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Prediction of fuel economy performance of engine lubricants based on laboratory bench tests

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ABSTRACT

Due to increasingly strict vehicle emissions limitations over the past two decades, fuel economy improvement continues to be a focal point in all aspects of engine and vehicle engine and operation. This paper describes a methodology to predict the quantitative influences of lubricant properties on CEC L-54-96 standard engine fuel economy test. High shear viscosities were measured by means of a Ravenfield Viscometer (Method ASTM D 4741), the boundary friction coefficient was measured at 100 °C by means of a High Frequency Reciprocating Rig and traction coefficient was measured at 100 °C by means of a Mini Traction Machine in a configuration ball-on-disk. Multiple linear regression procedure was used and an excellent correlation was obtained between measured and predicted fuel economy increment. Both the predictive equation and the diagram of sectors obtained in this work will be very useful in practice to calibrate the real role played by base stock, viscosity index improvers and friction modifiers in the development of new lubricants labeled as fuel economy.

1. Introduction

The lubricant industry is facing enormous challenges to develop products that function optimally under severe conditions for long operating periods. One other factor emerging from the automotive standpoint is finding ways to improve the vehicular fuel economy. In fact, due to increasingly strict vehicle fuel economy mandates over the past two decades, fuel economy improvement continues to be a focal point in all aspects of engine and vehicle engine and operation. This includes engine oil formulation, whose fuel economy improvement potential can be estimated in the interval from 1% to 4%, depending on the chosen baseline [1]. In response, all major global regions have established standard engine oil fuel economy tests, whether through industry groups (such as ILSAC, API, or ACEA), or through individual OEMs. Standardized fuel economy tests of lubricants are either in common use in the USA, Japan and Europe. Examples of such tests are the ASTM Sequences VID, VIE and the CEC L-54-96 (M 111) standard engine fuel economy test, which is part of the standards ACEA A1/B1, A5/B5, C1, C2, C3 and C4. These tests show that carefully formulated lubricants can make significant contributions in order to reduce fuel consumption by the optimization of internal engine friction. Nevertheless, the selection of optimal lubricant rheology and surface chemical properties to yield high fuel efficiency is quite complex because the overall friction within an operating engine originates from several different engine components, including the valve train, piston pack and bearings [2,3]. Each of these components subject the lubricant to different and widely-varying conditions of temperature, load and shear rate throughout an engine cycle. The net result is that there exists, within a firing engine, a balance of the different regimes of lubrication: boundary, mixed and hydrodynamic. On the other hand, under certain circumstances, some components of an engine are subjected to an elastohydrodynamic (EHD) regime of lubrication which is a particular case of hydrodynamic lubrication though it exhibits very different properties.

In addition to the standardized fuel economy tests that oils are required to pass to meet specifications, bench tests have historically been used to screen and assess the fuel economy performance of these oils [4–7]. These measurements are relatively quick and easy to obtain compared to the more sophisticated and expensive engine performance tests. Therefore, optimization of bench tests can be considered as a fascinating challenge for petroleum industry.

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The aim of the work reported in the current paper, carried out by the Spanish company REPSOL S.A. in cooperation with the Research Group of Physics and Chemistry of Linares, is to extent the regression approach to a systematic study of fuel efficiency effects of lubricants and, in particular, to investigate the quantitative influences of lubricant properties on CEC L-54-96 standard engine fuel economy test.

2. Material and methods

Key parameters of 21 commercial lubricants oils were evaluated in the Repsol Laboratory of Lubricants, which is placed in the Repsol Technology Centre at Móstoles (Madrid, Spain). This set of lubricant oils were selected from an industrial perspective. The high shear viscosity (η_{HTHS}) was measured at 150 °C by means of a Ravenfield Viscometer (Method ASTM D 4741). Other temperatures for the evaluation of shear viscosity were rejected in a similar way to previous works ([4,7]) because the use of method ASTM D 4741 guarantees highly reproducible measures. Nevertheless, the use of different temperatures for the evaluation of high shear viscosity could report good results too.

Boundary friction coefficient (μ_B) was measured at 100 °C by means of a High Frequency Reciprocating Rig (HFRR). In this test a 9.8 N load was applied to the fluid between a 6 mm diameter ANSI 52100 steel ball and an ANSI 52100 steel flat. The ball was oscillated over a 1 mm path at a frequency of 50 Hz. We proved that the HFRR measures the boundary friction coefficient under the referred experimental conditions. In particular we found that the friction coefficient measured by means of the HFRR changes when we use lubricants oils composed of the same base oil but different additive package. On the other hand, the friction coefficient remains constant when we use lubricants oils composed of different base oils but the same additive package.

Finally, the EHD traction coefficient (μ_{EHD}) was measured by means a Mini Traction Machine (MTM) in a configuration ball-on-disk. Temperature conditions from 40 to 100 °C and velocities up to 3500 mm/s were used in the tests. Measurements of the fuel economy increment (*FEI*) according CEC-L-54 were run at an accredited laboratory.

3. Theory

Throughout this paper an optimal correlation between the physical properties of oils and fuel economy performance was performed. The techniques used to perform these correlations were the same ones used previously by various researches to correlate oil properties to fuel economy performance measured in the sequence VIA engine test [4–7]. Given that the mathematical model obtained by means of a multiple linear regression procedure admits a maximum of three correlation parameters, we used a parameter that characterizes the hydrodynamic regime (HTHS viscosity), a second parameter that characterizes the boundary regime (boundary friction coefficient) and a third parameter that characterizes the EHD regime (friction coefficient in EHD regime). The mixed regime is part of our predictive model because the mixed regime is an unstable combination of boundary and hydrodynamic regimes. Therefore, the following equation was used:

$$FEI = A' + B'\eta_{HTHS} + C'\mu_B + D'\mu_{EHD} \qquad (1)$$

Where A', B', C' and D' are adjustable parameters which were calculated using standard statistical techniques.

It must be underlined, in order to check the validity of Eq. (1), that linear correlations between *FEI* and η_{HTHS} and between *FEI* and μ_B have been experimentally proved [8,9].

On the other hand, Eq. (1) shows a striking feature: as is widely known, the high shear viscosity (η_{HTHS}) characterizes the hydrodynamic lubrication regime, the boundary friction coefficient (μ_B) characterizes the boundary lubrication regime and the traction coefficient characterizes (under certain conditions) the elastohydrodynamic lubrication regime (in which case is named μ_{EHD}). In conclusion, the three lubrication regimes are included in the general form of Eq. (1).

4. Results and discussion

Multiple linear regression analyses have permitted us a precise evaluation of parameters A', B', $C'$and D' in Eq. (1). Table 1 shows the obtained results. Model A was obtained by correlating *FEI* with only η_{HTHS} values, model B was obtained by correlating *FEI* with η_{HTHS} and μ_B values and, finally, model C was obtained by correlating *FEI* with η_{HTHS}, μ_B and μ_{EHD} values. In order to select the optimal running conditions in the evaluation of μ_{EHD} values, some preliminary correlations were performed, which allowed us select an optimal load of 20 N and an optimal velocity of 2500 mm/s. Fig. 1 shows a typical curve obtained in a MTM test under the above mentioned experimental conditions and a slide/roll ratio (SRR) value of 100%. We would like underlying that it was carefully proved that under the above imposed experimental conditions oils formulated with similar kinematic viscosity but different base stock reported different values of traction coefficient and high shear viscosity. Additionally, formulas with different additive and same base stock blend provided similar values of traction coefficient. Therefore, we concluded that the point selected falls into the elastohydrodynamic lubrication regime (the reader should recall the complete Stribeck curve [10]). On the other hand we decided to use a slide/roll ratio (SRR) value of 190% in the multiple regression linear analyses. The reason for choosing this particular value is addressed in greater detail below. In view of Table 1 it is evident that the use of three variables (η_{HTHS}, μ_B and μ_{EHD}) provides the best adjusted coefficient of determination, R^2_{adj} , with a quantitative value of 0.9273. This means, from a practical point of view, that the *FEI* evaluated by means of the CEC L-54-96 standard engine fuel economy test is strongly influenced by the behavior of the lubricant oil in three different regimes of lubrication (hydrodynamic, boundary friction and elastohydrodynamic).

Fig. 2 shows the adjusted coefficient of determination versus the SRR in the curse of extensive MTM tests carried out at a temperature of 100 °C, a velocity of 2500 mm/s and a load of 20 N.

Table 1
Adjustment parameters A′, B′, C′, D′, adjusted coefficients of determination and standard deviation for models A, B and C obtained by multiple regression analysis.

MODEL	Hydrodynamic lubrication regime	Boundary lubrication regime	Elastohydrodynamic lubrication regime	A'	B′	C′	D′	R^2_{adj}	Standard deviation
A	η_{HTHS} (150 °C)			7.78	−1.64	–	–	0.7526	0.296
B	η_{HTHS} (150 °C)	μ_B (100 °C)		8.82	−1.48	−13.01	–	0.9248	0.163
C	η_{HTHS} (150 °C)	μ_B (100 °C)	μ_{EHD} (100 °C) SRR=189.79%; 20 N; 2500 mm/s	9.25	−1.43	−12.80	−24.48	0.9273	0.160