ASSESSMENT OF LOW VISCOSITY ENGINE OILS IN TERMS OF FUEL CONSUMPTION AND ENGINE WEAR IN HEAVY DUTY ENGINES FLEET TEST

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ABSTRACT

As a consequence of the increasingly stringent emissions standards in the world and, on the other hand, the foreseen shortage of fossil fuels, the application of low viscosity engine lubricants (LVO) is considered one of the most cost effective contribution to counteract these challenges. The aim of the test was to verify the potential fuel consumption benefits of using LVO in Heavy Duty Vehicles (HDV) found in literature, mainly obtained in engine bench tests, when they are working on real and “on-road” conditions. Parallel to this study, the performance of low viscosity lubricants regarding to engine wear was assessed, since the use of LVO could imply an increase in engine wear rate. Potential higher wear could result in a life cycle reduction for the internal combustion engines or higher maintenance costs, both non-desired effects. In order to achieve this goal, a sample of 39 urban buses comprising two engine technologies (Diesel and Compressed Natural Gas (CNG)) and four different lubricants were studied over more than 60000 km per vehicle, measuring daily mileage and fuel consumption, and also oil performance was monitored (with 3000 km sampling frequency) using a deep and extensive oil analysis program, specially engine wear was quantified using ICP-OES, in order to detect abnormal engine wear patterns.

Results obtained have shown a positive correlation between the use of LVO and fuel consumption reduction in HDV, both for Diesel and CNG. Regarding to oil performance, results indicate that engine wear do not show abnormal patterns due to use of LVO.

KEY WORDS: low-viscosity oils, fuel efficiency, engine wear

1.- INTRODUCTION

In recent years, increasing social concern on climate change as a consequence of global warming, foreseen lack of fossil fuels and related increasing in petroleum products prices has derived in a general interest for society to take actions to tackle CO_2 and other greenhouse gases (GHG) emissions and enhancing vehicles fuel economy. Since transportation activities contribute significantly to annual emissions, governments are proposing stringent legislation focused on fuel consumption and GHG emissions reductions. For the first time, these legislations will include HDV limits for pollutant emissions and fuel consumption. In the European Union context, approximately 25% of the road transport CO_2 emissions and about 6% of total EU emissions [1] are directly related to HDV.

Generally, vehicle fuel consumption reduction and in consequence CO_2 emissions can be faced by a wide range of solutions, divided in two main groups: vehicle development, e.g. aero dynamical improvements, new tire materials to reduce rolling resistance, electronic assistance to optimize vehicle driving, etc. On the other hand, internal combustion engine (ICE) efficiency improvement could contribute significantly to that defined objectives, for instance: by improving thermo-chemical dynamic processes or by reducing engine losses. Specifically, engine internal friction represents around 50% of the total mechanical losses [2], so any reduction in internal friction losses can be translated into a contribution for improving fuel economy. Regarding this last option, one interesting cost-effective way to reduce ICE internal friction is the usage of low viscosity oils (LVO) [3].

Generally, friction and lubrication characteristics of an engine tribological pair depend on variables as: engine load, engine speed and the viscosity of engine oil. The relationship of these three variables and the resulting friction performance is defined by the Stribeck diagram, shown in Figure 1. This diagram also defines the lubrication regime of a lubricated pair in relative motion, depending on the film thickness: hydrodynamic, when a fully lubricant film is formed between surfaces as a consequence of the relative motion; boundary, when direct contact between dry surfaces appears and lubricant additives play a key role on lubrication; and finally, mixed regime, when the lubrication regime presents boundary and hydrodynamic characteristics simultaneously. The hydrodynamic regime is the most susceptible regime to contribute to fuel economy improvement, since in this situation oil viscosity reduction will result into a low friction coefficient as long as the oil film thickness prevents the contact between the surfaces in relative motion.

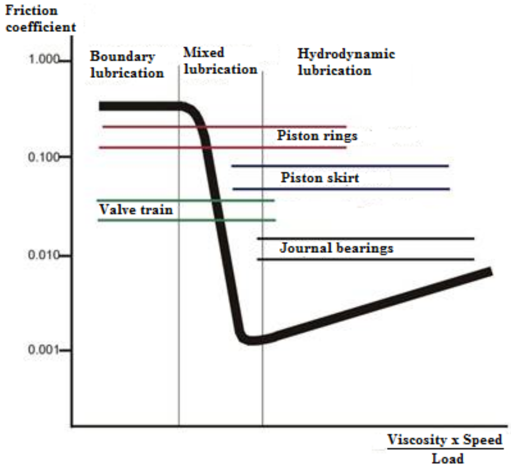

Figure 1.Stribeck diagram and lubrication regimes of main engine components.

The use of LVO in order to reduce friction losses has been present for several decades and many studies have been conducted about it, both in spark-ignition engines [4] and in compression-ignition engines, especially in the light-duty segment [5]. Literature research presents an average reduction in fuel consumption due to use of LVO ranging between 1% and 5%, depending on different factors related to engine and oil characteristics. As a result of these studies, the commercial SAE viscosity grades have been decreasing in the oil market.

The aim of fuel economy implies alternative challenges in oil formulations. Observing the Stribeck curve, a possibly stated hypothesis could be that a reduction in viscosity can modify the lubrication regime from a purely hydrodynamic friction to a mixed or even boundary friction regime, where wear could increase exponentially [6]. Also, this situation can contribute to accelerate oil degradation [7].

Recently, in order to investigate LVO effects on HDV fuel consumption, some tests have been performed in engine test bed with positive results, however, there is no significant information about the effect of LVO on fuel consumption and engine affection in “on road” conditions.
Attending this situation, a study has been proposed to evaluate the use of LVO in HDV in real world conditions for a proper and accurate quantification of fuel economy contribution, and also studying possible effects on engine wear and oil performance.

2.- EXPERIMENTAL DETAILS

As mentioned before, few significant data about LVO effect on fuel consumption on real fleet test are available, especially for HDV segment. For this study fuel consumption was calculated from the fuel refills data and the mileage performed obtained from the global positional system (GPS) of each bus being both values taken on a daily basis. Oil condition was monitored along all the tests. The design of the test, buses models involved and their characteristics, and used oils will be presented in this section.

2.1.- Fleet Test Design

To accomplish the main objective of this test, a long term test was defined where the daily fuel consumption of a group of control buses using market-commercial SAE grade oils was compared against a group of similar buses using LVO. It was considered that a great number of other variables during real service would affect the test: environmental conditions (e.g. weather and season of the year), road conditions (e.g. slope, average velocity, road quality), driving behavior and specific bus operation conditions variables (urban traffic, type of engine, number of passengers, vehicle weight, etc.), affecting the influence of LVO on fuel consumption.

2.2.- Vehicles in test

The bus fleet used for this test was the public urban bus fleet of the city of Valencia. In order to broaden the range of the test, three different engine technologies were selected: Compressed Natural Gas (CNG) and two Diesel engine powered vehicles with different emissions standards (Euro IV and Euro V) were considered, as shown in Figure 2.

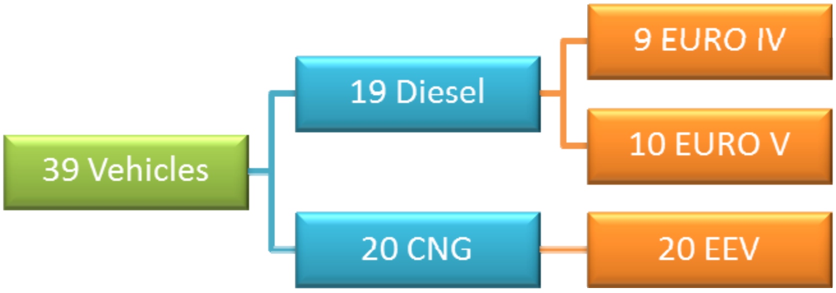

Figure 2. Vehicles used in the fleet test.

The list of main vehicle and engine characteristics is presented in Table 1. Please note that information shown in italics has been collected from aftermarket solutions providers. On the other hand, it is important to bear in mind that all fuels in this test were commercially available and they met national standard fuel requirements.

Table 1. Vehicle characteristics by bus model.

Bus Model	**Euro IV**	**Euro V**	**CNG**	**Bus Model**	**Euro IV**	**Euro V**	**CNG**
Model Year	2008	2010	2007	**Oil sump volume [l]**	31	29	33
Length/width/ height [m]	17.94/ 2.55/3	11.95/ 2.55/3	12/2.5/ 3.3	**bmep [bar]**	18.3@ 1000 rpm	13.5@ 1000 rpm	12@ 1000 rpm
Vehicle weight [tons]	17.5	12.7	12.1	**Thermal loading [W/mm2]**	2.85	3.97	2.33
Passenger capacity seated/stand	45/95	25/60	30/63	***Turbo-charging***	*Turbo+ Intercooler*	*Turbo+ Intercooler*	*Turbo+ Intercooler*
Engine displacement [c.c.]	11967	7200	11967	***EGR [-]***	*NO*	*NO*	-
Emission certification level	EURO IV	EURO V	EEV	***Valve train configuration***	*OHV*	*OHV*	*OHV*
Number of cylinders	6	6	6		*Roller follower (hardened steel)*	*Cam follower (steel)*	*Cam follower (steel)*
Related power [kW]	220@ 2200 rpm	210@ 2200 rpm	180@ 2200 rpm	**Reference buses**	5	5	10
Related torque [Nm]	1600@ 1100 rpm	1100@ 1100 rpm	880@ 1000 rpm	**Candidate buses**	4	5	10

2.3.- Oils

Taking into account that vehicles in test were in real-world operation while the test was performed, test lubricant selection was crucial, so two conditions were required for them: all oils needed to be commercial and approved by the buses original equipment manufacturers (OEM).

Oils that the fleet operator had been using until the moment of the beginning of the test were used as reference oils; 15W40 SAE grade oil for Euro IV buses and 10W40 Low Saps oils for the other engines. On the other hand, 5W30 SAE grade oil was selected as the low viscosity grade based on the requirements set by the engines OEM. Additionally, due the Low Saps restriction for the CNG buses, two oils needed to be used as candidates. The complete characteristics of these oils can be seen on Table 2.

Table 2. Baseline and candidate oils characteristics.

	OIL A	**OIL B**	**OIL C**	**OIL D**
Type	Baseline Diesel engine Oil	Baseline Diesel/CNG engine Oil	Low viscosity candidate Diesel 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 [mPa·s]	4.082	3.853	3.594	3.577
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

2.4.- Test duration

One main point detected in the test definition was that the effect of LVO over fuel consumption could be strongly difficult to assess directly on “on-road” conditions, so a large amount of dataset was required to obtain the narrow fuel consumption differences which were expected between control and candidate groups of buses. In order to achieve so, each of the 39 buses completed at least 60000 km mileage working with its respective oil, corresponding to two oil drain intervals (ODI) of 30000 km.

2.5.- Fuel consumption measurement

A daily basis calculation of buses fuel consumption was made by means of covered distance and liters of fuel consumed. Covered distance was measured via GPS, and fuel consumed was measured by refueling both diesel and CNG buses. While the diesel fuel dispenser measurements were saved directly in the computer maintenance management system (CMMS), CNG consumption measurement was made using a different approach. The CNG refueling facility was built in the way that all the CNG fleet had to be connected at the same time to the system. As the final pressure and the bus CNG tank volume are known, the initial pressure in the tank at the beginning of the refueling was used to calculate the amount of CNG refueled.

2.6.- Oil condition monitoring

To control the variation of oil condition along the test, oil sampling planning was established. The planning consisted in taking a 100 ml oil sample every 3000 km of mileage for every bus, completing more than 800 oil samples (21 by bus) at the end of the test. In order to characterize oil condition of the test buses, a broad range of techniques were used.

2.6.1.- Viscosity

It is one of the most contrasted and used parameters defining oil condition. Concretely, van Dam et al. [8], [9] have noted the importance of High-Temperature High-Shear (HTHS) viscosity, being more accurate for representing oil performance in real engine conditions. Thus, HTHS viscosity measurement was done by a multicellular capillary viscometer was used, according to ASTM D 5481.

2.6.2.- Physicochemical properties

Total acidity and basic indexes (TAN, TBN) were determined by potentiometric titration methods based on the procedures of ASTM D664 and D2896. Oil oxidation was analyzed by Fourier Transformed Infrared (FTIR) spectroscopy, following an “in-house” methodology based on ASTM D 7214.

2.6.3.- Wear analysis

In order to monitor and trend metal content of wear and additive element control, a methodology based on atomic spectrometry on an ICP-OES was used following the ASTM D 5185 standard.

3.- RESULTS AND DISCUSSION

In the following section, selected results will be presented, due to the huge quantity of data obtained. First of all, the fuel consumption difference between baseline and reference oil for each technology is presented, in Figure 3.

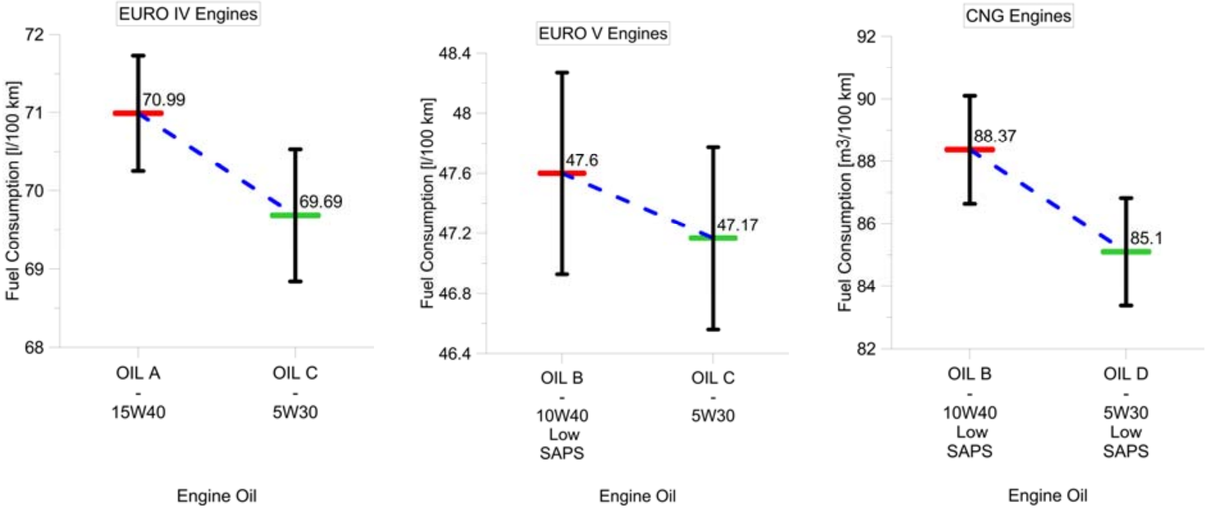

Figure 3. Fuel consumption difference for each technology: EURO IV (left), EURO V (center) and CNG engines (right).

Generally, buses using LVO (SAE grade 5W30 and 5W30 Low Saps, depending on engine technology) had less fuel consumption than the groups that used regular oils (SAE grade 10W40 Low Saps and 15W40). This difference varies depending on the bus model being 1.83% for the Euro IV, 0.98% for the Euro V and 3.71% for CNG buses. In Figure 4 the relationship between fuel economy improvement and bmep is presented, as indicator of engine thermo-mechanical stress.

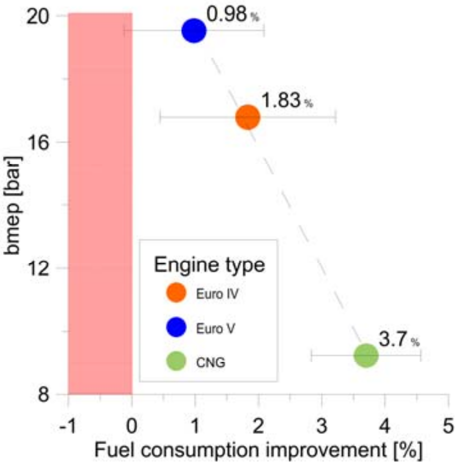

Figure 4. Fuel consumption improvement related to bmep for test engines.

As observed, CNG buses showed the best benefits on fuel consumption reduction due the use of LVO. But on the other hand, Euro V buses presented less than 1% improvement, and this result presented statistically non-significance. The main hypothesis for these phenomena is that engine characteristics leaded to high values of bmep that could induce longer periods of non-hydrodynamic lubrication regime during engine operation, thus reducing the effect of LVO.

Related to oil performance, HTHS dynamic viscosity was monitored along the ODIs, with the results presented in Table 3.

Table 3. HTHS viscosity for each engine technology, initial and final values, and variation along ODI.

Engine oil	**Engine technology**	**HTHS @ 150ºC initial [mPa·s]**	**HTHS @ 150ºC @30000km [mPa·s]**		**% variation**	
Oil A - 15W40	EURO IV	4,082	4,17	4,25	2,16%	4,12%
Oil B - 10W40	EURO V	3,853	3,97	4,08	3,04%	5,89%
Oil B - 10W40	CNG	3,853	4,22	4,47	9,53%	16,01%
Oil C - 5W30	EURO IV	3,594	3,65	3,69	1,56%	2,67%
Oil C - 5W30	EURO V	3,594	3,63	3,74	1,00%	4,06%
Oil D - 5W30	CNG	3,577	4,02	4,16	12,38%	16,30%

As shown before, HTHS viscosity generally presents non-significant variations when referred to diesel technologies, while a slight increase in CNG technology is observed. Another important item is that LVO formulations studied in this report presents excellent viscosity stability, showing that are optimized to maintain constant HTHS viscosity during the designated use, except for a slight increase in 5W30 Low Saps candidate oil.

In addition, lubricant degradation properties were measured along the ODI, and results are presented in Table 4.

Table 4. Total acid and base number variations for each engine technology, and oxidation measured by FT-IR at final ODI.

Engine oil	**Engine technology**	**TAN variation [mgKOH/g]**		**TBN variation [mgKOH/g]**		**Oxidation@30000km [Abs/cm]**	
Oil A - 15W40	EURO IV	+1,3	+1,3	-2,3	-3,3	13,6	13,8
Oil C - 5W30	EURO IV	+3,9	+4,2	-2,4	-2,7	12,3	13,3
Oil B - 10W40	EURO V	+2,1	+2,1	-3,3	-4,3	18,4	18,7
Oil C - 5W30	EURO V	+3,6	+3,1	-2,6	-2,5	13,8	14,2
Oil B - 10W40	CNG	+3,2	+3,2	-2,9	-2,8	19,8	20,6
Oil D - 5W30	CNG	+2,7	+2,4	-2,1	-2,1	21,1	21,0

The results showed that candidate oils presented more substantial variations in acidic and basic numbers in the case of diesel technologies, probably linked to a higher degradation rate suffered by these oils. In the case of CNG engines, more pronounced degradation in both spectra are observed, due to higher operation temperatures. Indeed, for oxidation measurements note that in EURO IV technology, lower demand for oil is observed, while in the EURO V and CNG engines mechanical and thermal stresses caused greater oxidation increasing. Another important point is that candidate oils present less oxidation than baseline oils in diesel engines, probably because of the use of different additive packages and base oils.

Regarding to engine wear, rates obtained during the test are shown in Table 5.

Table 5. Wear rates for each engine technology.

Engine oil	Engine technology	Wear rate Fe [ppm/1000 km]		Wear rate Cu [ppm/1000 km]		Wear rate Pb [ppm/1000 km]	
Oil A - 15W40	EURO IV	0,67	0,67	0,67	0,67	0,13	0,13
Oil C - 5W30	EURO IV	0,67	0,67	0,23	0,17	0,03	0,03
Oil B - 10W40	EURO V	1,33	1,67	0,13	0,17	0,50	1,00
Oil C - 5W30	EURO V	3,00	3,00	0,07	0,07	0,03	0,03
Oil B - 10W40	CNG	0,83	1,33	0,13	0,20	0,70	1,23
Oil D - 5W30	CNG	0,40	0,50	0,07	0,07	0,07	0,10

Observing the results, there is just one case where the use of LVO implies a wear rate increase, in EURO V engines. These engines presented the greatest iron wear rate, both in baseline and candidate oil. The main hypothesis is that this engine is under greater mechanical and thermal stress, and specifically the valve train system, based on a "cam follower" configuration that may contribute to this phenomenon. In addition, the presence of lead in vehicles equipped with Oil B, regardless of engine type, may refer to an additive depletion, and seems to be independent of the usage of LVO.

4.- CONCLUSIONS

This full-scale test has permitted an accurate and real quantification of potential fuel economy in HDV. The main conclusion is that the usage of LVO may imply an improvement in fuel consumption, but engine design and operating parameters, as the vehicle characteristics and type of work, determines the capability of each vehicle model to use LVO and perceive reductions in fuel consumption.

In addition, LVO usage does not necessarily involve a different engine wear performance, since the candidate 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. The synergy between base oil and additive packages have permitted candidate oils to maintain key characteristics and assure oil performance along the ODI.

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