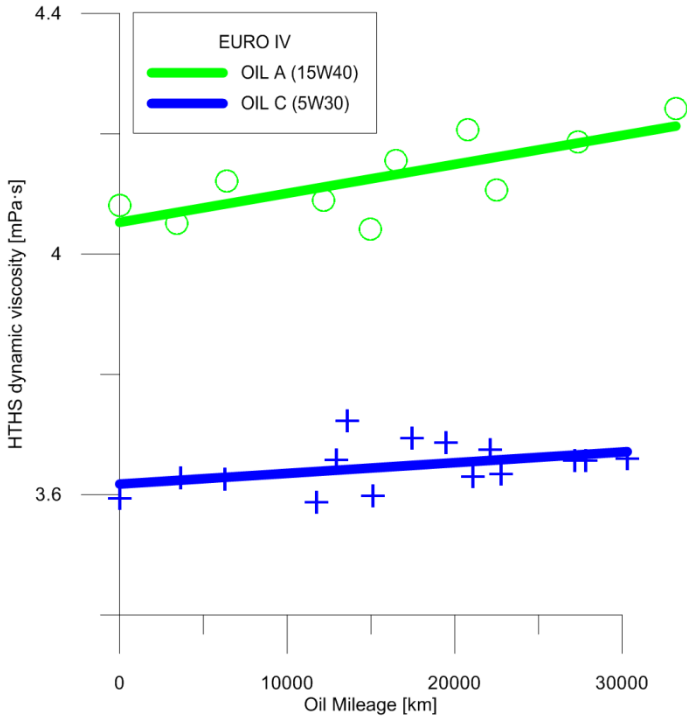

Figure 3. HTHS viscosity for EURO IV engine using oil A (15W40) as reference and oil C (5W30) as candidate.

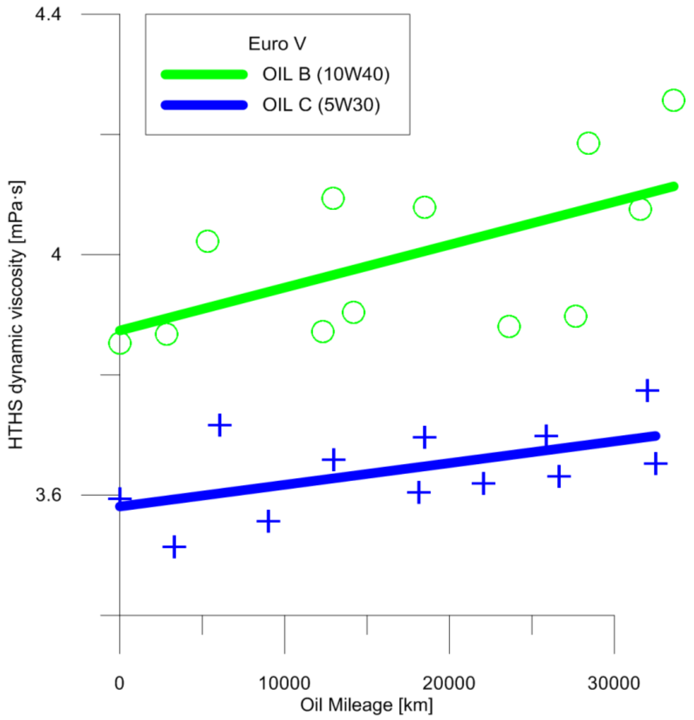

Figure 4. HTHS viscosity for EURO V engine using oil B (10W40) as reference and oil C (5W30) as candidate.

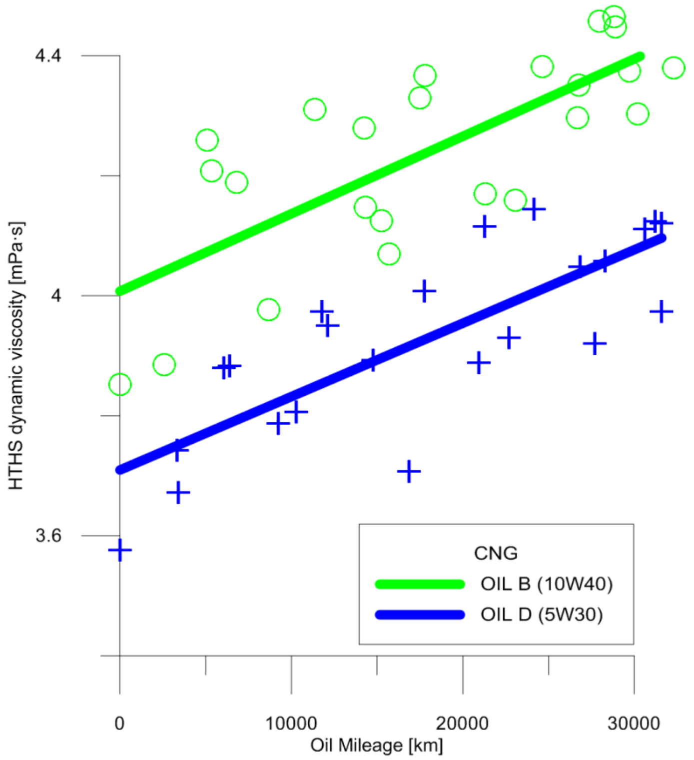

Figure 5. HTHS viscosity for CNG engine using oil B (10W40) as reference and oil D (5W30) as candidate.

Observing the previous graphs some important aspects can be highlighted:

HTHS viscosity presents non-significant variations along the test in diesel technology, with two clearly established trends. While the baseline oil (high viscosity) presents a slight increase during the ODI, candidate oils presented negligible variation. This situation can be linked with the oil formulator efforts to assure good fuel economy performance in LVO products where HTHS is intended to be strictly controlled along the ODI.

In CNG technology, a mild increase in HTHS viscosity value is observed, but the viscosity gap between oils (baseline vs. candidate) is maintained along the ODI. Probably, this mild increase appears as a consequence of higher thermal stress suffered by these oils, and the consequent oxidation. On the other side, the same gap during all the ODI assures that in a comparative way between both oil types, the fuel economy effects will be the same independently of the moment considered in the ODI.

4.2 Engine wear

Referring to engine wear, different metals performance and trends were observed. For a better understanding and explanation, wear results have been grouped according to different phenomena, and also a fraction of points have been hidden in figures for a more clear presentation.

4.2.1 Iron concentration patterns

Iron concentration, as a direct indicative of engine wear has presented some interesting trends. Firstly, there exists differentiated concentration patterns in each technology using the oils designed as reference oils, as shown in Figure 6.

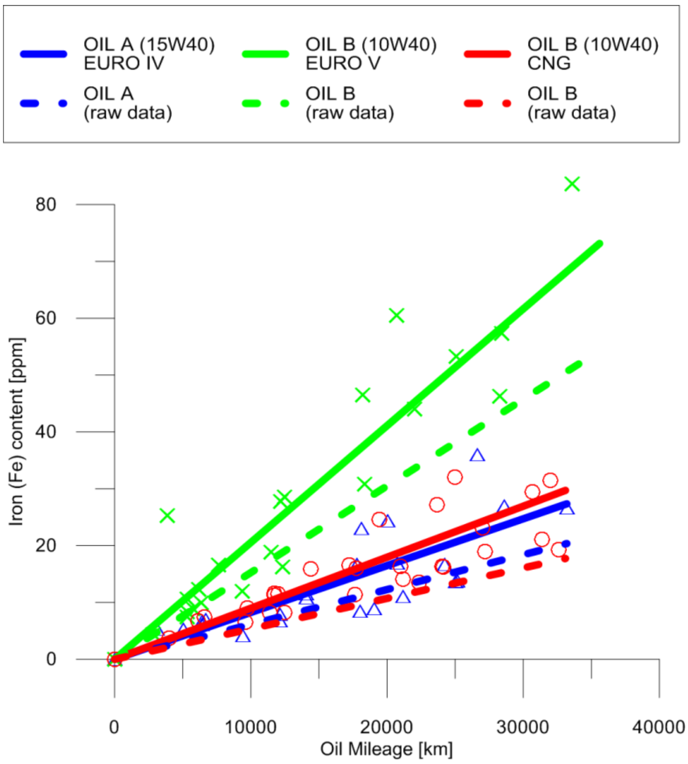

Figure 6. Iron content rates of reference oils.

An important point is the relationship between wear rate and oil consumption. There are studies pointing out that a correction in wear trends is necessary due to the dilution effect derived from the addition of fresh oil (topping up) required as a consequence of oil leakages and consumption [52], so in this study a mass conservation approach was conducted. Considering this situation, the results are depicted for both cases in Figure 6, 8, 9 and 10, on one hand considering raw data (using a dotted line) and on the other hand the trend obtained applying a correction factor to consider the dilution effect of oil topping up.

As can be observed, iron rates are quite similar for those engines with lower mechanical stress that can be represented by bmep or by thermal loading. Bmep is a relative engine performance measure, obtained by dividing the work per cycle by the cylinder volume displaced per cycle [2].The Euro V diesel engine, with the highest bmep value, consequently shows the higher iron rate observed during the oil drain interval. Obviously, it could be considered that some part of this difference can be linked to the own oil formulation differences too, but not the whole value. Later, with the results obtained when using LVO a deeper analysis can be done.

In Figure 7 is depicted the relationship between iron wear rate and engine thermo-mechanical stress, presented in terms of brake mean effective pressure (bmep) and thermal loading. Thermo-mechanical stress can be linked with Stribeck number, since there is a relation with load and temperature of the tribo-contact.

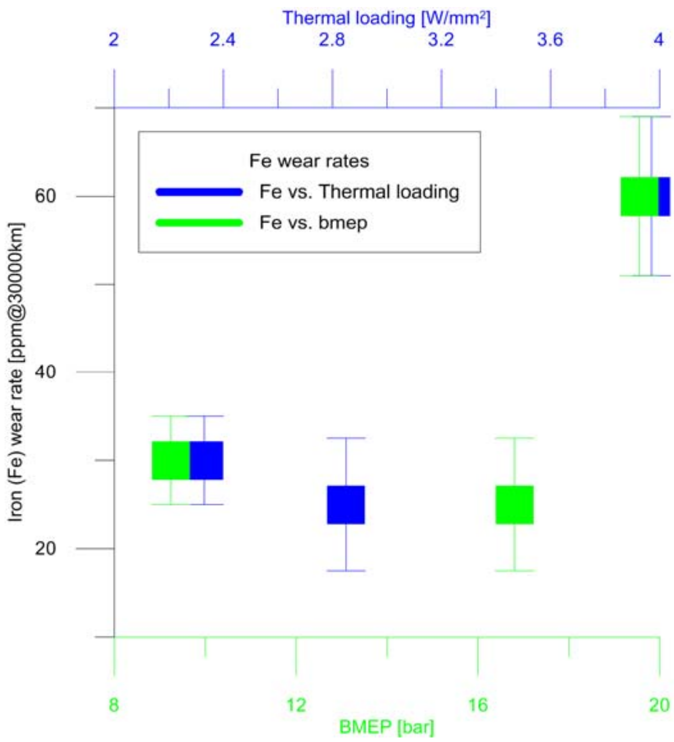

Figure 7. Iron rates and thermo-mechanical stresses.

As can be observed, Figure 7 presents a relation between iron rates and thermal loading values for each engine, used as a thermo-mechanical stress indicator, thus representing a dependence of lubrication performance and engine mechanical and thermal loads, derived from changes in the lubrication regimes and consequently in tribological performance.

The effects in terms of iron rate as a consequence of the usage of LVO are depicted in Figure 8.

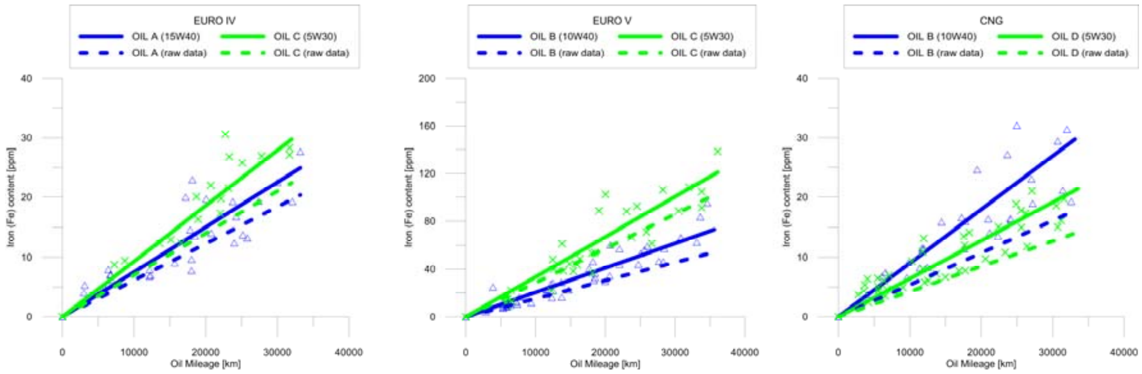

Figure 8. Iron rates presented for each engine technology: EURO IV (left), EURO V (center) and CNG engine (right).

As can be observed on previous graphs, those engines lower stressed: EURO IV and CNG, present no significant difference in iron rate when using LVO. Even more, in the case of CNG engine, a reduced iron rate has been obtained that can be associated to the higher low viscosity oil quality. On the other hand, the specific case of EURO V engines has shown substantially higher iron rates.

The most likely hypothesis for this phenomenon is the combination of two origins. Firstly, this EURO V engine is the most stressed of the study, as it presents the highest bmep and thermal loading, resulting in increased mechanical efforts in the system. Additionally, the main difference with other engine types is the valve distribution system, based on OHV (Over Head Valve) with cam follower steel without heat treatment, where the camshaft directly pushes the valve tappet. As shown above, this tribological configuration can lead to increased wear rate in this system, since it is working in the most adverse lubrication regime.

4.2.2 Lead wear patterns

It has also been observed an exponential increase in lead content beyond 20,000 km in Oil B (10W40) in both engine types: EURO V and CNG, but this situation is not present in candidate oils. Trends are shown in Figure 9 and Figure 10, for each engine technology.

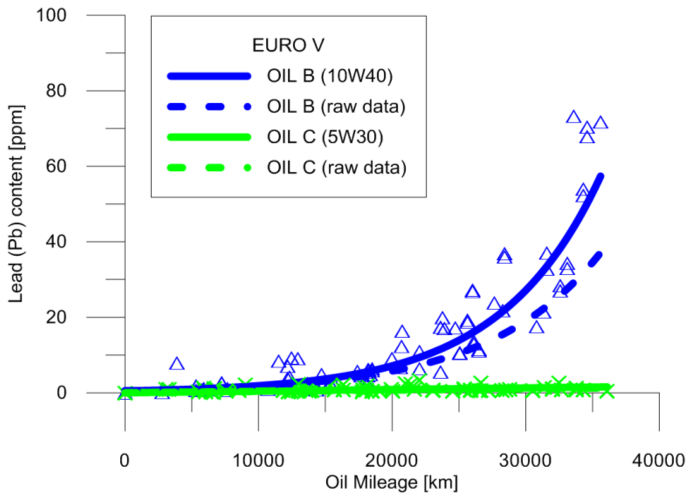

Figure 9. Lead content in EURO V engine for oil B (10W40) and oil C (5W30).

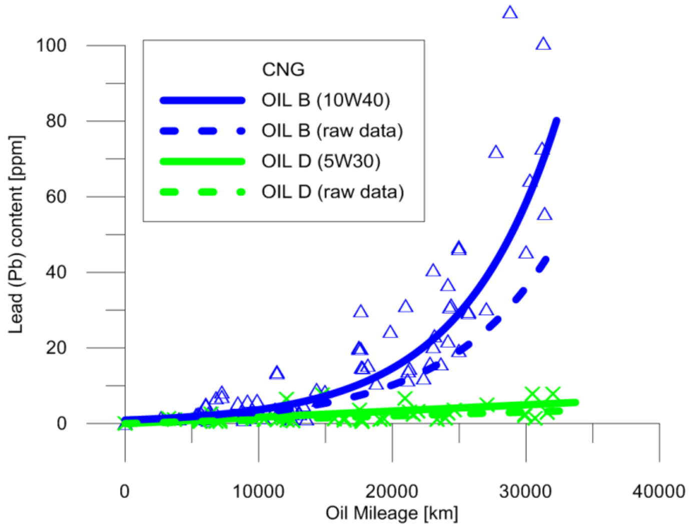

Figure 10. Lead content in CNG engine for oil B (10W40) and oil D (5W30).

The most feasible explanation could be linked to additive depletion. For oil B, after 20,000 km anti-wear additives have been almost absolutely depleted (FT-IR measurements have been performed to assess this situation) and an acidic attack against Babbitt metals appears leading to the situation previously mentioned. In the case of the LVO, the higher content of anti-wear additives, let to obtain a longer period of usage where this corrosive wear is under control, obtaining very low lead wear rates.

4.2.3 Silicon presence in oil

During the test, a malfunction in air filter system in some particular CNG vehicles produced high dust ingress, resulting in some interesting trends associated with three-body abrasive wear. In Figure 11 and Figure 12 general results are depicted, where it can be clearly observed the direct relation between silicon content and abrasive wear concentration.

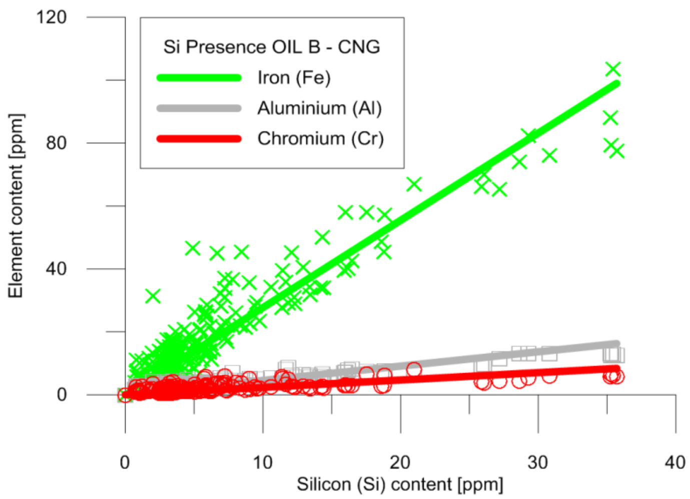

Figure 11. Wear metals in CNG engine using oil B (10W40) versus silicon content.

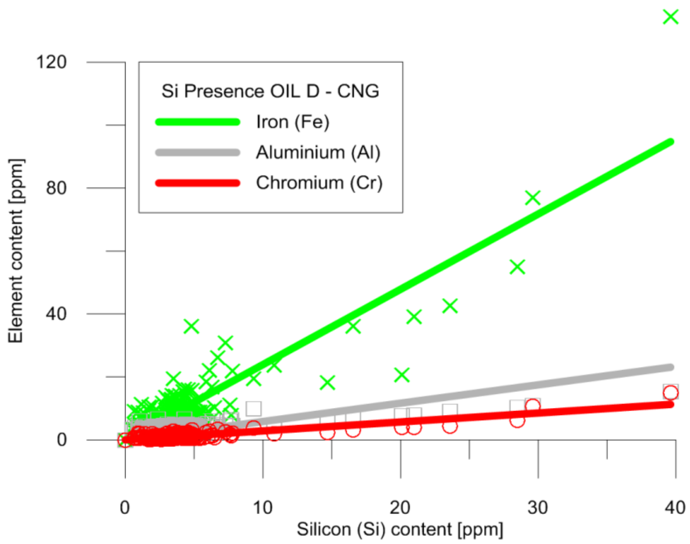

Figure 12. Wear metals in CNG engine using oil D (5W30) versus silicon content.

Consequently from this situation, there have been detected divergent wear trends between vehicles using same engine oil, especially in iron (Fe), aluminum (Al) and chromium (Cr), related with silicon ingression versus those vehicles that have not suffered this problem related with air filters, so this results were not included in the main study of iron trends.

4.2.4 Other wear metals

Table 4 summarizes the results observed in other metals, where some of the patterns mentioned above are also detected. Results obtained for copper and aluminum present the same trends observed for lead patterns. On the other hand, chromium rates, present on running surface of piston rings, have been affected in a similar way than iron pattern but in a lower level as can be observed.

Table 4. Wear metals and rate for each category.

Oil	Engine technology	Al level [ppm@30000 km]		Cu level [ppm@30000 km]		Cr level [ppm@30000 km]	
OIL A (15W-40)	EURO IV	3	4	20	20	1	1
OIL C (5W-30)	EURO IV	4	4	7	5	1	1
OIL B (10W-40)	EURO V	7	7	4	5	3	3
OIL C (5W-30)	EURO V	4	5	2	2	4	4
OIL B (10W-40)	GNC	5	6	4	6	4	5
OIL D (5W-30)	GNC	4	4	2	2	2	2

4.3 Oil consumption effects

The last part of this study comprised the measurement of oil consumption, pointed out as another important aspect to be accounted of LVO usage. For that, historical data from each engine type was required, and also oil topping up for each vehicle in the test fleet was continuously monitored. Results obtained for each engine technology are presented in Figure 13.

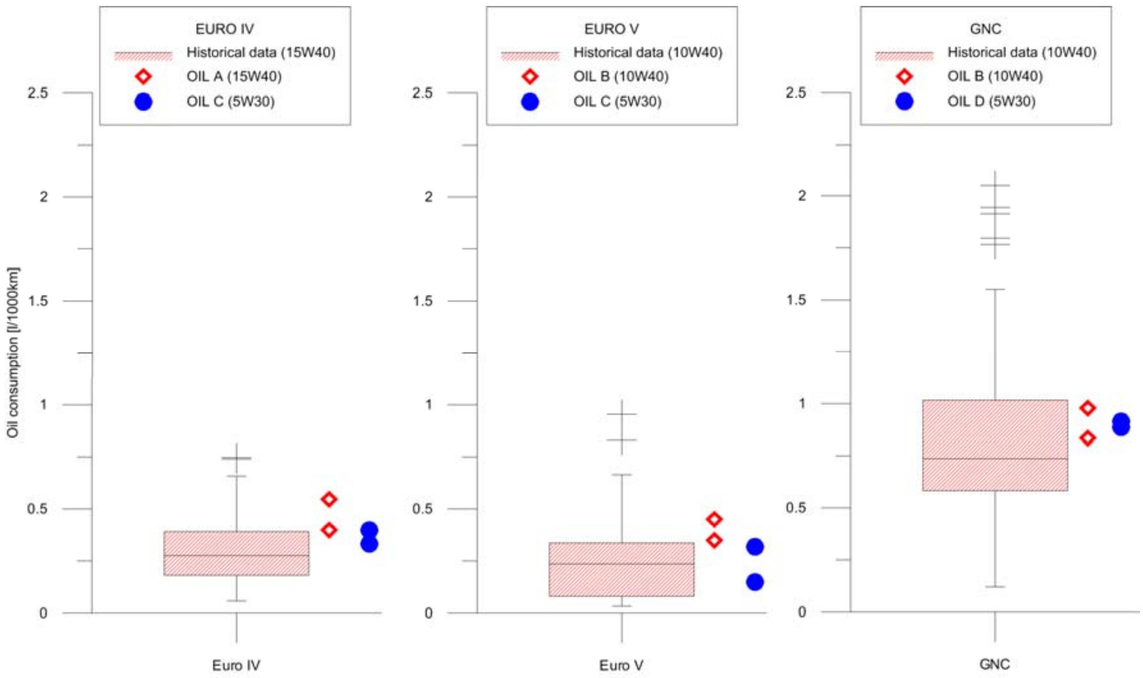

Figure 13. Oil consumption measurement for each engine technology: EURO IV (left), EURO V (center) and CNG (right).

Results obtained indicate that there is no significant evidence of oil consumption increases as a consequence of LVO usage; but, as can be clearly observed there are very important differences between engine technologies or design, with a clear higher consumption on that CNG engines versus Diesel engines.

5. Conclusions

This study in a real fleet working under real world conditions has permitted to obtain many interesting conclusions that can help fleet operators and oil formulators to understand better these phenomena and address critical issues regarding LVO. The main conclusions of this study are the following:

The use of LVO does not necessarily involve a different wear performance, since the candidate low viscosity oils used in engines EURO IV and CNG have shown no increased wear compared to baseline, probably because both oils have the ability to withstand thermo-mechanical stress levels of these engines.

However, in some engine-oil formulation combination differences have raised, due to particular engine greater mechanical and thermal stress, or an additive depletion independent of the usage of LVO.

Meanwhile, in CNG engines divergent values with the rest of the fleet category have been observed, due to a significant presence of silicon, which has favored three-body abrasive wear.

On the other hand, candidate formulations studied in this test seem to be optimized to maintain to offer fuel economy, thus maintaining constant HTHS viscosity during their usage, except for a slight increase in CNG technology. This performance points out a good synergy between base oil and additives in order to ensure lubrication in engine tribological pairs.

Probably, this has led to limited oil consumption. Data showed no significant difference between using LVO against baseline oils in terms of oil consumption, and also showed that values are within the normal operating range of each technology, being engine type much more significant than oil viscosity.

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