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**Conference paper**

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# Influence of gasoline engine lubricant on tribological performance, fuel economy and emissions

Peter M Lee and Martin Priest

School of Mechanical Engineering, University of Leeds, Leeds. UK

## ABSTRACT

The requirement for increased performance, improved fuel economy and reduced emissions is constantly sustaining the demand for research into combustion, fuels and lubricants. Due to the nature of the operation of an engine and the current market climate the lubricant not only has to respond to these requirements, but also to changes in engine design, fuelling methods and fuel types, increased power densities and developments in emissions formation and after-treatment. This paper will describe advances made at the authors' institution to elucidate the influence of gasoline engine lubricant on tribological performance, fuel economy and emissions, giving examples of work undertaken and then look to future possible lubricant demands.

## 1. INTRODUCTION

The lubricant influences the tribological performance, fuel economy and the emissions of the internal combustion engine. The interaction between the lubricant, the piston ring pack and its environment plays the most significant role in the control of oil consumption, affecting emissions, fuel economy and fuel economy retention through friction, and overall engine performance, such as wear. It is an artefact of the design of the ring pack and the need for there to be some lubrication between rings and liners that a small amount of oil passes the top ring and enters the combustion chamber. This results in oil consumption as it is lost to the exhaust where it adds to the emissions. This consumed oil also reduces the effectiveness of the gasoline after-treatment catalysts by forming a film of phosphorus over the catalytic surface. For this reason oil manufacturers are being legislated to reduce the quantity of sulphur and phosphorus contained in engine oil (from 0.12% in 1994 through 0.10% in 2001 for GF-3 to 0.08% in 2004 for GF-4). Some of the thinnest oil films in an engine are found between the top ring and the liner, at times operating in boundary lubrication conditions, as shown in Figure 1, hence permitting contact between these components, and it is partly for this reason that the piston assembly accounts for 40-60% of total engine friction.

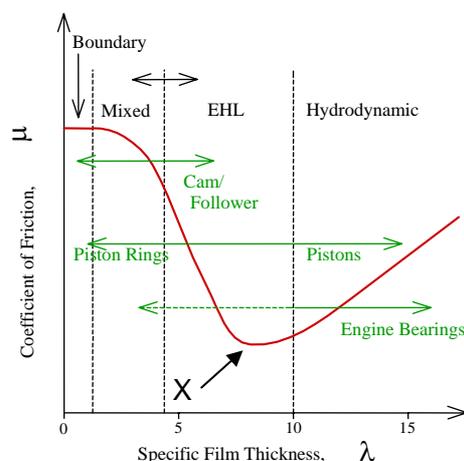


Figure 1 – Stribeck diagram showing engine components and lubricant regimes

With the continued drive towards fuel economy improvements from lubricants the average lubricant viscosity is being reduced in order to attain operation at the lowest coefficient of friction, point X in Figure 1. This reduces friction in the engine due to the reduction of shear of the lubricant where a lubricant film is present. However lower viscosity lubricants are inherently more volatile which may lead to them releasing more hydrocarbons and constituents into the exhaust stream. In the development of the new GF-5 specification this is being considered by additive companies developing low volatility phosphorus additives to prevent this entering the exhaust stream and damaging the catalytic converters. It is not possible to simply remove the phosphorus as it is an efficient tried and tested anti-wear and anti-oxidant additive. The use of reduced viscosities for thinner oil films also increases the chance of component contact and hence wear at piston top dead centre ring / liner interface.

Due to the mature design of the ring pack the vast majority of the oil in the ring pack is however not lost to the combustion chamber but flows back down to the sump and is replenished by 'fresh' oil from the sump. When the oil is in the ring pack it experiences high temperatures, above 200°C, and mixes with the blow-by gas and un-burnt oxygen in this region. It is due to this that the oil degrades, primarily by oxidation, and after sufficient degradation the viscosity increases resulting in a reduction in fuel economy retention. Degraded oil also results in reduced overall engine protection. It is this degradation that provides the impetus for the oil to be replaced and hence it is crucial to elucidate in order to prolong the useful life of the oil. It is the behaviour of the oil, the reaction processes that occur and the flow mechanisms of the oil through the ring pack that need to be understood in order to aid the development of oils that will meet these ever increasing and conflicting demands.

## **2. WORK UNDERTAKEN**

At Leeds much work has been undertaken to understand the tribological behaviour of oils and degraded oils and their effect on engine friction, wear, flow mechanisms in the engine and film formation. A number of specialist techniques have been developed for use with a single cylinder Ricardo Hydra gasoline research engine. This engine is based on a General Motors 2.0 litre, 4 cylinder production engine (c. 1988) of 86mm bore, 86mm stroke and indirect unleaded gasoline injection. A selection of these techniques and results are discussed below.

### **2.1 Lubricant degradation in the Top piston Ring Zone (TRZ) of the piston assembly**

Degradation of the lubricant in the piston ring zone of the internal combustion engine has by far the largest influence on the overall performance of the engine and the useful life of the lubricating oil. As the oil degrades in this region acids are formed and the antioxidants in the oil are consumed. Slowly the viscosity of the oil increases and this results in increased friction and reduced fuel economy. It is from this region that the lubricating oil enters the combustion chamber and is burnt, adding to the emissions. It is therefore imperative that an understanding of the tribology in this region is investigated. To enable this oil has been sampled from the rear of the top piston ring during the fired operation of the engine. This oil is extracted by drilling a hole through the back of the piston ring groove to the inside of the piston and a pipe taken from here through a protective stainless steel sheath to the bottom of the crankshaft. At this point it is constrained only to prevent contact with the crankshaft as it is routed to the exterior of the engine and into collection vials. The pressure difference between the combustion chamber and the atmospheric pressure outside the engine forces the oil, ideally as a mist contained within the gas, along the pipe, Figure 1. This gas/mist stream is directed onto the side of the collection vial where the oil drops out of the gas stream and collects in the vial and the gas extracted. This method was first proposed by Saville et al [1] and used on diesel engines. Much development work has been undertaken resulting in the reliable system that now operates on this petrol engine and a number of studies have been reported [2-5].

The level of degradation of the lubricant was quantitatively determined by using the fourier transform infrared (FT-IR) absorption technique to measure the concentration of carbonyl-containing species present at wave numbers 1690-1750  $\text{cm}^{-1}$  as described by Coates and Setti [6]. These carbonyl groups contain ketones, carboxylic acids, esters and lactones. This work has clearly shown that degradation occurs in the TRZ of the engine and that little degradation occurs in the sump oil, as shown in Figure 2.

Additional work into the chemical mechanisms of the degradation of the oil was undertaken at the Chemistry Department, University of York. Readers interested are directed to papers from that institution [3, 7-9]. Some results for carbonyl concentration are presented in Figures 3 and 6, and described in section 2.3.

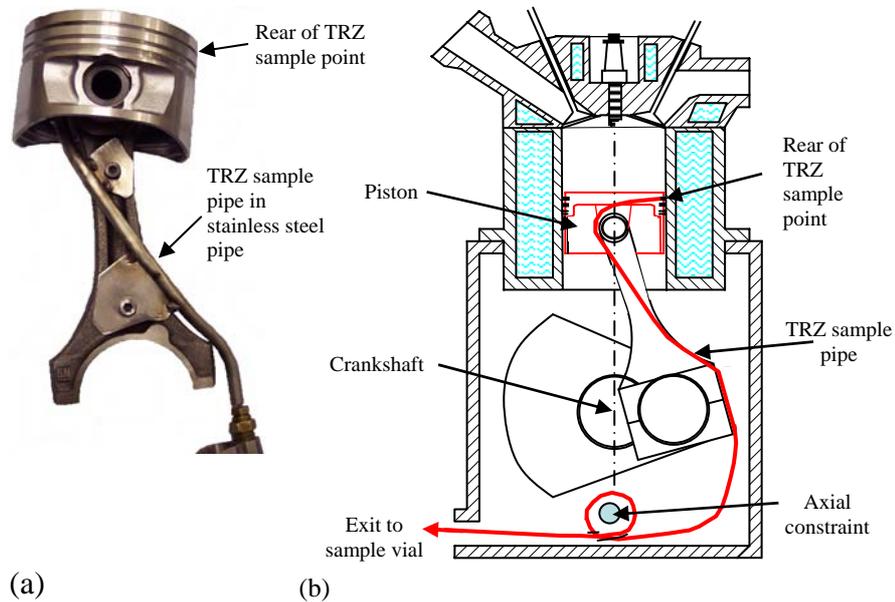


Figure 2 – TRZ piston (a) and schematic of engine (b) with sample pipe, after [10]

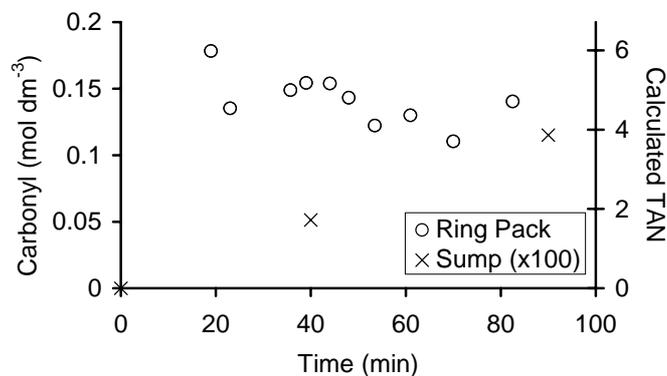


Figure 3 – TRZ oil carbonyl levels and sump carbonyl levels (x100), after [3]

## 2.2 Top Ring Zone (TRZ) oil characterisation

In order to fully understand the tribological effect of the oil in the TRZ of an engine it is necessary to characterise this oil. A comprehensive sampling programme was undertaken to collect 25ml of TRZ oil at 1500 r/min and three different engine loads using the TRZ sampling method described in the previous section. Fresh oil and used sump oil samples were also collected as listed in Table 1. Each 25ml of oil took 40hrs of engine running to complete and were subjected to a number of tribological, chemical and rheological tests that have aimed to characterise the oils. In order to do this work with such small quantities some standard tests had to be re-designed including the Mini Traction Machine (MTM™), (PCS Instruments, London, UK) and the TE77™ reciprocating tribometer, (Phoenix Tribology Limited, Newbury, UK). The reader is referred to Lee et al [4, 5] for a more complete explanation of this work which is beyond the scope of this paper. The most notable result from this research was that the lubricant in the ring pack is significantly different from that in the sump and hence drawing conclusions from sump samples is misleading. Of significance is the level of volatiles, Figure 4, formed by quenching of the combustion process on the liner wall, found in these ring pack samples. These volatiles are representative of soot pre-cursors as well as the heavier mass fuel

elements. It is possible for these volatiles to enter the gas state and be drawn into the exhaust gas, having a detrimental effect upon emissions. With consideration to future problems posed to lubricant formulation, initial work has suggested that bio-fuels are likely to have increased absorption levels into the TRZ oil and, ultimately, the sump. This will change the sump oil formulation from the optimum designed and may effect the frictional characteristics of the oil throughout the engine resulting in reduced fuel economy.

Oil sample name	Oil sample conditions
33% load TRZ*	33% maximum engine load at 1500 r/min
50% load TRZ	50% maximum engine load at 1500 r/min
75% load TRZ	75% maximum engine load at 1500 r/min
First 15 min	First 15 min from cold start at 1500 r/min
Fresh oil	Fresh Shell Helix Super 15W-40
40 h sump oil	Used sump oil after 40 h at 50% maximum engine load 1500 r/min

\*TRZ = top ring zone

Table 1 – table of oil samples, after [4]

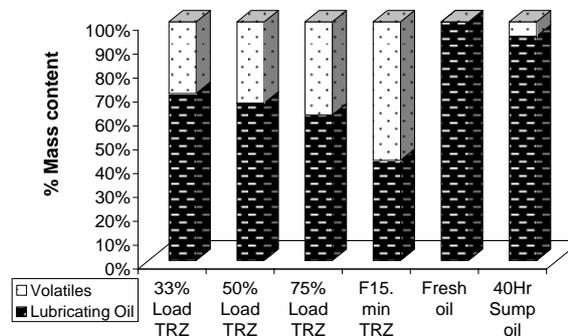


Figure 42 – Volatile content of oil samples measured by GC, after [4]

Figure 5 shows the friction results obtained from this extracted oil when tested in a Plint TE-77 reciprocating tribometer. The test parameters were set to simulate the ring and liner contact conditions in the most severe conditions just after combustion and the material used was that of the engine liner for both the pin and the plate. It is clear from the figure that there are distinct differences between all the samples, but most notably between the sump oil and fresh oil samples and the four top ring zone samples which is the oil that lubricates the ring/liner interface.

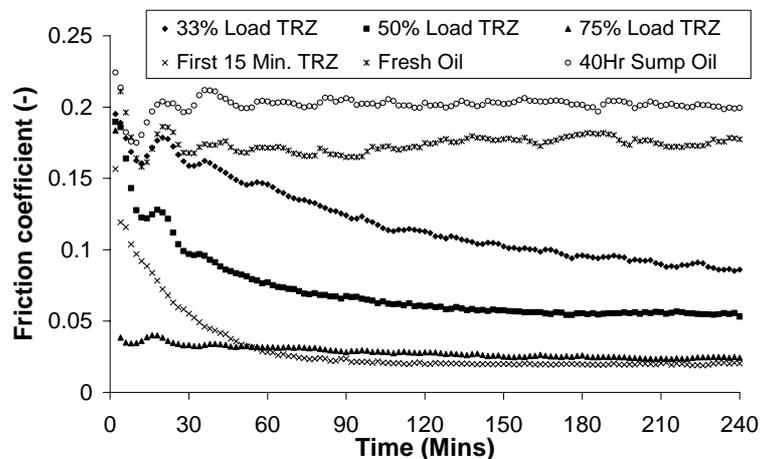


Figure 5 – Plint TE77 reciprocating tribometer flat cast iron pin on cast iron plate, 2.6MPa, 5mm stroke, 25Hz, 100°C, after [4]

### 2.3 Flow rates through and residence time in the ring pack

As oil primarily degrades in the ring pack it is important to know how much oil is present in the ring pack and the period of time for which that quantity of oil is exposed to the degradation process for any given engine condition. This knowledge will give indications for oil drain intervals and, combined with frictional analysis, some projected indication of the fuel economy retention times for oils. In order to understand this the flow of the oil through the ring pack and the residence time of the oil must be found.

By taking both TRZ samples and sump samples, and measuring the carbonyl concentration of both sets of samples it is possible to calculate the flow rates of degraded oil from the ring pack to the sump. This is because if the sump is maintained at 70°C, a temperature at which negligible degradation occurs, the degradation of the sump oil is caused by the degraded oil returning from the ring pack. This results in a steady increase in degradation in the sump over time. Figure 6 shows the carbonyl species in the sump increasing (b) compared to the fairly constant level of degraded sample taken from the ring pack (a) with respect to time. The results presented are for the same speed, 1500 r/min, and three different loads as indicated on the graph. The 50% load experiment was undertaken twice to investigate repeatability. The carbonyl content does not start at zero for the sump oil at the start of the test. This is because, despite flushing the engine, residual carbonyl from previous tests was present in the sump oil.

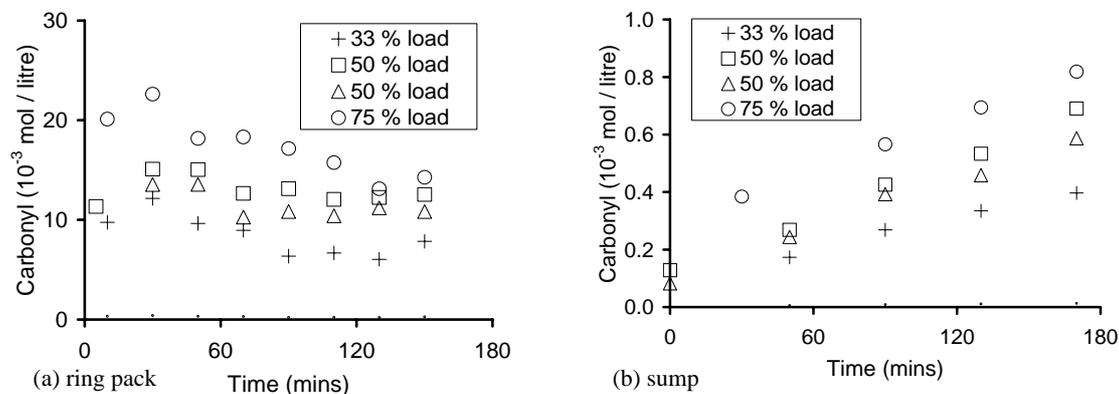


Figure 6 – Degradation levels measured by carbonyl in the ring pack (a) and sump (b) with respect to time at 1500rpm and loads as shown, after [11]

With the addition of a second sump containing a hexadecane marker, it is possible to change the sumps supplying the engine at the same time as samples start to be taken for analysis from the TRZ. This allows the increase in the hexadecane marker present in the TRZ to be measured as the oil in the first sump is replaced in the ring pack by the marked oil in the second sump. It is then possible to calculate the residence time of the oil in the ring pack based upon the time taken to replace the sump 1 oil in the ring pack with sump 2 marked oil. Work has been undertaken to study the effect of load and speed on this phenomena and it has been shown that degradation levels increase with engine load, due to increased TRZ temperatures. In order to undertake this work both sumps were maintained at the same temperature (70°C) and both sump oils were pumped through a switch valve designed to be fixed on the main gallery inlet of the engine. This ensured thermal shock to the engine was prevented, no air was entrained in the oil at switch over and that the changed oil was supplied to the engine as close as was practically possible. Table 2 presents the residence times obtained during this work and Figure 7 shows the flow rates. Again the length of this paper precludes a full explanation and readers are directed to Lee et al [12]

		Speed (rpm)		
		1000	1500	2000
Load (%)	33		6.0	
	50	9.0	5.5	7.5
	75		4.0	

Table 2 – Residence times in the Piston Assembly with respect to engine speed and load, after [12]

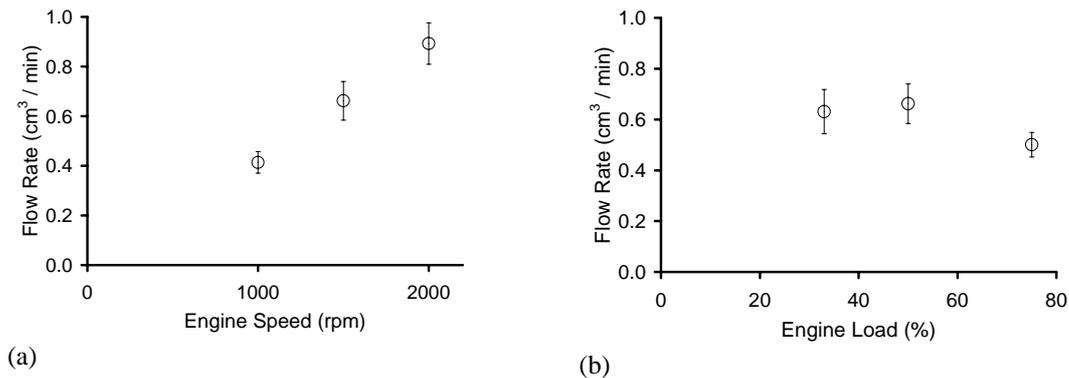


Figure 7 – Flow rates through the piston assembly with respect to (a) engine speed and (b) engine load, after [11]

Initial research [12], Figure 8, suggests that a higher viscosity lubricant will flow through the ring pack more slowly than a lower viscosity lubricant. Therefore as lubricants degrade and hence become more viscous they may remain in the ring pack, exposed to the degradation process, for longer. Although the speed at which the oil in the ring pack degrades will remain the same it will become highly degraded due to being present for longer and so it is likely to result in higher levels of sludge, varnish and then deposit formation before the lubricant is due to flow back to the sump. This will have additional detrimental effects on fuel economy over and above the increased viscosity of the lubricant as well as affecting the action of the rings and hence ultimately affecting emissions as they will no longer seal against the bore correctly.

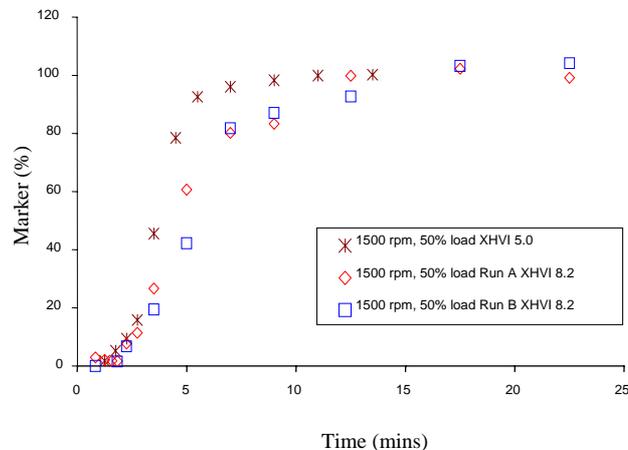


Figure 8 – Effect of lubricant viscosity on residence time, from [12]

## 2.4 Engine Friction Measurement

The vast majority of the frictional losses in an engine are attributable to the three main tribological sub-systems of an engine; the piston assembly, engine crankshaft bearings and the valve train. Experimental methods have been developed for the Hydra engine at Leeds that allow the losses in all three tribological components to be measured while the engine is fired. This involves the use of specially designed torque transducers on the drive pulleys of the valve train, the indicated mean effective pressure technique to obtain the piston assembly friction and the calculation of crankshaft bearing losses by subtraction. This method has confirmed that between 40 and 60% of the total engine friction is due to the piston assembly and has shown the effect of speed and lubricant viscosity on power-loss in the piston assembly, Figure 9. This work has been reported by Mufti et al [13, 14].

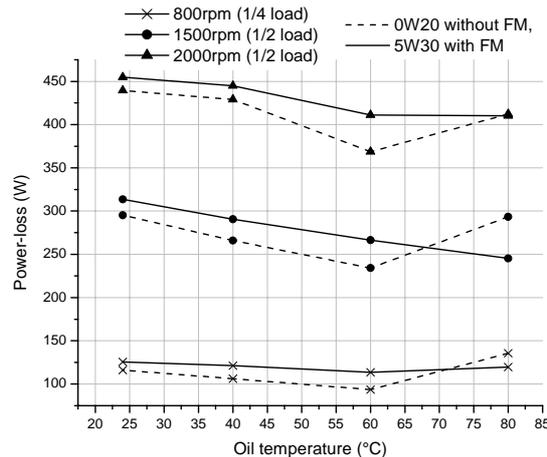


Figure 9 – Comparison of piston assembly friction power loss for SAE 0W20 without FM (friction modifier) and SAE 5W30 with FM lubricants, after [14]

It can be seen from Figure 9 that the lubricant viscosity and additive package directly effect the power loss experienced in the piston assembly. Lower viscosity lubricants at lower temperatures result in lower power losses. However these lubricants have higher power losses at higher temperatures as they move from the lubricated to boundary or mixed lubrication regime earlier than higher viscosity lubricants. This has a negative impact on fuel economy due to the resulting higher friction.

This method has subsequently been used to validate the bench top work undertaken as described in section 2.5 and would be an invaluable tool in the investigation of the effect of lubricant degradation on the major tribological components of the engine.

## 2.5 Fuel administered friction modifiers

Although the use of lower viscosity lubricants to obtain improved fuel economy works for most of the engine it is not successful for all parts of the piston assembly. Where there are lubricant films, for example between the piston skirt and liner and mid stroke between the rings and the liner it does reduce frictional losses due to the lubricant shearing more efficiently. However when the piston is at top dead centre and bottom dead centre of the stroke, where boundary lubrication occurs, the thinner films result in less protection and higher friction is experienced due to contact between the rings and the liner. This is also undesirable for liner and ring wear. One possible method of resolving this is to use the effect of fuel dilution in the top ring zone to carry surface friction modifiers to the ring pack via the fuel as it is injected into the engine. Initial investigation using a bench top tribometer and model friction modifiers has been undertaken at the institution of the authors. A TE77™ was set up with a ring on liner section and two oil supplies. One oil contained a low viscosity oil to replicate the viscosity in an engine due to fuel dilution, the other sump contained the same oil, but with the chosen friction modifier at 2% w/w. The TE77 was run for an hour before the sump was changed to the friction modifier containing oil for an hour and then changed back to the original sump supply. Results showed that an immediate reduction in friction occurred and that this tailed off close to the original value when the oil was changed back to the original supply. This work was undertaken with three different additives as shown in Figure 10.

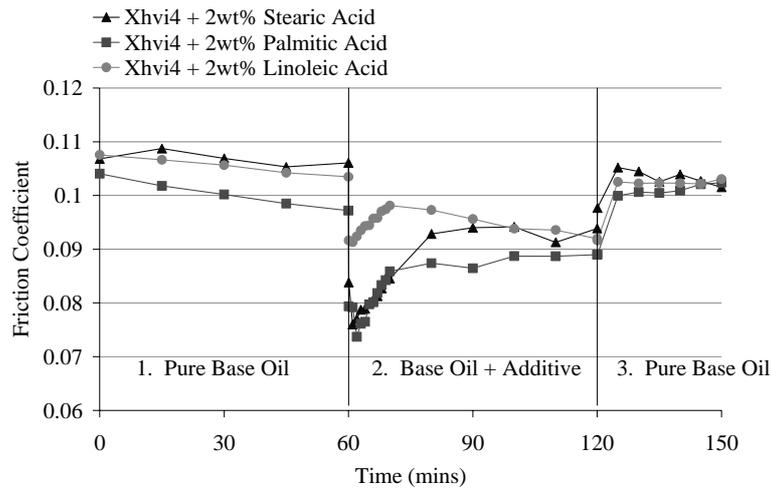


Figure 10 – TE77 piston assembly friction coefficients for non additivised oil and three different additivised oils.

Following on from this screener test chosen additives were run in the Hydra Engine under fired conditions with the additives placed in the fuel as oppose to the oil. When the fuel supply was changed a drop in friction was observed. This change was less than on the TE77 as the TE77 test operated in boundary condition for the majority of the time, where as the ring pack in the engine operated in boundary only at and near TDC and BDC. This work is explained in more detail in Smith et al. [15].

### 3. FUTURE OUTLOOK

There is no indication that the ever increasing and conflicting demands placed upon gasoline lubricants will abate in the foreseeable future. In the medium term OEMs are pushing towards fill for life oils and are increasing power densities using modern technologies such as gasoline direct-injection turbo charging, second stage turbo charging, improved air handling and EGR technologies, advanced combustion chamber design and variable valve timing combined with variable valve lift volume ('valvematic'). The new ILSAC GF-5 oil specification is scheduled for mid 2009 (with factory fill from 2010). Although specifications are yet to be finalised OEMs have identified major areas where they would like to see improvements. These include fuel economy and fuel economy retention throughout the oil drain interval, improved emission-control systems protection and increased sludge protection, deposit and oxidation control. ILSAC has identified low-temperature viscosity, high- and low-temperature corrosion, turbocharger protection and filter clogging protection as additional requirements. Aeration control is a renewed concern due to modern engines using oil as a hydraulic fluid in cam phaser devices, variable valve actuators, timing chain tensioners and hydraulic lash adjusters that allow for variable valve timing. Over the need to meet these increased requirements both OEMs and engine oil manufacturers have agreed that GF-5 motor oil should be backward compatible to prevent damage due to misapplication. As such GF-5 motor oils will be the most technologically advanced motor oil produced to date. Beyond this ILSAC GF-6 is planned. So what may be expected of lubricants beyond 2009? The European and US drive towards Bio-fuels will have an effect on lubricant /fuel compatibility with new chemical degradation processes occurring in the ring pack. Additive packages will most likely evolve still further to meet the three basic demands of improved fuel economy, better emission system compatibility and greater lubricant stability. Ever improving engine technology, downsizing and the various modes of hybridisation and new materials will result in further, as yet unknown, demands on the engine lubricant. Additionally a cradle-to-grave approach is likely, bringing consideration of biodegradability and recyclability. Currently engine lubricants are essentially additive packs mixed into base oil, which contains biological components. It is however highly likely that in order to meet the high anti-oxidant GF-6 specification the oil will have to be fully synthetic.

## 4 CONCLUSION

The engine lubricant has a direct effect upon overall engine performance, in particular initial fuel economy, fuel economy retention, exhaust emissions and emission aftertreatment devices. There is also interaction with between the lubricant and the fuel in the top ring zone region which has implications on fuel economy and lubricant degradation rates. Before the lubricant can play its full part in responding to the new technologies, maintaining fuel economy throughout extended oil drain intervals and further reducing emissions continued research is required to elucidate the fuel/lubricant interactions and the effect of lubricant degradation. With the continued increasing demand on the engine lubricant it is essential that it be considered as an integrated component in the same way as fuels, exhaust system controls and combustion systems are considered in order to achieve optimal system performance. Yet, to date, there is no evidence of this. Indeed, lubricant design is expected to respond to the often conflicting requirements placed on it by legislators, formulation restrictions, modern technologies and OEMs.

## ACKNOWLEDGEMENTS

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