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EVALUATION OF AN EXPERIMENTAL LUBE OIL ON PISTON FRICTION, ENGINE PERFORMANCE AND VEHICLE ACCELERATION[1]

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Abstract
Two engine lubricant oils were investigated in regard to friction and vehicle performance. The products were a typical high viscosity commercial oil used at the Brazilian market and a low viscosity lubricant containing especial additives and friction modifiers, designed for racing applications. Comparison of the piston system friction was measured using the floating liner engine. Piston/Rings/Liner (PRL) friction was measured in 4 regimes, representative of urban conditions. In average, the low viscosity oil presented 52% lower friction, ranging from - 46% at 1500 rpm/20Nm to -59% at 2500 rpm/20Nm. The lube oils were also tested on a production 4 cyl., 1.4L gasoline engine, brake power gains from 1.9 to 2.7 % were observed with the low viscosity lube oil. The same oils were tested also regarding vehicle acceleration. The low viscosity oil showed from 4.4% reduced acceleration time from 40-60 km/h up to 6.3% from 60-100 km/h.
Keywords: Lubrication; Viscosity.

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2 *MAHLE Brazil*
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1 INTRODUCTION

Reducing fuel consumption and emissions are seen as a major industry driver. As lubricants play an important role in reducing friction, using optimized products can lead to significant energy savings and also contributes for reducing CO2 emissions. Since friction losses represent a significant portion of the consumed fuel, changes in the engine friction will affect the performance, fuel economy and emissions. In terms of lubrication regimens, it is usually accepted that friction losses due to fluid-film represents 2/3 of the total friction losses while the mixed-film or boundary regime is responsible to 1/3 of the losses. Measuring the friction mean effective power (FMEP) using a driving dynamometer is the easiest way to evaluate the engine friction loss, but the test conditions are different from the actual ones. When comparing different variants, measuring fuel economy is the most used procedure, but it is difficult to isolate each system / component contribution. The different methods to measure engine friction are described in item 2.4.

Generally low viscosity oils are preferable since they present lower friction in hydrodynamic conditions, e.g. crankshaft bearings and piston rings at mid-stroke. So most of the fuel economy oils are 5W-30 or have even lower viscosities. Meanwhile, other engine tribo-systems as valve train and piston rings during the combustion stroke require especial additives to reduce friction in boundary conditions. Also operating parameters as high load, low speed and high temperatures tend to increase boundary friction. Friction modifiers (FM) are additives that are supposed to react with the metal surfaces and reduce the asperities contacts, thus reducing boundary friction. So they are very effective in these situations.

2 LITERATURE REVIEW

2.1 Effect of Oil Viscosity

The relationship between the oil viscosity and FMEP was studied by several authors. Taylor et al.(1) found different relations due to specific tribological pairs present at the engines as follows:

- Pistons / rings /liners – FMEP = f $(\eta)^{0.5}$, η – Lubricant dynamic viscosity (mPa.s)
- Bearings - FMEP = f $(\eta)^{0.75}$, as the hydrodynamic friction is more dominant
- Valve train wear – FMEP generally increases with viscosity decrease, due to the boundary lubrication.

Since the piston system is thought to dominate engine friction, the authors concluded that it is a good assumption that FMEP varies with the square root of the lubricant viscosity. Bartz(2) mentioned that reducing engine oil viscosity by one SAE grade will result in fuel consumption reduction from 0.6 to 7.5% depending on the engine condition. Tseregounis, Mcmillan e Olree(3) found a difference in fuel economy up to 3.5% between SAE 10W-40 and SAE 0W-10, especially under the city portion of the EPA test. In the same study, the influence of friction modifiers was higher in the highway portion of the EPA test than for the city portion. Cater, Bolander e Sadeghi(4) compared different viscosity oils in a motored floating liner as well as by numerical simulation. The higher viscosity oils, SAE 30 and 40, presented higher friction at mid-stroke but lower friction at the piston reversal points. The majority of the studies converge that the best way to correlate oil viscosity and engine performance is by means of High Temperature High Shear (HTHS) viscosity, since the test conditions

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are more similar to the real engine operation. Hoshino, Kawai e Akiyama[5] evaluating different oil viscosities in terms of fuel economy on a chassis dynamometer and using U.S. FTP procedure got to the conclusion illustrated on Figure 1. Lowering the HTHS viscosity up to 2.6 mPa.s, the engine performance was improved. However, further viscosity reductions lead to a drop in fuel economy due to increasing friction in mixed/boundary regime caused by thinner oil films.

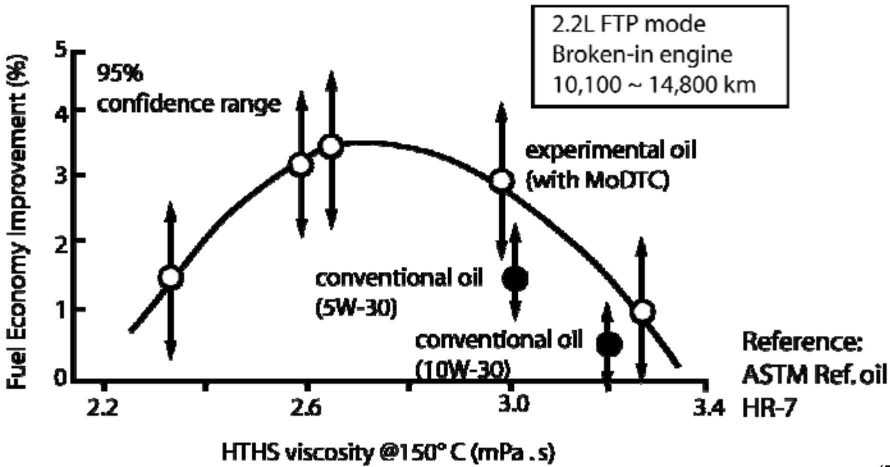

Figure 1 – Relationship between HTHS viscosity and Fuel Economy Improvement.[5]

2.2 Effect of Friction modifiers (FM)

Since FM additives reduce boundary friction and this lubrication regime is found in every engine, the use of FMs is globally adopted on the oil formulations, especially those designed for fuel economy. The most used FM types are Molybdenum based and also the organic components for ashless applications. Generally, fuel economy engine oils are formulated with both low viscosity base oils and FM additives. So it is difficult to find a study where the benefits of each technology are evaluated separately. Green and Risdon[6] reported that molybdenum FM improves gasoline engine fuel economy by 3 to 5 % while Tseregounis and McMillan[7] found fuel economy improvements from 1 to 3% when using organic and Molybdenum FM on gasoline engine oils. In their studies, Skjoedt et al.[8] tried to separate the contribution of each formulation change, e.g. base oils, viscosity grade and friction modifiers. In the cited work, they used two engine conditions, one for high hydrodynamic friction and another for high boundary friction. They found that Mo based FM reduces friction by 15% in high boundary friction conditions, but only 7% at high hydrodynamic friction conditions. In this same study they also evaluated organic FMs and obtained friction reductions of 7% and 6% for each of the engine conditions. So they concluded that for both FMs, friction reduction is greater at high boundary conditions and also that Mo FMs are more effective than organic FMs since they form a stronger surface layer on the metal components. Hoshino, Kawai e Akiyama[5] obtained an average reduction of 1.5% in fuel economy in the U.S. FTP test procedure while using an API SJ oil containing Molybdenum FM in comparison to conventional low viscosity oil.

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2.3 Effect of Base Oils

It is obvious that, when formulating very low viscosity oils, as 0W-20, 0W-30 or 5W-30, the use of synthetic oils are imperative. Meanwhile, using synthetic oils allow obtaining additional benefits in terms of friction reduction, as:

- Formulations could contain less Viscosity Index Improvers (VII) additives which generally have lower lubricity;
- Some synthetic oils contain molecules of high polarity that are absorbed onto metal surfaces creating a strong and protective oil film. So, the type of base oils can also have a big effect on the engine friction losses.

Skjoedt et al.[(8)] calculated the friction mean effective power (FMEP) in gasoline engines and found up to 16% reduction when using synthetic oils in comparison to mineral oil formulations, specifically at high boundary regimes. They concluded that this reduction was due to a strong lubricant surface formed by the adhesion of the synthetic oils to the engine surfaces.

2.4 Engine Friction Measurement

Heywood[(9)] defines engine friction work as “the difference between the work delivered to the piston while the working fluid is contained within cylinder (i.e., during the compression and expansion strokes) and the usable work delivered to the drive shaft”. Friction work is usually divided in:

- Pumping work: work expended to draw the fresh mixture though the intake system and into the cylinder, and to expel the burned gases from the cylinder and out of the exhaust system.
- Components friction: work to overcome the resistance to relative motion of all moving parts of the engine.
- Auxiliaries: work to drive the engine accessories as the fuel, water and oil pumps, fan etc.

Mechanical losses in an internal combustion engine account for approximately 10% of the total energy of the consumed fuel. This amount represents around 25% of the effective power at full load, more at part loads. E.g., at idle or no-load, 100% of the indicated power is consumed by friction. The piston and the piston rings are the largest contributors to the mechanical losses, but the relative share varies with engine type and load condition. Figure 2 shows the energy distribution for a 2.0L SI engine at full load/5000 rpm.

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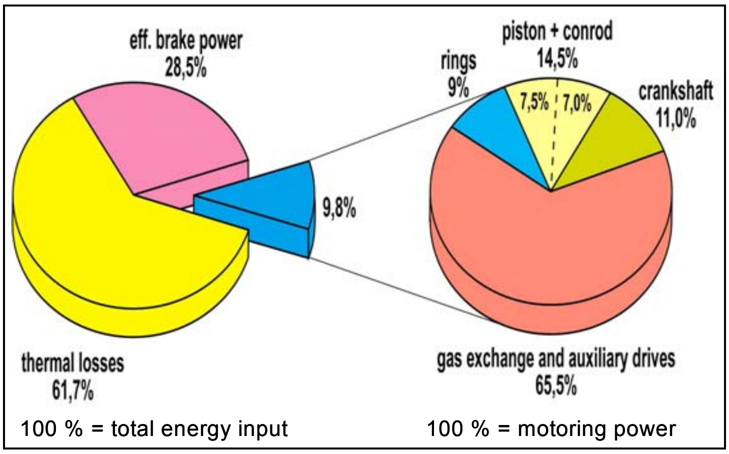

Figure 2 - Breakdown of total energy and engine mechanical losses.[10]

Engine friction is difficult to be accurately measured. The more common methods are:

- **Indicated Power:** Friction is defined by the difference between Indicated Power and the measured Effective Power.
- **Direct Motoring:** Direct motoring of the engine is the most common method to estimate friction losses. The power required to motor the engine includes the pumping work. However, motoring tests measure the friction without the combustion loads, underestimating the friction.
- **Morse Method:** In the Morse test, individual cylinders in a multi-cylinder engine are cut out from firing, and the reduction in brake torque is determined while maintaining the same engine speed.
- **Willans Method:** A plot of fuel consumption versus brake output obtained from engine tests at a fixed speed is extrapolated back to zero fuel consumption.
- **Specific Fuel Consumption, brake power:** Not exactly a friction measurement, but friction changes can be estimated due to changes on the engine Specific Fuel consumption or power when testing two engine configurations. As the precision is relatively low, it is advisable to try this method only when significant friction reductions are expected.
- **Floating Liner:** The Musashi Floating Liner is a mono-cylinder engine with unique devices to measure friction forces of piston/rings/cylinder. It was developed in the Musashi Institute (now Tokyo City University) by Profs. Furuhama and Takiguchi.[11] Basically, the floating liner consists in a modified mono-cylinder engine, where the liner has vertical freedom and a load cell measures the piston/piston ring vertical load applied to the liner (Figure 3).
- Other, similar, floating liner devices have been developed, by different researchers.[4] A Musashi Floating Liner was used in this work as described in item 3.2.

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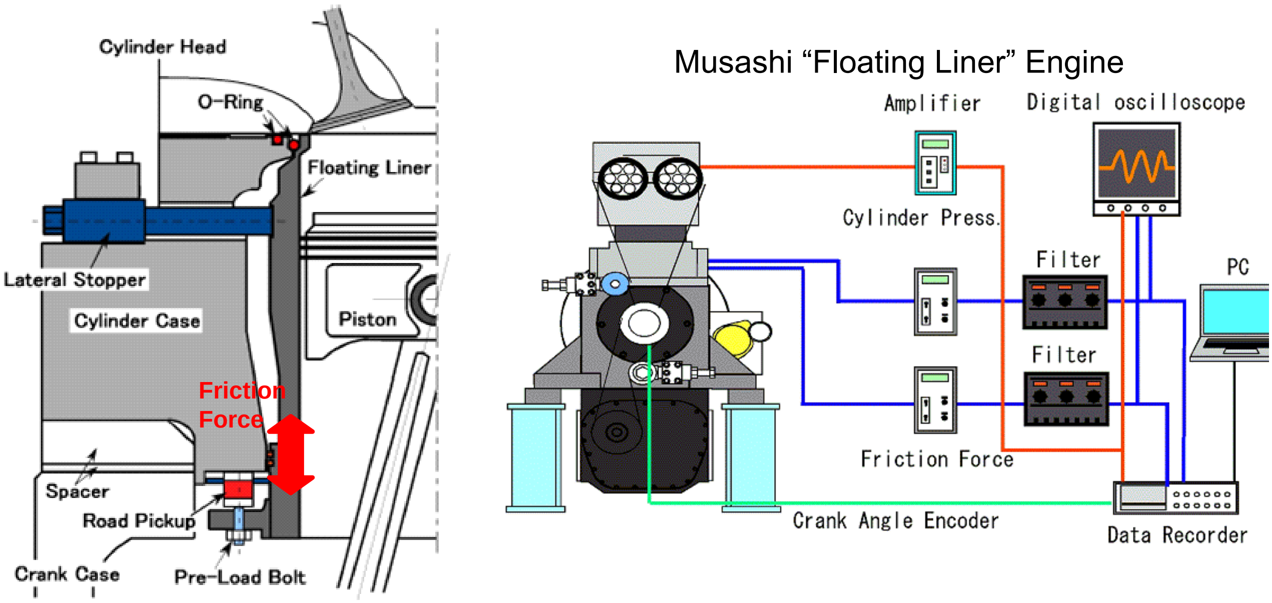

Figure 3 - Schematic view of the Floating Liner.

3 EXPERIMENTAL DETAILS

The main objective of this study was to compare three different measurement methodologies available at Mahle and Petrobras to evaluate oil influence on engine friction and engine performance. These methodologies are used for tribology and performance evaluations and each method covers a different, although related, aspect as:

- Floating liner engine test - Directly measures the friction forces between the piston system and the cylinder, informing the potential of friction reduction due to the use of especially designed engine oils;
- Engine dynamometer test - Performance and fuel consumption of the complete engine can be measured, but not the individual tribo-systems contributions;
- Vehicle acceleration test - Allows performance tests in vehicle application and also the measurement of fuel consumption. Its results can easily be associated to racing engine oils performance.

Therefore, it was supposed to be very interesting to compare how different would be the results obtained in each methodology

3.1 Lubricant Oils

As mentioned, two very different engine oils were used in order to have a significant difference on the tests results. The first one is a commercial oil for passenger cars, SAE 20W-50, API SJ, regularly used by the Brazilian car fleet. The second one is an especial lubricant developed for racing cars, SAE 0W-30, formulated with proper additives for reducing engine friction. The main characteristics of both oils are presented in Table 1.

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Table 1– Physical-Chemical characteristics of the two oils used in this study

Oil Characteristic	Oil A – SAE 20W-50	Oil B – SAE 0W-30
Viscosity at 100°C, cSt	20.80	11.23
HTHS at 150°C, cP	4.5	2.6
Friction Modifier	No	Yes

As it can be observed on Table I, the oil viscosities are quite different. For example, the HTHS of **Oil A** is almost twice of **Oil B.** The Viscosity Indexes are also very diverse and on Figure 4 it is showed the viscosity variation with temperature for both oils. Additionally **Oil B** contains friction modifier additive while **Oil A** has no FM. Therefore, as **Oil B** has all the elements required for engine friction reduction, better performance results are expected when using **Oil B** rather than **Oil A**.

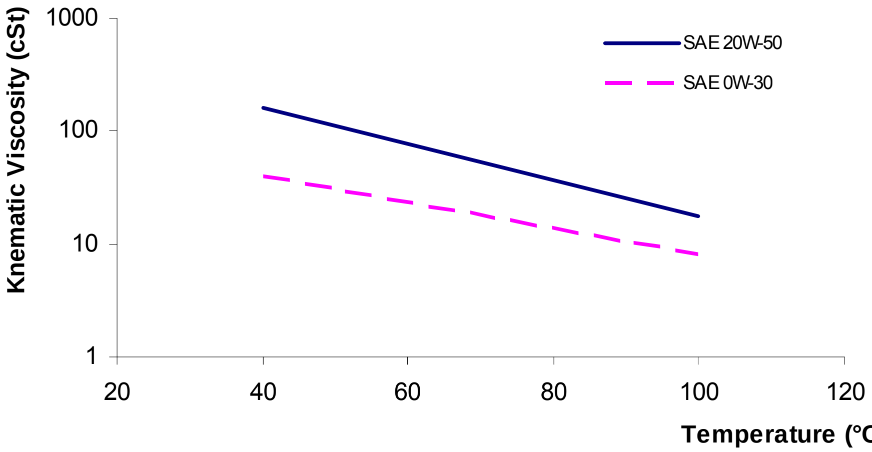

Figure 4 – Kinematic Viscosity Variation with temperature.

3.2 Floating Liner Tests

In this study, friction was measured in 4 operation conditions (see Table 2). All conditions are part load, typical of urban use. Crankcase oil temperature was kept at 85±1 ºC at the main gallery, Cylinder temperature 100±1 ºC at mid-stroke, Anti trust side for all regimes. The tests were made with gasoline 98 RON. Piston and rings are typical SI North American ones.
After few hours of conditioning, the try-out with the 2 different lube oils was made as described below:

- In each test, 3 sequences of the 4 test regimes were measured
- The engine was filled with the high viscosity, 20W-50 oil. Piston / Ring / Liner (PRL) friction was measured.
- After oil draining, the lube oil was changed for the low viscosity, 0W-30. After a very short conditioning, PRL friction was measured.
- After oil draining, the high viscosity oil was filled again. After a very short conditioning, PRL friction was measured. Some “carry over” from the low viscosity can be expected, especially due to the FM additive presence. A better flushing-in and a longer lube aging would be advisable, but that would consume more time than the dedicated for this study. A longer aging would also dictate head block disassembly to change the sealing of the floating liner, introducing other experimental errors.

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Table 2 - Floating Liner Test Characteristics

Engine Type	Single Cylinder, 4 stroke SI gasoline
Displacement (liter)	0.65
Bore x Stroke (mm)	96 x 89.2
Compression rate	9.7
Operation Conditions (Speed and torque)	1500 rpm @ 20 Nm, 31 Nm 2000 rpm @ 20 Nm 2500 rpm @ 20 Nm
Cylinder Temp. [ºC]	100 ± 1 (at mid-stroke)
Oil Temp. [ºC]	85 ± 1 (at main gallery)

The measured PRL friction showed large differences, see figure below. In average, the low viscosity oil presented 52% lower PRL friction, ranging from - 46% at 1500 rpm/20Nm to -59% at 2500 rpm/20N. The replication of the test with the high viscosity oil showed in average 11% lower PRL friction than the 1st assembly, probably due to the mentioned “carry over” effect. As the engine BMEP was kept constant and the low viscosity oil produces less friction, Peak Cylinder Pressure (PCP) was 6 to 13% lower in each operation regime for the low viscosity lube oil than with the high one. The lower PCP might have influenced the friction force around TDC, but probably was not relevant for the FMEP, once the piston speed is low around TDC. Anyway, eventual influence is much lower than the measured difference due to the oils.

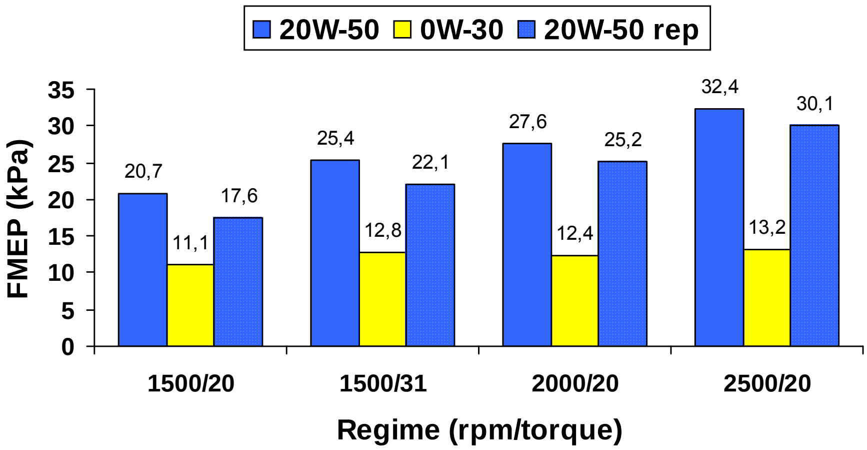

Figure 5 – Measured FMEP.

The floating liner allows the resolving of friction forces along the stroke. Figures 6 to 8 show the measured friction force and the combustion pressure along the crank angle. As discussed in the introduction, lower viscosity grades usually lead to lower friction forces at the mid-stroke, but higher at the reverse points, where mixed regimes dominate. The use of friction modifier additives on the racing lube oil promoted that even around the reversal points, the friction forces were only slightly affected when compared to the high viscosity lube. In the plots, negative friction forces only indicate their direction, opposite to the engine head.

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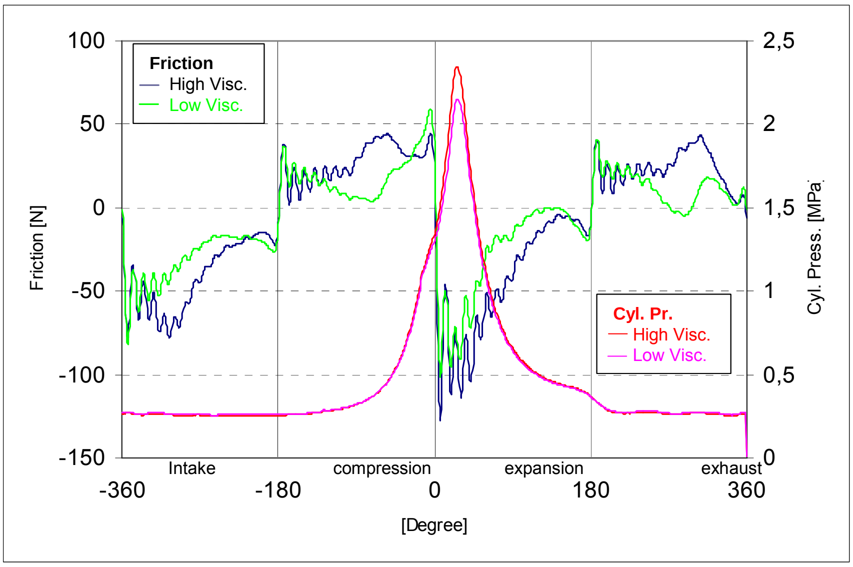

Figure 6 – Friction force and Combustion Pressure at 1500 rpm/20 Nm.

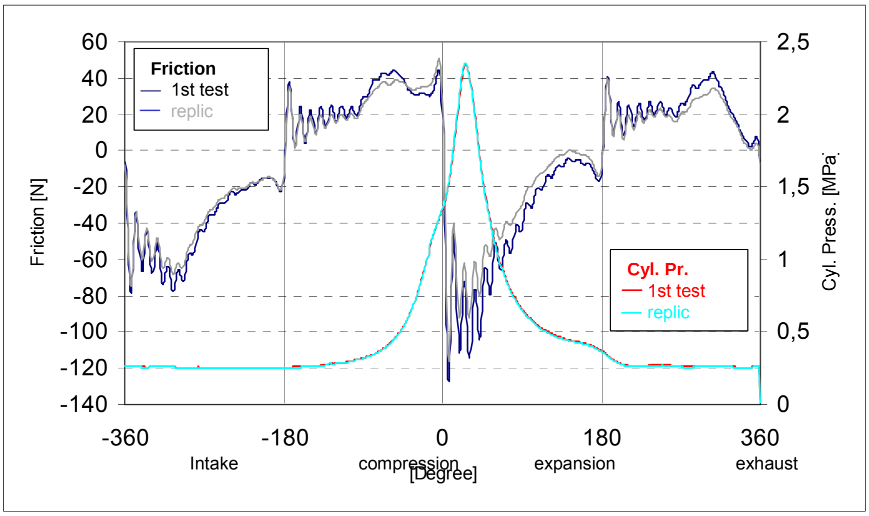

Figure 7 – 1500rpm/20Nm - High viscosity lube oil. 1st test versus replication after the low viscosity oil.

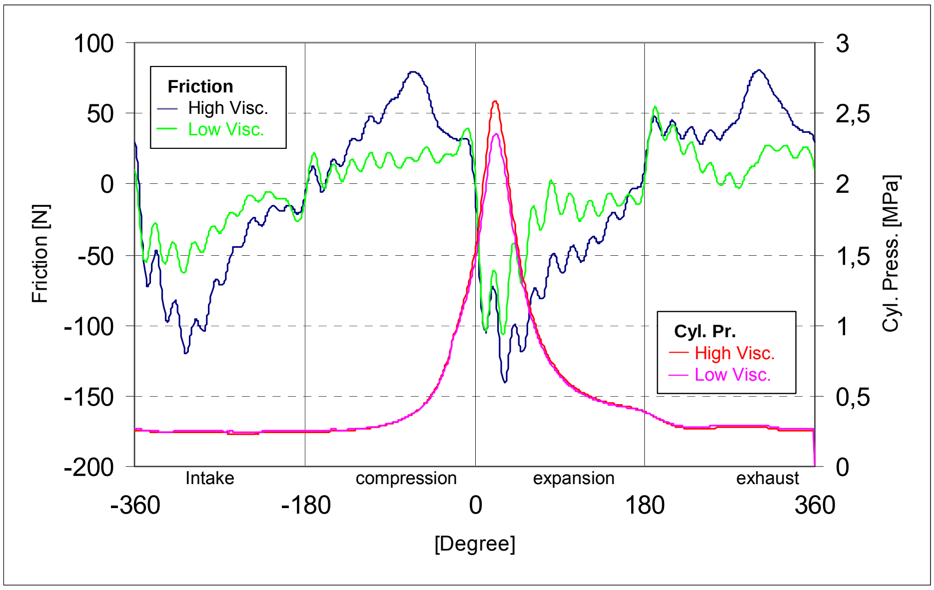

Figure 8 – 2500rpm/20Nm - High versus low viscosity.

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3.3 Friction Forces at Different Speeds

At 20 Nm, the combustion pressures were similar at 1500, 2000 and 2500 rpm, allowing a direct investigation of the engine speed influence for both oils. For the low viscosity oil, the effect of speed is not very evident. See figure 9. On the other hand, increase in viscous shear friction in the mid-stroke is clear for the high viscosity lube oil (Figure 10).

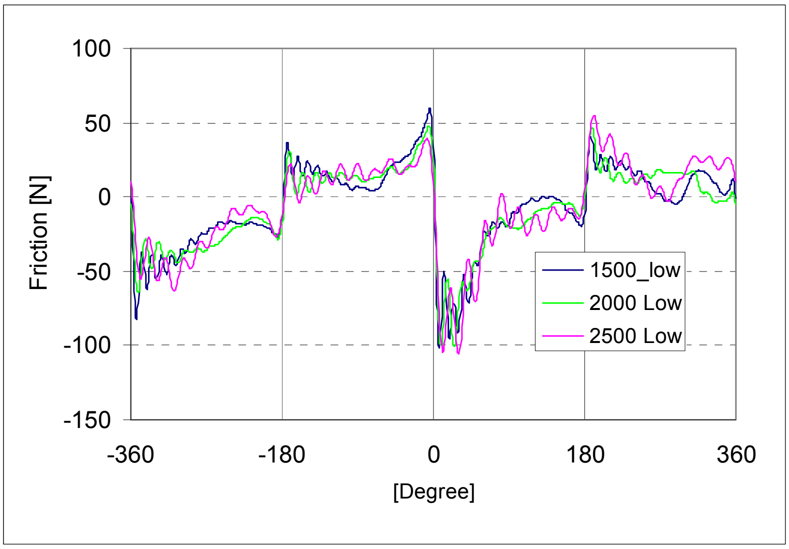

Figure 9 – Measured Friction Forces at different engine speeds. Low viscosity lube oil.

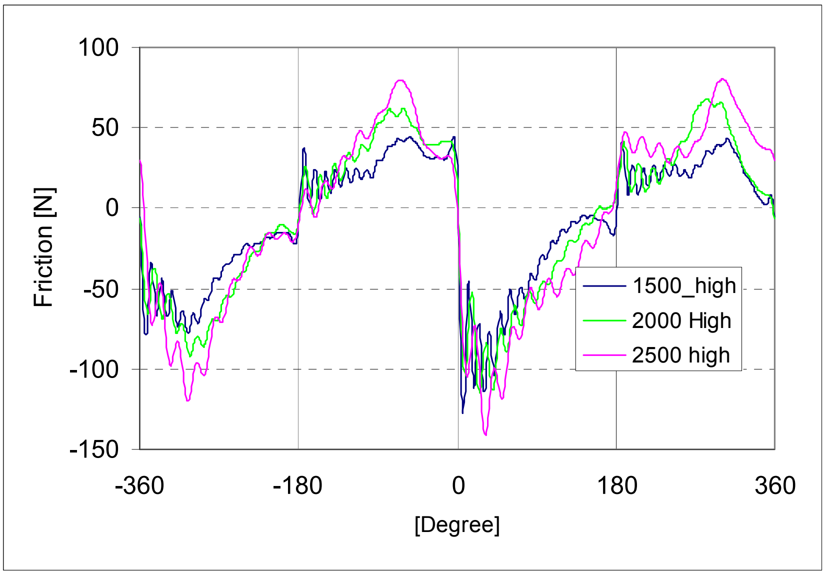

Figure 10 – Measured Friction Forces at different engine speeds. High viscosity lube oil.

3.4 Dynamometer Engine Tests

The two lubricants were also analyzed in a dynamometer engine test. The test engine was a gasoline FIAT 4 cylinder 1.4 L PFI engine. The dynamometer used was a Borghi Saveri DES 2000 controlled by an AVL Puma Open system. Oil temperature was monitored, but not controlled, as to accommodate for different temperature levels between the two lubricants. The measurements were made in steady-state, full load, after all the temperature and pressure values were considered stable. The test

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procedure was to measure three consecutive points of different speeds with one minute reading each point. Figure 11 shows the values of the average of the four consecutive power measurements. First the high viscosity lubricant was evaluated, then the low viscosity lubricant, and then, in order to verify the deviation of data between oil changes, a second measurement was made using the high viscosity lubricant. The power difference between the first and last measurements with the same lubricant was less than 0.25%.

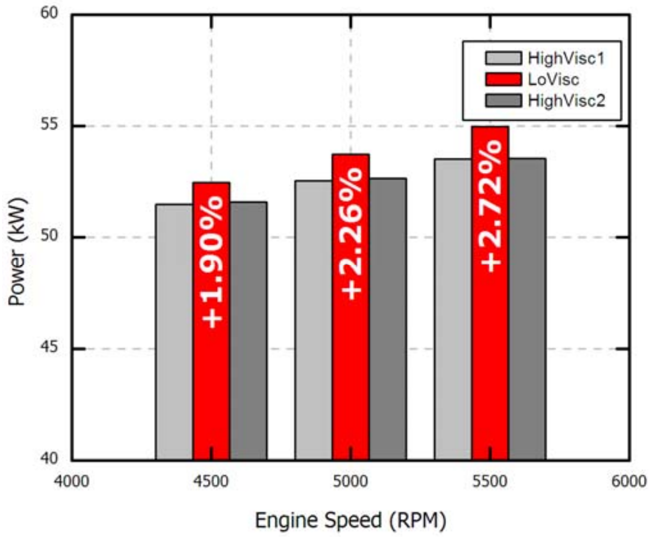

Figure 11 – Power output of both lubricants on the engine dynamometer test.

A power gain of 1.90% was obtained at 4500 rpm between low and high viscosity lubricants, to a maximum of 2.7% at 5500 rpm. The high viscosity lubricant was measured before and after the low viscosity to watch for result deviations, which were lower than 0.25%. The difference on brake mean effective pressure for each speed was 18.6, 20.4 and 22.6 kPa respectively at 4500, 5000 and 5500 rpm. At high speeds, engine friction plays a more important role in the peak power loss, so a reduction in friction leads to a greater improvement in the power output. An indication of this phenomenon was the steep increase in the oil temperatures observed at high speeds.

3.5 Vehicle Acceleration Tests

To better understand the difference between the two lubricants in real life situations, a vehicle acceleration test was also performed. The Brazilian “Nelson Piquet” International race track was used as the location of the measurements. The test procedure is based on the recommended practice SAE J1491:2006 and consists of the time difference between 40 to 80 km/h and 60 to 100 km/h full throttle accelerations. Measurements of 40 to 60 km/h and 60 to 80 km/h were also performed. The selected gears were second and third gear, respectively. To eliminate the wind influence, the test value consists of the average between accelerations in opposite directions of the track, and are only valid if the wind intensity is bellow a threshold value. The speed is measured by an optical sensor, mounted in the vehicle side. For each speed interval, at least 8 measurements were made. Since there were only two lubricants being evaluated, the statistical analysis

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consisted of an unpaired t-test for average differences. The confidence level was 95% (p level < 0.005).

The selected vehicle was a FIAT Palio 4 cylinder 1.0 L PFI gasoline. The small engine displacement means that there is a high area-to-volume ratio, which means the friction-to-power ratio was also high. A reduction in the friction losses, therefore, would have a greater impact on the acceleration time difference. The results presented in figure 14 indicate a statistical difference between all speed intervals. From 60 to 100 km/h, the low viscosity lubricant had a highly significant 6.27% reduction in acceleration time.

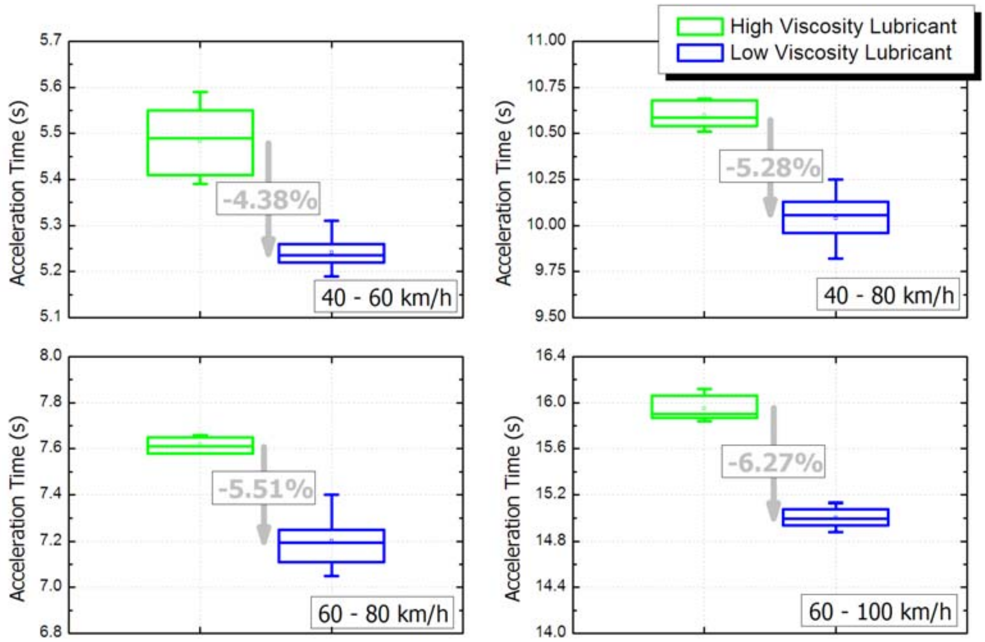

Figure 12 – Acceleration times with the two lubricants on the track test with 1.0L gasoline engine vehicle.

In Figure 13, the main results of all the three tests (Floating liner, Dynamometer performance and vehicle acceleration) are summarized. Although each test has its own characteristic and consequently its proper results, one can observe the same trend, i.e. an increase on the benefit at more severe conditions. The floating liner, although measuring only the piston/ring/liner friction, was able to correlate with the changes of the total engine. It also allowed a detailed analysis of the friction force along the stroke which is useful for development, e.g. high friction near the reversal points have little influence on the engine power, once the speed is close to zero, but can be indication of potential failures due to abnormal wear or scuffing.

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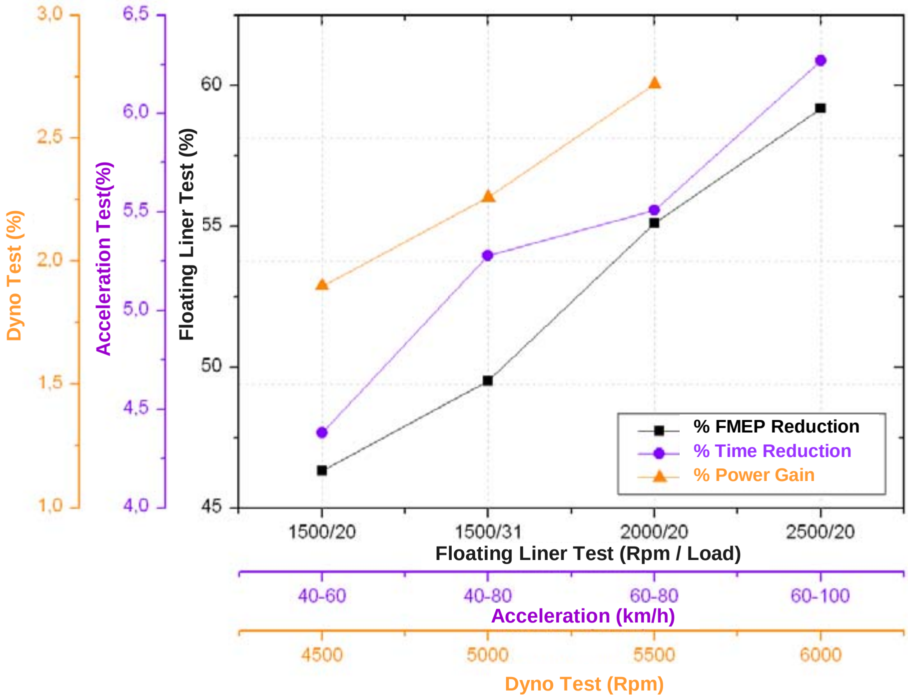

Figure 13 – Summary of main results of floating liner, dynamometer and vehicle acceleration tests.

4 CONCLUSIONS

All the test results confirmed the prospects of engine performance benefits when using the low viscosity racing oil. The significant differences in composition of the lubricants were obviously responsible for such results. Both dynamometer and track tests are closer to real applications and showed significant differences between the two oils. Specifically the acceleration times resulted in an impressive time reduction, which illustrates the importance of searching for friction reduction through lubricant composition. On the other hand, the floating liner test allows a more detailed and resolved analysis, showing e.g. the different friction behaviour at different piston speed along the stroke. The floating liner also showed good adherence to the actual engine and vehicle tests.

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