

Impact of Viscosity Modifiers on Gear Oil Efficiency and Durability: Part II

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ABSTRACT

This paper outlines the second part in a series on the effect of polymeric additives commonly known as viscosity modifiers (VM) or viscosity index improvers (VII) on gear oil efficiency and durability. The main role of the VM is to improve cold temperature lubrication and reduce the rate of viscosity reduction as the gear oil warms to operating temperature. However, in addition to improved operating efficiency across a broad temperature range compared to monograde fluids the VM can impart a number of other significant rheological improvements to the fluid [1]. This paper expands on the first paper in the series [2], covering further aspects in fluid efficiency, the effect of VM chemistry on these and their relationship to differences in hypoid and spur gear rig efficiency testing.

Numerous VM chemistry types are available and the VM chemistry and shear stability is key to fluid efficiency and durability. The trend of increased drivetrain power density and reduced sump volume places even more burden on the fluid film protection with increasing load in the contact and increased number of duty cycles per volume of fluid further increasing shear loss severity. Simply dropping viscosity in gear lubricants does not necessarily yield efficiency benefits and reducing viscosity too far can compromise both efficiency and durability through reduced fluid film protection although it is typically hard to determine these viscosity limits empirically. However, a number of rheological properties can be readily measured and related to key lubrication regimes in which VM systems can be differentiated on operational efficiency whilst maintaining fluid film protection. This paper builds on the differentiation of VM technologies with particular focus on the impact of speed and load on energy losses associated with the fluids and elaborates further on the contribution of viscosity to efficiency.

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Table 1. Viscosity modifier chemistries used in comparison

	KV100 ^a	KV40 ^a	VI	BV40 ^b	POUR POINT ^c	HTHS ^d
	(cSt)	(cSt)		(cP)	(°C)	(cP)
New VM	17.58	102.5	189	41500	-57	6.02
DPMA	17.21	106.7	177	49000	-51	5.85
PAO100	16.92	112.8	164	57000	-48	5.36
PIB	17.63	127.2	153	88000	-54	5.56
Brightstock	17.52	174.7	103	TVTM	-27	5.05

a – Kinematic viscosity at 40°C (KV40) and 100°C (KV100), ASTM D2270-10

b – Brookfield viscosity at -40°C (BV40), ASTM D2983

c – Pour point (°C), ASTM D5950

d – High temperature, high shear at 150°C (HTHS), CEC L-36-90

INTRODUCTION

The first instalment of this series on the impact of viscosity modifiers (VM), on automotive gear oil (AGO) fluid efficiency described the rheological properties of a series of appropriately shear stable VM chemistries for automotive gear oil applications blended at equal kinematic viscosity at 100°C. The fluids were blended to SAE 75W90 and compared to a Newtonian SAE 80W90 brightstock fluid [2]. The comparison of the rate of reduction of kinematic viscosity 40°C (KV 40) and 100°C (KV 100) (defined as viscosity index (VI)) was significantly different by VM chemistry type even at approximately equivalent shear stability, with high VI fluids enabling lower viscosity at ambient temperature with higher viscosity at extreme high temperature operation. Moreover, elastohydrodynamic (EHD) film thickness and EHD traction could be substantially affected across a wide temperature range independent of VI and efficiency benefits were observed through changing between different highly shear stable VMs at equivalent kinematic viscosity at 100°C. Summary of fluids for evaluation:

- *Viscosity modifier*: selected from a range of highly shear stable automotive gear oil VM technologies ([Appendix 1](#))
- *Kinematic viscosity (100°C)*: 17.5 cSt (SAE 90 grade viscosity)
- *Additive performance package (10 wt% treat)*: A Total Driveline Lubricant (TDL) for transmission and axle applications
- *Base stock*: PAO-4 for VM containing fluids, Group II for brightstock

The fluid properties are summarised in [Table 1](#) and are listed by VM chemistry type (see also [Appendix 1](#)).

Substantial differences in viscosity at lower temperatures can be observed with more effective VM systems, such as DPMA and the New VM (for instance the kinematic viscosity of the SAE 80W90 brightstock fluid is 160% higher than the new VM at 20°C). The VM types are ranked by VI and low temperature fluidity, in addition their response to high temperature, high shear rate conditions are also documented. The high VI and low shear loss of the New VM result in a high HTHS, a good indicator of fluid film protection under the high shear rates in gear contacts.

Whilst viscosity (and so VI) influence efficiency this study continues the evaluation of these fluids to provide more in depth evaluation of the conditions under which efficiency differences can be obtained beyond simply reducing viscosity by examination of spur gear and hypoid efficiency comparisons.

EXPERIMENTAL

EHD Traction measurements: The fluids were evaluated using a mini traction machine (MTM) commercially available from PCS instruments UK. A concentrated contact forms between a steel ball and polished steel disc allowing one to measure the traction of a given fluid. A series of discrete measurements were made at a speed of 2.5 m/s and a Hertz pressure of 1 GPa between 40°C to 120°C in 20°C temperature increments and slide to roll ratio (SRR) of 0-50%. For the purposes of modeling outlined below traction coefficient at 10% SRR was interpolated from the values determined at temperatures defined above to give an estimated traction coefficient at test fluid temperature at a given condition.

EHD film thickness measurements: EHD film thickness measurements were carried out using a commercially available ultra-thin EHD film thickness tester manufactured



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by PCS Instruments. An optical interferometry technique is used to measure fluid film thickness under rolling conditions in highly concentrated contact formed between a steel ball and a coated sapphire disc. The films were measured at a Hertz pressure of 0.5 GPa at 20°C temperature increments between 40°C and 120°C. For the purposes of modeling outlined below EHD beta and gamma parameters were determined by interpolation from the values determined at temperatures defined above to give an estimated value at test fluid temperature at a given condition.

Spur gear efficiency: The FZG spur gear efficiency test rig uses a four-square gear test principal where the load (torque) is mechanically preloaded. The input torque required to drive the gears at a given preload torque and speed, once compensated for other losses including bearing losses, is essentially the loss due to the fluid efficiency. The severity of the rig and gear set is accounted for by comparison to baseline reference test results. The lower the required input torque, the lower the energy loss in the system and the more efficient the fluid is under those conditions.

FZG spur gear (FVA.345) test condition summary:

- Speed [RPM]: 87, 348, 1444, 3479
- Pitch line velocity (m/s): 0.5, 2, 8.3, 20
- Load torque [Nm]: 0, 94.1 (at 90 °C only, all speeds), 183.4, 301.5 (at 90 °C only, all speeds)
- Temperature [°C]: 40, 60, 90, 120
- Each test was run 4 times and the average coefficient reported
- Reference fluid: 80W gear lubricant

Hypoid gear efficiency: A fired engine full scale rig simulation of the North European Drive Cycle (NEDC) was developed on a broken in European OEM passenger car rear differential. The rear differential was installed on a dedicated passenger car efficiency test stand equipped with high accuracy bearing-less torque meters. The rig was fitted with Eddy current dynamometers. The drive cycle was programmed according to theory loading and coast down profile appropriate for the parent vehicle as though it were on chassis dynamometer testing for a conventional NEDC. The input rotating speed was programmed to match theory rotating speed according to the parent vehicle wheel speed. A total of 5 repeats of each fluid were run.

Results and Discussion

The different rheological behavior between the VM containing fluids can result in clear differences in efficiency as presented in the summary of FVA.345 spur gear efficiency outputs in [Figure 1](#) below. Each no load and EHD loss coefficient is a relative measure of a series of conditions compared to a baseline test to give the loss coefficient as a relative value where lower relative losses are attributable to more efficient fluids. This methodology accounts for rig

severity. The data clearly show that VM blends operate more efficiently than a Newtonian brightstock fluid (a lower coefficient indicates a more efficient fluid). Further, the New VM distinguishes itself from the other VMs. Even at 90 °C (nearing isoviscous across the blends, all were formulated to target KV100 of 17.5 cSt) there is a clear offset in efficiency attributable to other fluid properties.

However, the test procedure involves 41 individual stages of different speeds, loads and temperatures using the conditions cited above in the experimental section but only a summary of the overall response of the five test blends is shown in [Figure 1](#). The magnitude of the contribution of traction and film thickness can be inferred but not directly correlated when viewing the data in this manner. Furthermore the output does not describe actual torque values or the impact of viscosity. A wealth of data exists, therefore, that was outside the scope of the first paper [2] on this subject and the individual load, speed and temperature phases will be examined in more detail.

Having established significant differences in EHD traction, EHD film thickness and VI between the VMs [2], the principal aim of the study presented herein is to identify more clearly the regions in which viscosity (and therefore VI) will dominate measured efficiency and at what point other factors contribute more to efficiency. Further to this a correlation of this study to fluid efficiency in full scale rig testing in a hypoid gear without fluid temperature control will also be determined.

Spur Gear Efficiency

In comparing the relative efficiency (input torque) to viscosity at individual load and speed conditions there is an expectation that if reducing viscosity were the only positive impact on efficiency we would expect to see a series of overlapping responses from different fluids on an ever reducing continuum as viscosity is lowered, with the span of the individual response on this continuum dictated by the thickening properties of the VM (VI) within the temperature range of operation (i.e. the range of viscosity covered by the fluid at the four different test temperatures). This is over simplified and a lower limit in viscosity will likely be reached beyond which point fluid film support is not maintained and a loss in efficiency will occur due to frictional losses as EHD, mixed and boundary conditions begin to dominate. In addition to viscosity, other fluid rheological properties can create a step change in the response and it is these differences that make the VM systems more or less efficient despite appearing viscometrically equivalent.

In the following section the input torque of low and high speed phases are compared to the dynamic viscosity of the fluids at test temperature at two different loads. The discussion has been split into three different speeds. The dynamic viscosity of the fluids has been measured at the four test temperatures of 40, 60, 90 and 120°C. Further data exploration is covered in the following section to correlate

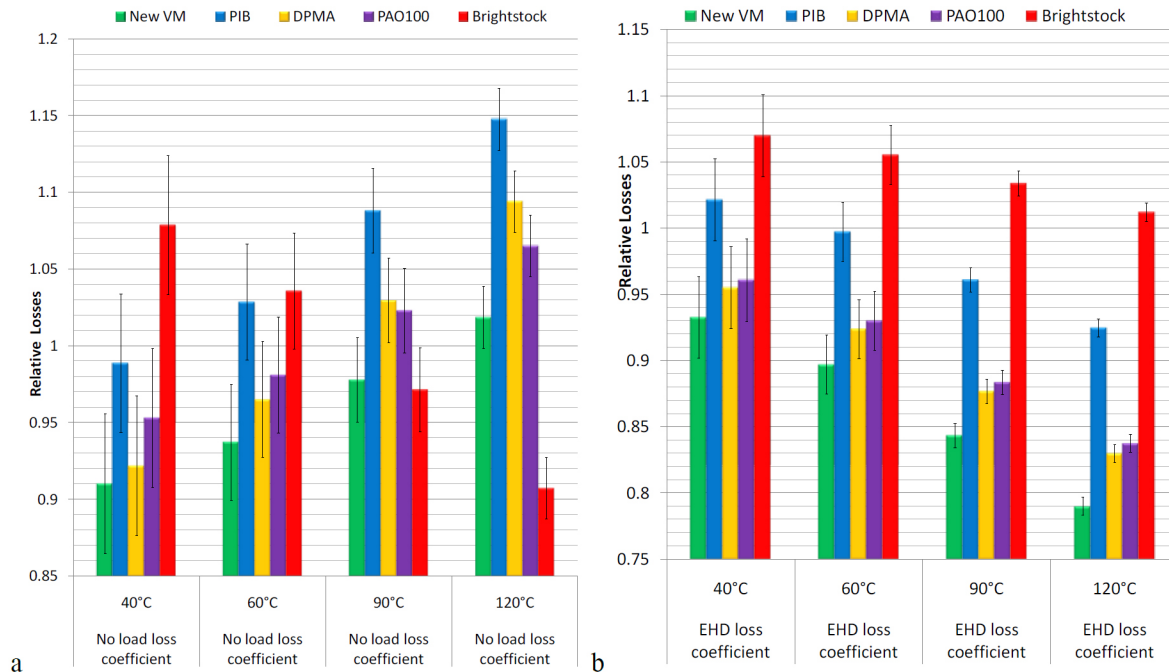


Figure 1. Effect of viscosity modifier on spur gear efficiency coefficient from FVA.345, a. at no load and b. under EHD conditions

additional factors driving efficiency under a given set of test conditions.

Low Speed Efficiency Measurements

Figure 2 shows the input torque responses by fluid type at both no load and moderate load (183.4 Nm, load stage 7). Both plots show a positive slope of viscosity versus efficiency at high viscosity and a negative slope at low viscosity, i.e. efficiency improves as viscosity is reduced from >100 mPa.s but generally the fluids then become less efficient as viscosity approaches 10 mPa.s. Figure 2 indicates:

- At low speed improved fluid efficiency is not linked to exclusively to reducing viscosity
- The higher the load, the lower the impact of reducing viscosity
- The properties of the VM chemistry types can play a role a more significant role than viscosity under moderate load

Additionally, the required torque input under no load (Figure 2a) is relatively low compared to higher load (Figure 2b) and furthermore the differences between the VM types are negligible in this instance. However, the deviation in the input torque-viscosity relationship at low viscosity is particularly interesting indicating that even churning losses do not always improve as viscosity is reduced [4].

At moderate load the difference due to VM type is pronounced resulting in typically lower torque input to meet the higher load, low speed conditions compared to the brightstock blend (Figure 2b). The trend clearly shows at high and low viscosity extremes that efficiency is hampered. Moreover the data vary by VM type quite substantially at

moderate load, i.e. factors other than viscosity are creating an offset in efficiency by VM type as some are clearly more efficient than others. The viscosity at input torque minima is typically 55-70 mPa.s and is much higher than at the higher speeds presented below, with higher viscosity being required to effectively separate moving parts at low speed it is clear that some fluids are better placed to achieve this but ultimately follow a similar trend with respect to viscosity alone.

The low speed regime is particularly difficult to deconvolute owing to the complex nature of the boundary, mixed and EHD contributions to the efficiency losses. The point at which each fluid passes into boundary contact and the film thickness within the EHD contact will influence efficiency under these conditions. To a first approximation the offset in efficiency by VM type can be related to the traction of the fluid in addition to viscosity. The MTM traction responses for the test fluids are shown in Figure 3 against the dynamic viscosity. The data shows the New VM, DPMA and PAO 100 blends to all have much lower traction at 10% SRR than the PIB or brightstock blends. The trend between fluids is equivalent at all SRR values evaluated (up to 50%) and this trend is generally in line with input torque differences seen in a given fluid at a given viscosity in Figure 2b. The standout case in this instance being the PAO100 containing fluid, this is suggestive that viscosity and traction are the two principal factors governing efficiency at low load, moderate torque but additional properties may also influence the fluid.

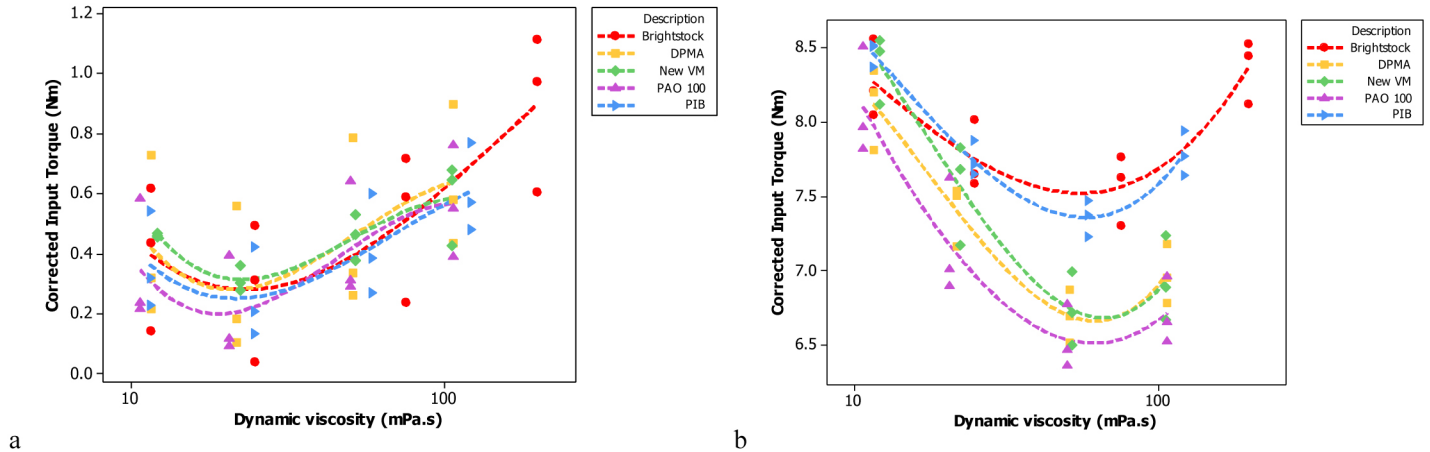


Figure 2. Plot of dynamic viscosity-input torque (efficiency) at 87 RPM, a. no load (0 Nm) and b. moderate load (183.4 Nm)

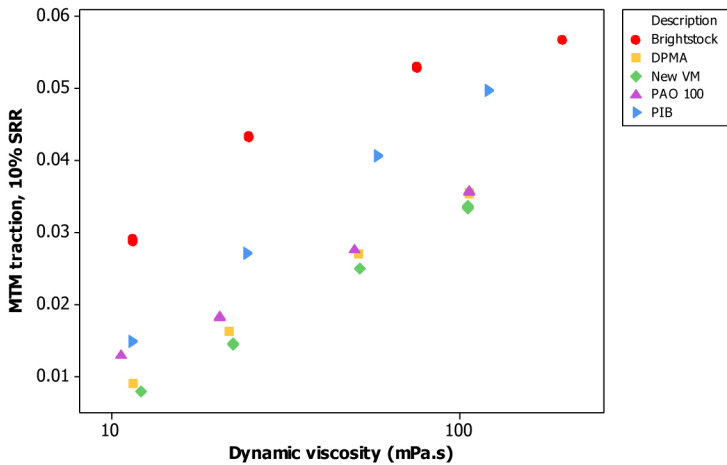


Figure 3. Plot of EHD Traction (10% SRR) vs. log(dynamic viscosity)

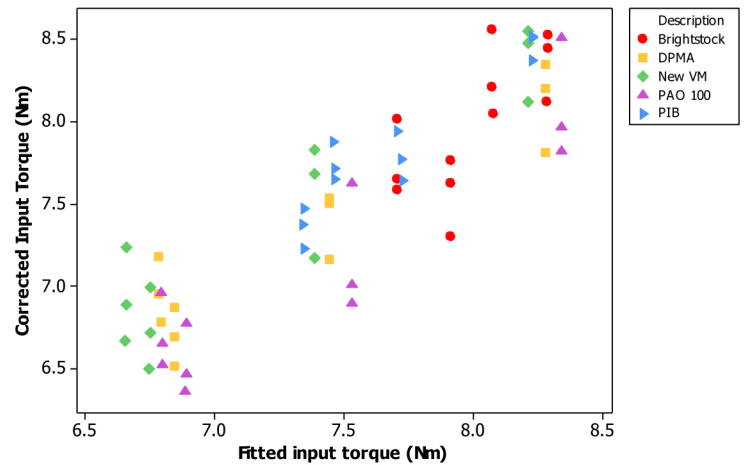


Figure 4. fitted input torque based on EHD traction (10% SRR) and dynamic viscosity

The interaction of the viscosity and traction at low speed, moderate torque (87 RPM, 183.4 Nm) can provide a model to fit expected input torque to actual input torque (Figure 4), although the situation is more complex than this owing to some potential contribution of mixed lubrication regime. Of particular note is the tendency of PAO100 efficiency to be underestimated indicating factors beyond viscosity and traction, again illustrating different VM chemistries can also influence low speed, moderate load efficiency beyond just traction and viscosity and it stands to reason under these conditions that EHD film thickness will play a role and needs further consideration.

Describing the plot in Figure 4, Fitted Input torque = $12.73 - 4.08 \log_{10}(\text{Dynamic Viscosity}) - 94.24 (\text{MTM traction, 10\% SRR}) + 78.44 \log_{10}(\text{Dynamic Viscosity}) * (\text{MTM traction, 10\% SRR})$

Equation 1.

The maximum EHD film thickness (asymptote) and curvature of EHD film thickness response were correlated to dynamic viscosity. Whilst the EHD film thickness at high speed correlated well with viscosity, the curvature (i.e. the rate at which the EHD film builds) and also the low speed behavior of the EHD film thickness did not correlate to viscosity and provided two additional related parameters to explore. In order to utilize this to model the impact of EHD film thickness on efficiency the asymptote, curvature and low speed behavior of the EHD response were assigned the descriptors *alpha*, *beta* and *gamma* respectively. Figure 5a shows the EHD film thickness response and a predicted EHD