CO_2 emissions reduction by using low viscosity oils in public urban bus fleets

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Abstract

CO_2 emissions and fuel consumption reduction in road transportation has become one of the most relevant concerns either for governments, OEMs and final users, especially fleet owners and managers, led mainly by global warming and rising fuel prices concerns. For vehicles driven by internal combustion engines (ICE) the fuel consumption rates are directly related to CO_2 emissions, the latter being a consequence and an efficiency indicator. A wide variety of solutions have arisen to overcome this challenge ranging from hybridization to changes in the vehicle-design looking for more aerodynamic profiles, to solutions like eco-driving courses for drivers or the usage of alternative fuels such as biofuels. All of these solutions vary in technical complexity, implementation costs and terms. One proven cost-effective way to reduce the fuel consumption is the use of low viscosity oils (LVO) in order to reduce the engine inner friction, reducing by this way the amount of energy required to move the engine parts resulting this in a fuel consumption reduction. This paper presents a study where the effect of the use of LVO on urban transport buses on the CO_2 fleet spot and fuel consumption, based on a comparative test where 39 buses worked for nearly a year separated in two groups each of them carrying either LVO or standard viscosity oils.
Keywords: CO_2 emissions reduction, fuel consumption, urban buses, fleet test.

1 Introduction

Global warming has been directly linked to the presence of greenhouse gases (GHG) in the atmosphere. The consequence of global warming includes rising biosphere temperatures which could sorely unbalance the required minimum conditions needed to sustain life. The main anthropogenic GHG emissions are carbon dioxide CO_2 (93%), methane CH_4 (6%) and nitrous oxide N_2O (1%). These emissions are the consequence mainly from waste decomposition, agricultural activities, industrial activities not related with energy production and the use of energy. Transport sector has undergone a serious growth and it has been translated into the CO_2 emissions too (52% from 1990 to 2013) putting the focus on it as one of the key players to tackle in order to control and reduce global warming. In 2011, the transport sector was responsible for near 28% of Europe, CO_2 emissions of which 91.6% can be related to road transport [1].

In order to reduce the impact of road transportation on CO_2 emissions in Europe, the European commission has obligated car manufacturers to ensure that their new car fleet does not emit more than 130 g CO_2/km by 2015 and 95 g CO_2 /km by 2021, however legislation which includes heavy duty vehicles (HDV) which are responsible for nearly 6% of Europe CO_2 emissions are still in discussion [2].

Regarding road transport, especially for vehicles using Internal Combustion Engines (ICE) an obvious approach to reduce the CO_2 emissions is to tackle the different sources of vehicle losses. This can be done in very different ways as reducing air drag with more aerodynamic vehicle shapes, controlling the tires pressure, using Kinetic Energy Recovery Systems (KERS), applying hybridization or reducing engine friction losses. Taking into account the reduction targets expected from the oncoming regulations, it is unlikely to find a single solution complying the normative reductions; it is more probable that the integration of several solutions could lead to accomplish the proposed goals. One proven cost-effective way to increase engine efficiency is the use of low viscosity oils (LVO) in order to reduce the friction losses in the lubricated pairs of the engine which represent nearly 10% of the total losses making them a good target in order to enhance engine efficiency, hence reducing CO_2 emissions.

This paper shows the results of a test focused on the assessment of LVO over fuel consumption and CO_2 emissions of a public transport buses fleet. To perform this, 39 buses of 3 different bus models of EMT-Valencia have been using regular SAE 15W40 and SAE 10W40 Low SAPS engine oils as reference oils and SAE 5W30 and SAE 5W30 Low SAPS engine oils as candidates in order to find fuel consumption differences over a 60000 km mileage corresponding to two Oil Drain Intervals (ODI). In addition for one bus model the effect of using LVO also in the differential has been assessed comparing SAE 80W90 as reference and SAE 75W90 as candidate oil. Finally, the fuel consumption differences have been translated into CO_2 emissions terms in order to evaluate the CO_2 footprint reduction.

2 Test description

The test objective was to compare the fuel consumption of a representative group of urban buses using different engine oils which viscosities ranged from SAE 15W40 and SAE 10W40 Low SAPS to SAE 5W30 and SAE 5W30 Low SAPS.

To accomplish this, a long term test where the daily fuel consumption of a group of control buses using market-standard SAE grade oils was compared against a group of similar buses using LVO was proposed. As the reader may have noticed, a great number of other variables during real service will affect fuel consumption as the environmental conditions (e.g. pressure, weather, season of the year), route conditions (e.g. route grade of slope, average velocity, so on), driving behaviour and specific bus operation conditions variables (urban traffic, number of passengers, vehicle weight, rolling resistance, type of engine, so on), masking the effect of oil viscosity over bus fuel consumption expected to be as low as 1% [3]. Under these conditions, it is important to perform a wide number of test in order to stablish a fuel consumption value statistically significant for each treatment.

To fulfil this requirement a long term test involving a considerable amount of buses of Valencia public transport fleet (EMT-Valencia) was implemented. The test characteristics are explained below.

2.1 Test buses

39 buses of 3 different models were used to assess the effect of LVO over their fuel consumption. Two of this bus models use a diesel powertrain, and the other one use a CNG powertrain meeting Euro emissions standards EURO IV, EURO V and EEV respectively [4]. From now on, Diesel buses meeting EURO IV emission standards will be address as Diesel I buses, in the same way Diesel buses meeting EURO V emissions standards will be address as Diesel II buses. All CNG buses belong to the same model and meet EEV emission standards and they will be referred simply as CNG.

The 39 vehicles were distributed in the three models as follows; 9 Diesel I buses, 10 Diesel II buses and 20 CNG buses. The vehicle characteristics per model can be seen in fig. 1 and table 1.

Diesel I Diesel II CNG

Figure 1: Bus models used during the test.

2.2 Fuel consumption calculation and test duration

A daily basis calculation of buses fuel consumption was made by means of bus mileage and liters of fuel consumed. Covered distance was measured via GPS, on

Table 1: Buses characteristics.

Bus Model	Diesel I	Diesel II	CNG
Year	2008	2010	2007
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
Cylinders	6	6	6
Emission certification level	EURO IV	EURO V	EEV
Max. effect power [kW]	220@2200 rpm	210@2200 rpm	180@2200 rpm
Max. effect [Nm]	1600 @1100 rpm	1100@1100 rpm	880@1000 rpm
BMEP [bar]	16.8 @1100 rpm	19.55 @1100 rpm	9.24 @1000 rpm
Thermal load [W/mm^2]	2.85	3.97	2.33
Turbo-charging [-]	Turbo+Intercooler	Turbo+Intercooler	Tutbo+Intercooler
EGR [-]	NO	NO	-
Valve train config.	OHV Roller Follower	OHV Cam Follower	OHV Cam Follower

the other hand, fuel consumed was measured by refueling both diesel and CNG buses. As it was stated before large amount of data must be taken in order to secure that minimum differences in fuel consumption can be observed; taking this into account, two complete phases of 30000 km each per bus were completed (fig. 2). Each of these two phases corresponded to buses ODI. It has to be mentioned that differential LVO effects on fuel consumption were tested as well for Diesel I buses during phase II.

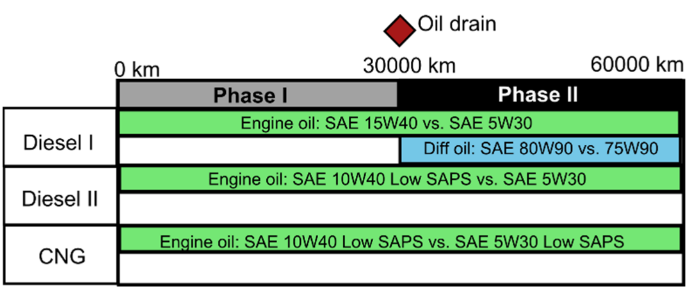

Figure 2: Test phases including the oils studied per bus model.

2.3 Test oils

As the main goal of the test was to evaluate the effect of LVO over fuel consumption and CO_2 emissions it was critical to establish one parameter to choose correctly the different oils to test. Van Dam *et al.* [3, 5, 6] have demonstrated that for HDV, the two most relevant oil rheological characteristics regarding fuel consumption are the kinematic viscosity at 100ºC (kv@100) measured under ASTM D-445, and High Temperature High Shear Viscosity at 150ºC (HTHS@150) measured under ASTM D4683, CEC L-36-A-90 (ASTM D

4741), or ASTM D 5481. In order to evaluate the difference in fuel consumption terms of the different oils the test design include the use of one common oil as reference and one candidate oil with lower values of kinematic viscosity (kv@100) and HTHS. Due the different oil standards required by the bus models OEM's it was not possible to use the same LVO and reference oil in all the models; additionally being some buses still in guarantee period only approved commercial oils were used as candidates. The main characteristics of engine and differential oils can be seen in table 2.

Table 2: Test oil characteristics.

Oil	15W40	10W40 Low SAPS	5W30	5W30 Low SAPS	80W90	75W90
Used as	Ref	Ref	Cand	Cand	Ref	Cand
Buses	Diesel I	Diesel II + CNG	Diesel I + Diesel II	GNC	Diesel I	Diesel I
Base oil	API G-I	API G-III	API G-III + G-IV	API G-III + G-IV	-	-
kV@40ºC [cSt]	108	96	71	68	131	102
kV@100ºC [cSt]	14.5	14.4	11.75	11.7	14.3	15
HTHS@150ºC [cP]	4.082	3.853	3.594	3.577	-	-
Viscosity Index [-]	>141	>145	>158	<169	105	154

3 Results

In order to assess the effect of LVO over the fuel consumption of the buses, the whole data set was submitted to Analysis of Variance (ANOVA) technique to identify the significance of the experimental variables considered.

From the facts exposed in the experimental setup section, it is clear that the experiment could not be completely randomized, (e.g. all oils tested in all bus models or all bus models set to work in all possible routes). Taking into account this situation the ANOVA analysis was made by bus model, blocking the variability in fuel consumption due differences among buses model and routes. This sort of inconvenience could not be handled due to fleet operation requirements.

Variables used to perform the ANOVA analysis were:

- Daily temperature.
- Oil mileage.
- Month.
- Oil type.
- Differential oil type.
- Oil type x Differential oil type.

The last two of the listed variables are only applicable to Diesel I buses.

3.1 Diesel I buses

After completing two ODI and performing the ANOVA analysis, it was proven that engine oil viscosity had an effect over Diesel I buses fuel consumption. The buses using SAE 15W40 showed a fuel consumption of 70.9 l/100 km which represents a difference of 1.83% with respect to buses using SAE 5W30 which consumed an average of 69.69 l/100 km as it can be seen in fig. 3. This difference is statistically significant with 95% of confidence level.

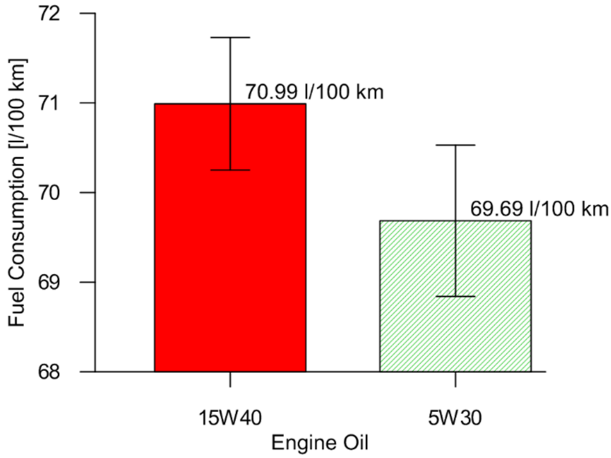

Figure 3: Fuel consumption differences between reference (SAE 15W40) and candidate (SAE 5W30) buses.

In the same way, the effect of differential oil viscosity was proven through ANOVA. As in the case of engine oil, the less viscous oil leads to lower fuel consumption (70.54 l/100 km for SAE 80W90 in contrast to 70.13 l/100 km for SAE 75W90), yet this difference was not statistically significant so even when results seem to be logical it is not possible to make any claim in favour of LVO.

3.2 Diesel II buses

The fuel consumption difference between the buses using reference SAE 10W40 LVO and the buses using candidate SAE 5W30 was 0.98% (as can be seen in fig. 4). However, these differences could not be proven as statistically significant.

3.3 CNG buses

After carrying out the 60000 km mileage, the buses that used SAE 5W30 Low SAPS gave a fuel consumption of 85.1 Nm^3/100 km, considerably lower than the 88.37 Nm^3/100 km of fuel consumption given by the buses using SAE 10W40 Low SAPS. For CNG buses, this difference of 3.7% is statistically significant, demonstrating again the benefits of using LVO in terms of fuel consumption (fig. 5).

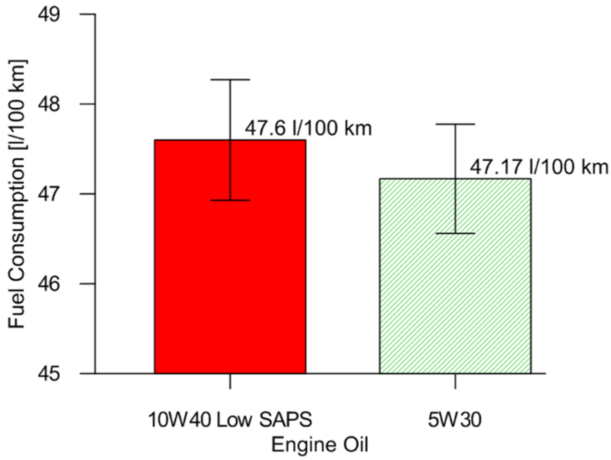

Figure 4: Fuel consumption differences between reference (SAE 10W40) and candidate (SAE 5W30) buses.

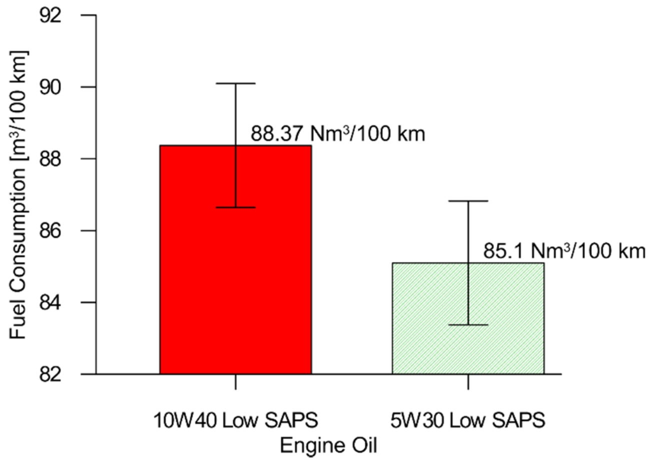

Figure 5: Fuel consumption differences between reference (SAE 10W40 Low SAPS) and candidate (SAE 5W30 Low SAPS) buses.

4 Analysis

4.1 The role of engine design and working parameters

Taking into account the results displayed on the previous sections it is clear that engine LVO led to lower fuel consumption values for two of three models involved in the test. However, no difference could be established for Diesel II model between reference and candidate buses. Taking into account the achieved break mean effective pressure (BMEP) by each engine and the fuel consumption reduction reached by means of LVO a good correlation comes up as it can be seen in fig. 6. The resulting correlation shows how high values of BMEP tends to cut down the effect of LVO over fuel consumption.

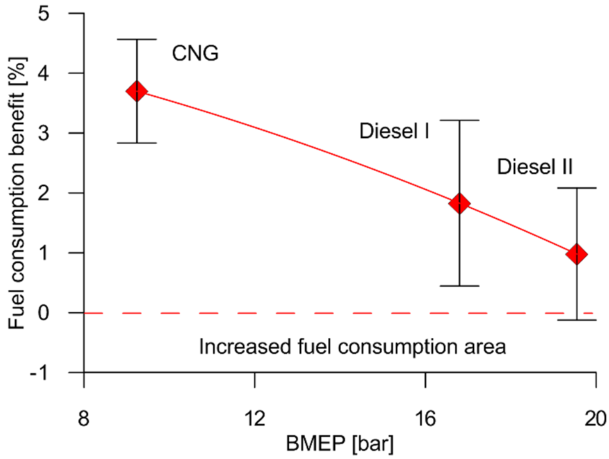

Figure 6: Correlation between BMEP of the different engines and the given fuel consumption benefits in percentage.

A possible good explanation can be done examining what is happening in the different lubricated pairs of the engine, this can easily be done with the Stribeck curve (fig. 7), which correlates the friction coefficient of any lubricated pair with the three main parameters ruling its behaviour; lubricant viscosity (μ), relative speed between moving parts (U) and the normal force held by the pair (F). The relation between these three variables defines three main lubricating regimes;

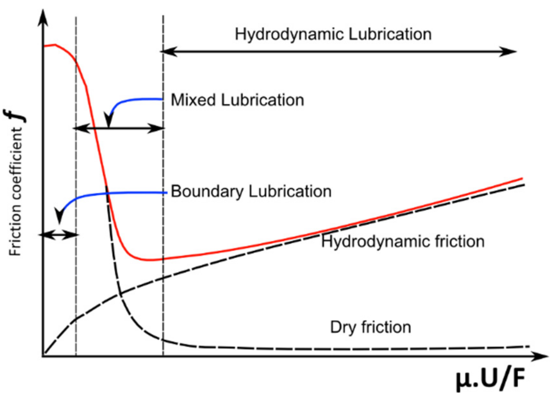

Figure 7: Stribeck curve: the friction coefficient of every lubricated part can be described by means of the lubricant viscosity μ, relative speed U, and normal force held by the pair.

the hydrodynamic regime, where relative speed is high, loads are relative low and the lubricant viscosity is in a state that could generate sufficient pressure to sustain a lubricant layer thick enough to prevent contact between parts. In this regime, the friction coefficient is directly correlated to lubricant viscosity and is precisely here where LVO can do some changes in fuel consumption reduction. The opposite case is when loads are high and speed is low enough to inhibit a lubricant layer formation hence allowing contact between parts. And finally the mixed regime which is a mixture of hydrodynamic and boundary regimes.

Reaching high values of BMEP mean that high load values are taking place in the engine hence the friction coefficient in the Stribeck curve is moving towards left that is, changing lubrication regime towards mixed or even boundary where friction is higher.

4.2 Engine and differential LVO synergy

For this type of analysis sometimes it is important to find if there is any level of interaction between certain variables. To figure out how was this interaction and if it has an impact on fuel consumption, it was included in the model, resulting into a positive but not statistically significant interaction between the two levels of the oils as it can be seen in table 3, where despite the lack of significance, it is clear that engine LVO combined with differential LVO give the lowest fuel consumption value in comparison with other combinations. As expected the highest fuel consumption occurs if both oils correspond to reference viscosity.

Table 3: Fuel consumption values for the different treatments of engine and differential oils at two levels.

Engine oil	Diff. oil	Fuel consumption [l/100 km]
5W30	75W90	69.52
5W30	80W90	69.84
15W40	75W90	70.74
15W40	80W90	71.23

4.3 CO_2 emissions carbon footprint reduction

It is interesting to translate this fuel consumption reduction into CO_2 emissions reductions. The normal procedure to calculate the equivalence involves knowing the elementary composition of fuel to calculate the amount of carbon in it, then supposing a stoichiometric combustion, a carbon balance is made in order to calculate the amount of CO_2 produced in the reaction. The complete method and formulas for calculation can be found in the appendix.

For Diesel I buses and CNG buses which obtained statistically significant differences, the CO_2 emissions reductions per kilometre were 34.29 g/km and 70.14 g/km respectively. It is worth remembering that each of the test buses covered an average 60000 km mileage during the test hence, the total amount of

CO_2 emissions reduction per Diesel I and CNG bus using LVO is easy to plot, being this values 2.05 CO_2 Tons and 4.2 CO_2 Tons respectively.

5 Conclusions

- LVO have been proven as an effective way to reduce fuel consumption and CO_2 emissions.
- During the field test, SAE 5W30 LVO gave lower fuel consumption than SAE 10W40 and SAE 15W40 for the three bus models used.
- For Diesel I buses, SAE 5W30 oil gave 1.8% of fuel consumption benefits compared to SAE 15W40. In the case of differential oils, despite of showing lower fuel consumption, it was not possible to statistically state that SAE 75W40 lead to lower fuel consumption compared to SAE 80W90.
- Each Diesel I bus using SAE 5W30 engine oil emitted 2.05 CO_2 Tons less than their counterparts using SAE 15W40 engine oil.
- For Diesel II buses, SAE 5W30 oil gave 0.98% of fuel consumption benefits over 10W40 Low SAPS, however this difference was not statistically significant.
- For CNG, SAE 5W30 Low SAPS gave 3.7% of fuel consumption benefit over SAE 10W40 Low SAPS.
- Each CNG bus using SAE 5W30 Low SAPS engine oil emitted 4.2 CO_2 Tons less than their counterparts using SAE 10W40 Low SAPS engine oil.
- The effectiveness of LVO to reduce fuel consumption relies strongly on the mechanical and thermal loads of the engine.
- Not all possible treatments could be set to perform a Latin-squared test due buses involved were at service throughout the test.
- For fleet tests where repeatability is poor due noisy factors, a high number of test runs is required to obtain fuel consumption differentiation.

Appendix

CO_2 emissions are a direct product of fuel combustion. As B10 and CNG were the two fuels used in the test, the elementary composition of these fuels would be required to perform the calculation. The following compositions can be supposed:

- Diesel: $C_{12}H_{22}$
- Biodiesel B100: $C_{19}H_{35}O_2$
- CNG: CH_4

The combustion reactions of these fuels are
Diesel:

$$2C_{12}H_{22} + 35O_2 \rightarrow 24CO_2 + 22H_2O$$

Biodiesel B100:

$$C_{19}H_{35}O_2 + 26.75O_2 \rightarrow 19CO_2 + 17.5H_2O$$

CNG:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

If carbon molar mass is 12 g/mol, oxygen is 16g/mol and hydrogen is 1 g/mol, the molar mass for each fuel and combustion product are:

Compound	Molar mass [g/mol]
CO_2	44
CH_4	16
$C_{12}H_{22}$	166
$C_{19}H_{35}O_2$	295

Hence the CO_2 emissions per g of fuel are:

Fuel	CO_2/fuel [g/g]
Diesel	3.18
Biodiesel B100	2.83
CNG	2.75

Being these values taken from the conversion values from IDAE (Instituto para la Diversificacion y Ahorro de la Energía. Ministerio de Industria, Energía y Turismo). Given the fuel densities:

Fuel	Density
Diesel	835 g/l
Biodiesel B100	880 g/l
CNG	1098 kg/Nm^3

With the given values the equivalent CO_2 emissions for a given fuel consumption could be calculated by:

$$CO_2 emssions \left[\frac{g}{km}\right] = fuel\ consumption \left[\frac{l}{100km}\right] \times fuel\ density \left[\frac{g}{l}\right] \times CO_2 equivalence \times \frac{1}{100}$$

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