

Enhanced Anti-Wear Performance Induced by Innovative Base Oil in Low Viscosity Engine Oil

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ABSTRACT

The oil and additive industry is challenged to meet future automotive legislations aimed at reducing worldwide CO₂ emissions levels. The most efficient solution used to date has been to decrease oil viscosity leading to the introduction of new SAE grades. However this solution may soon reach its limit due to potential issues related to wear with lower engine oil viscosities. In this paper, an innovative solution is proposed that combines the use of a new tailor-made polyalkylene glycol (PAG) with specific anti-wear additives. Valvetrain wear measurements using radionuclide technique demonstrates the robustness of this solution. The wear performance was also confirmed in Sequence IVA test. An extensive tribological evaluation (film formation, wear and tribofilm surface analysis) of the interactions between the base oil and the anti-wear additives lead us to propose an underlying mechanism that can explain this performance benefit.

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INTRODUCTION

CO₂ reduction and energy savings have been important drivers in the transportation industry over the decades and is strongly supported by the international community in order to reduce the environmental impact and to help drivers and fleet owners to reduce transportation costs. To meet these requirements engine manufacturers have been implementing new solutions into the market such as engine downsizing and the use of lower viscosity engine oils. On the one hand, engine downsizing has the benefit of improving the overall engine efficiency by increasing the engine operation under medium and high loads. On the other hand, reducing engine oil viscosity reduces engine friction losses by decreasing the oil film thickness in lubricated contacts. Predictions show a significant market share increase of SAE 5W-20 and SAE 0W-20 oil viscosities [1]. Furthermore the SAE J300 standard has adopted the new low viscosity grade SAE 16 to reflect this request from the community [2].

Although several authors have demonstrated fuel economy improvement when reducing engine oil viscosity [3], others have reported an increase in wear rate when using low viscosity engine oils [4, 5]. The decrease in oil film thickness caused by lower oil viscosity is one of the obvious causes for increased wear but the phenomenon is also worsened by higher contact pressures due to engine downsizing. Consequently oil formulations have to adapt to

these new constraints to continue improving both fuel economy and wear protection in order to reduce the total ownership cost of light and heavy duty vehicles.

Recent work [6] has demonstrated the benefit for fuel economy improvement when using group V base oil in modern engine oil formulation, especially polyalkylene glycols (PAGs). Cuthbert *et al.* [7] draw similar conclusions regarding friction benefits but also report some wear issues with PAGs compared to typical engine formulations potentially caused by the fast depletion of the anti-wear additives in PAGs containing lubricants. This observation suggests a compatibility issue between PAGs and the additive used in the study probably caused by specific PAGs characteristics such as its higher polarity compared to conventional group I to IV base stocks. Similarly Waraa *et al.* [8] show a wide range of wear rates using group V base oil in freight trucks lubrication applications emphasizing the connection between group V base oil chemical structure and anti-wear performance.

This paper aims to demonstrate that innovative basestocks, specifically tailor-made PAGs, can help to improve wear protection when associated with tailored additive system, thereby facilitating the use of lower engine oil viscosities to improve fuel economy. It will be shown in this study that interactions of PAGs with the whole formulation are responsible for this performance improvement; the basestock alone does not carry relevant anti-wear performance for engine lubrication application.



LUBRICANT FORMULATION

'Traditional' PAGs were developed in the 1940's [9] and are currently used in different industrial applications due to key performance attributes such as high viscosity index (VI) and excellent deposit protection. A chemical structure of this traditional PAG's type is presented in Figure 1. One of the traditional PAG's disadvantages remains that they are not oil miscible. This issue was overcome by The Dow Chemical Company by incorporating butylene oxide into the manufacturing process [10] thus producing Oil Soluble Polyglycols (OSP). This opened up new possibilities for lubricant formulators. Specifically, adapted formulations for this OSP basestock have demonstrated its clear ability to provide fuel economy and engine cleanliness in a wide range of gasoline and diesel engines [6].

More recently, a second generation of OSP's, OSP High Viscosity Index (OSP HVI), has been developed with an even higher VI and enhanced low temperature properties [11, 12], offering another level of high performance lubricant. It was notably demonstrated that this basestock could achieve additional fuel economy in dedicated formulations. Fleet test result also demonstrates this solution is available to be implemented in commercial product [13]. The chemical structures of these three different types of PAGs are described in Figure 1. R, R' and R'' represents alkyl groups.

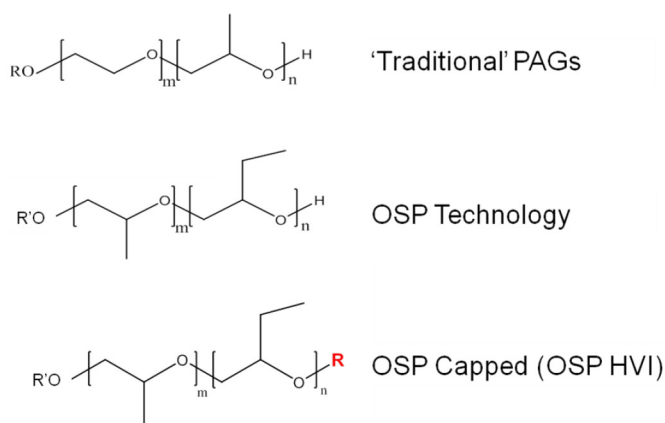


Figure 1. Chemical structures of the different generations of PAGs. Traditional PAGs use ethylene oxide and propylene oxide as raw materials, OSPs use propylene oxide and butylene oxide as raw materials and OSP HVI have the same raw materials as OSP but these molecules are also alkyl-capped. R, R' and R'' represent alkyl group.

Key characteristics of these basestocks illustrating the differences between OSP18 and OSP18 HVI are shown in Table 1. As Noack volatility of PAGs is dependent on the additive environment, a Noack range is given rather than a specific number. One can easily see that OSP18 HVI has remarkable viscometrics designed for bringing performance in engine oils.

In order to illustrate the interactions between base oils and additives, a series of binary mixtures composed of one base oil and one anti-wear additive is detailed in Table 2. The selected base oils are PolyAlphaOlefins (PAO), OSP18 and OSP18 HVI, all have a kinematic viscosity of 4cSt measured at 100°C. The anti-wear additives AW-1, AW-2, AW-3, AW-4 and AW-5 are representative from current engine oil formulations. Each binary mixture is designed

to contain a phosphorus content of 500ppm. The objective of these formulations is to evaluate the impact of the base oil on anti-wear performance in different additive technologies.

Table 1. Viscometrics and volatility of OSP18 and OSP18 HVI. Typical PAO 4 figures are shown for comparison.

Analysis	Methods	Units	PAO 4	OSP18	OSP18 HVI
Kinematic Viscosity at 100°C	ASTM D445	mm ² /s	4,0	3,9	3,9
Viscosity Index	ASTM D2270	-	120	125	185
Cold cranking simulator viscosity at -35°C	ASTM D5293	mPa.s	1000	4000	1100
Noack Volatility	CEC-L-40-93	%w	13	10-12	9-11

Table 2. Basic formulations investigated in tribological tests.

	AW-1	AW-2	AW-3	AW-4	AW-5
PAO 4	X	X	X	X	X
OSP18	X	X	X	X	X
OSP18 HVI				X	X

This study aims at evaluating the impact of PAG as a base oil component in fully formulated environment. Recent work helped us to optimize an additive package containing specific types of dispersants, detergents, anti-wear, anti-oxidants and friction modifiers. The additives involved in the interactions responsible for the enhanced wear protection are not detailed in the paper. The performance of optimized formulations is presented here. Details of the formulations evaluated in this paper are presented in the Appendix. Their additive system is similar, only the base oils ratio is modified in order to meet the SAE 5W-20 and SAE 0W-20 grades.

METHODOLOGY

This study was designed to demonstrate that interactions between additives and OSP18 HVI improve the protection against wear. This will be demonstrated firstly in tribological tests and then confirmed with in-house motored engine tests (radionuclide technique) and also industry standard engine test (sequence IVA).

A discussion follows to identify the underlying action mechanism, based on the analyses of the tribofilm and its growth. Details of different test techniques are summarized below.

Tribological Tests

Pin & Vee Blocks

For the initial phase of the study a Pin & Vee blocks bench test was used to measure the anti-wear performance of the different candidate oils. Internal studies have demonstrated relevant correlations between this test and full engine test. As illustrated in Figure 2, a steel pin (x mm in diameter) rotates between 2 steel vee blocks under an

adjustable load. After a 5min running-in period, the test runs for 180min under 1335N load and a pin speed of 290 rpm. At the end of the test the wear scar on the pin is measured by the loss in diameter. The reproducibility concerning the wear scar is around 20 μm within the same measurement campaign.

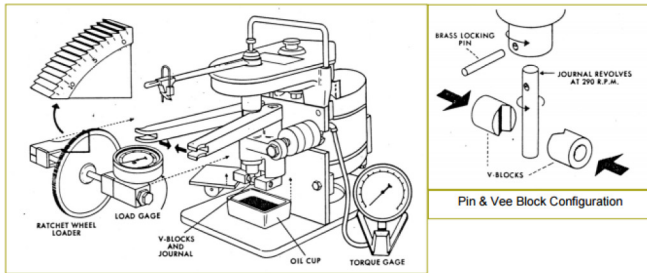


Figure 2. Pin & Vee block wear test illustration

It is important to note that wear measurement is useful to screen the anti-wear performance, however, this test do not provide any insight into the tribo-chemical reactions taking place in the contact, which is the mechanism responsible of protection against wear.

For this purpose, others tools are needed. In this paper, Mini Traction Machine (MTM2 - PCS Instruments) was used.

MTM2 - Ball-on-Disk

In thin-film rubbing contacts, tribofilm formation is generally assumed to begin at sliding asperity contacts. To achieve these conditions the ball-on-disk configuration of a MTM2 apparatus is relevant, as shown schematically in Figure 3. A ball (steel 100Cr6, roughness (Ra) <10nm) is loaded and rotated against the flat surface of a rotating disc (steel 100Cr6, roughness (Ra) <10nm) immersed in lubricant at a controlled temperature.

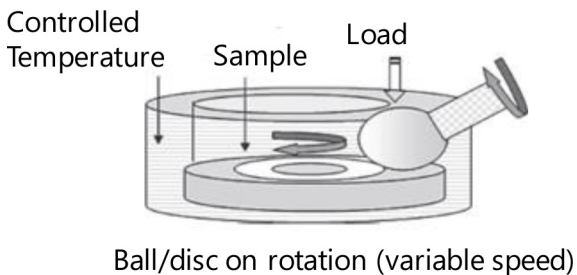


Figure 3. Schematic of MTM2 apparatus.

The ball and the disc are driven by independent motors in order to accurately select a ratio between sliding and rolling (SRR) and to precisely control the load. This system could then easily generate tribofilm. It is also equipped with a spacer layer imaging (SLIM) system that uses optical interferometry to visualize and measure the tribofilm thickness. The procedure alternates between traction coefficient measurement and tribofilm thickness measurement. Two different test protocols are used as shown in Table 3 to investigate the effects of load and slide to roll ratio (SRR). These two protocols are representing different conditions seen by a real engine.

Table 3. MTM2 operating conditions. Two protocols are used, Low load and High Load, in order to investigate the load and SRR impact on the tribofilm generation.

	Low Load protocol	High Load protocol
Temperature	100°C	100°C
SRR	50%	150%
Load	30N	50N
Duration	120 min at 0.1m/s	180 min at 0.1m/s
Stribeck curve	Stribeck 0,010 to 3 m/s 6 in 7 500 s	Stribeck 0,010 to 2 m One every 10 000 s

Sequence IVA Wear Test

To assess the anti-wear performance of the PAG based formulation compared to group III formulation, Sequence IVA engine tests were conducted according to the standard ASTM D6891. The Sequence IVA test, part of the international oil specification ILSAC GF-5, is run on a Nissan 2.4L engine and evaluate the ability of the candidate oil to reduce camshaft lobe wear. The test method alternates between two distinct stages. The first stage corresponds to idling condition, with engine speed set at 800rpm, oil cylinder head temperature at 50°C, engine torque at 25N.m and lasts 50min. The second stage is run at 1500rpm, oil cylinder head temperature at 60°C, engine torque at 25N.m. These two stages are repeated 100 times to reach 100h of testing [14]. At the end of the test each camshaft lobe wear is measured and the average value is reported in the final report.

Motored Valvetrain Wear Test

The wear protection capability of oils G15/0553 and G15/0554, without and with PAG respectively, was evaluated with a motored valvetrain rig using a radionuclide technique where the entire top surface of a tappet and the entire width of the cam nose and 5 mm on either side of the nose were activated. The tappet surface was activated with Co56 while the cam lobe surface was activated with Co57 by bombarding the surfaces with a proton beam. The initial radioactivity was 17-22 MBq/mg. The depth of the activated surface was about 15 μm . The wear evaluations were conducted on a motored valvetrain rig where a single cam lobe rotated against a single tappet. One cam lobe was cut from a production V6 engine intake camshaft, bored and press fitted on to a shaft, which was driven by a 2 hp motor. A production tappet was mounted on a production spring in the same manner as in an engine. The tappet reciprocated inside an aluminum sleeve made of the engine material and maintained the same clearance between the tappet and the sleeve as in the engine. The tappet was in contact with a steel valve having an equivalent mass of an intake valve. The contact area of the tappet and the cam lobe was lubricated by a jet of engine oil at 85 psi and 95°C. The camshaft was rotated at 500, 1000, and 1500 RPM for a total of 100 hours. To ensure good repeatability, the lash, tappet roughness, and camlobe roughness was closely controlled in each test. Figure 4 demonstrates the test-to-test repeatability with a GF-5, SAE 5W-20 oil. The additive package used in the GF-5, 5W-20 oil is not the same as the other fully formulated oils used in this study.