SAE Number 2008-28-0121

VII Effects on the Formulation and Operating Temperature of Multigrade Gear Oils

R. Cocks, C.D. Neveu, P. Hutchinson
RohMax Additives GmbH, Kirschenallee; Darmstadt, D64275, Germany

ABSTRACT

Fluids used in manual transmissions of automotive engines must be formulated to perform many critical functions. These include good synchromesh performance, easy shifting at low temperature, protection against corrosion, high load carrying capacity, low friction, good resistance to pitting, good thermal and oxidative stability and elastomer compatibility.

Improving fuel efficiency and reducing CO_2 emission of cars and trucks has become a major challenge for the industry. The vehicle transmission can have a significant impact on overall efficiency, and design changes leading to reduced friction and weight of the transmission can place increased demands on the lubricant. At the same time, lower lubricant viscosities are being specified to reduce energy losses due to fluid friction.

Viscosity is one of the critical properties of a gear lubricant. Transmission oils must be sufficiently fluid at low temperature in order to minimize energy losses due to friction and to provide easy gear shifting. On the other hand, the viscosity of the fluid must be high enough at high temperature to avoid excessive wear. The operating temperature for gear lubricants keeps on increasing as a result of higher engine output, increased vehicle loading and improved aerodynamic body styling that reduces airflow around transmission. Fluids are expected to perform their functions over a longer time span and many transmissions are now “fill for life”. Therefore, an important objective in formulating gear lubricants is to minimize the operating temperature of the oil through the selection of proper gear additives and base stocks.

To reflect these changes and to bring the standard more in line with OEM expectations major upgrades to the automotive gear lubricant viscosity classification SAE J306 have taken place in recent years. Viscosity limits are tightened, and lower viscosity grades introduced, resulting in a larger number of SAE grades. A major change was the addition of a stay-in-grade requirement using the tapered Roller Bearing test (TRB) according to the method CEC L-45-A-99.

Highly shear stable polymeric VI Improvers are often used to formulate fill for life gear lubricants providing the viscosity profile needed to operate over a wide range of temperature. The stricter limits of SAE J306 also means that only the most shear stable polymer VII options are suitable. The selection of the VI Improver must be based on its contribution to viscosity at low and high temperature, its shear stability, its thermal and oxidative stability but also, as indicated earlier, on its ability to minimize friction under the critical load conditions encountered in gear boxes and axles.

Meaningful screening tests are necessary to select the most effective combination of additives and base stocks. The influence of the lubricant composition on the level of friction in gears has been evaluated using different devices. They range from a passenger car run on a chassis-dynamometer in a temperature controlled room, to test rigs consisting of a gear box or of a rear axle driven against a dynamometer by an electric motor [2-7].

Among the rig tests, the Achsial-Rillen-Kugel-Lager test (ARKL, Axial Groove Ball Bearing), a modified four-ball apparatus, proved to be a fast and efficient tool for determining the level of friction in gear lubricants [4, 5]. In the ARKL, the higher the friction, the higher the temperature increase of the test oil over the course of the test. A good test for the determination of the mechanical efficiency is the modified FZG test as per PV 1456 [6], where the torque loss is measured. Both test methods were developed by VW and showed good correlation to a 1.6 l, 55 kW VW Polo and to a transmission test [4-7].

We evaluated the influence of the base stock type and viscosity and of the VI Improver chemistry and molecular weight.

Key words: Viscosity, gear lubricants, ARKL, VI Improver, SAE J306.

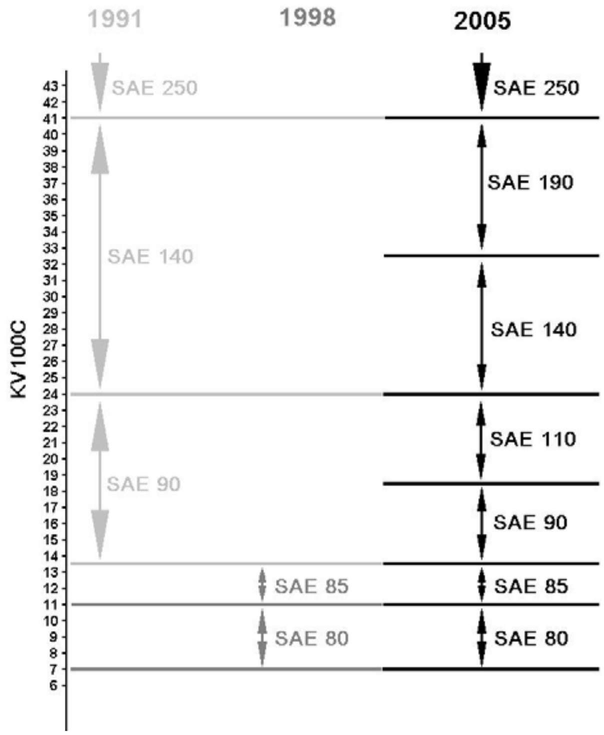
INTRODUCTION

SAE has long recognized the importance of the viscosity of gear lubricants at low and high temperature. SAE J306 OCT91 defined grades based on (a) the kinematic viscosity at 100 ºC and (b) the dynamic viscosity measured using the Brookfield viscometer at a temperature that depends on the grade.

Since the time the classification was defined, major improvements have taken place in terms of gear design and metallurgy, and gear oil formulations in order to meet the ever increasing expectations of the users and the OEM's. In particular the OEM's strong desire to improve fuel economy and hence meet emission requirements has driven many of these design changes. Modern vehicle designs use smaller, more compact transmissions employing lower lubricant volume. This places significant higher mechanical stress on the fluid which can lead to viscosity loss due to the shearing of polymeric VII additives.

Automotive gear lubricants have to operate over a wide temperature. In order to provide adequate protection in all conditions, the viscosity of the fluid must be low enough at low temperature to reach all parts of the transmission and avoid excessive viscous losses and thick enough at elevated temperature to protect the gears against excessive wear

Figure 1: Changes to KV100C limits for SAE J306 since 1991.



The technical improvements discussed above and the increased interest in improving the efficiency of transmissions through the use of less viscous lubricants has led to two revisions of the SAE J306 viscosity classification in the past 10 years. In 1998 two new light viscosity grades, the SAE 80 and SAE 85 were introduced enabling passenger car OEMs to specify oils with improved fuel consumption. In 2005 two new grades, SAE 110 and 190 were added. They reduce the viscosity range of SAE 90 and SAE 140 which, because of their new lower upper viscosity limit become fuel efficient grades for commercial vehicles. In 1998 the introduction of "stay-in-grade" after a very severe shear test recognized the fact that many gear lubricants were fill-for-life fluids that had to operate in higher power density transmissions.

Viscosity Index Improvers VIIs that improve the viscosity-temperature performance of base stocks are often used to formulate gear lubricants. These polymeric VIIs must meet the stringent viscosity requirements of SAE J306 before and after shear and only the most shear stable products are suitable for gear formulations. Careful balancing of the base oil type and concentration is needed to accommodate the large concentration (up to 40%) of these shear stable polymer VIIs.

The ability of a lubricant to reduce overall friction stems from different properties depending on the prevailing lubrication regime. Under low load, the viscosity of the fluid at both low and high shear stress is of prime importance. Under high load, when elastohydrodynamic contacts occur, friction is controlled by the high pressure rheological properties of a lubricant. Therefore, two oils having the same SAE grade may show significantly different friction properties in gear boxes. Considering that frictional losses in gears increase the lubricant temperature, fuel efficient lubricant should operate under lower temperature in a defined environment. Meaningful screening tests have been developed to select the most effective combination of additives and base stocks that provides the lowest friction. The influence of the lubricant composition on the level of friction in gears has been evaluated using different devices. They range from a passenger car run on a chassis-dynamometer in a temperature controlled room, to test rigs consisting of a gear box or of a rear axle driven against a dynamometer by an electric motor [2-7].

Among the rig tests, the Achsial-Rillen-Kugel-Lager test (ARKL, Axial Groove Ball Bearing), a modified four-ball apparatus, proved to be a fast and efficient tool for determining the level of friction in gear lubricants [4, 5]. In the ARKL, the higher the friction, the higher the temperature increase of the test oil over the course of the test. A good test for the determination of the mechanical efficiency is the modified FZG test as per PV 1456 [6], where the torque loss is measured. Both test methods were developed by VW and showed good correlation to a 1.6 l, 55 kW VW Polo and to a transmission test [4-7].

OPERATING TEMPERATURE.

ARKL Test

The test rig is a modification of the Shell four-ball-apparatus (DIN 51350 part 1). The bearing is placed in a well-insulated bearing holder that is filled with 40 ml of test oil. The bearing (type N° 51208) is driven at 4000 RPM under a load of 5000 N for two hours.

In less than two hours, the oil temperature reaches a temperature plateau that depends on the level of friction taking place in the rig. High friction resulting from viscous drag increases the oil temperature that in turns decreases the oil viscosity. Lower viscosity results in a reduction of the frictional losses and thus in a lower increase of the oil temperature. The equilibrium temperature in the ARKL test is reached, when the heat generation of the system is equal to the loss of thermal energy through conduction and convection. The equilibrium temperature is thus the result of a very complex thermodynamic process in which the oil viscosity, its lubricity and its ability to exchange heat with the rest of the system are at play.

INFLUENCE OF BASE STOCK

Earlier work done with the ARKL test showed that the temperature increase was dependent on the oil type [5]. To further understand what is happening in the ARKL test, we completed a series of experiments on mineral oils, PAOs and esters. All oils contain 0.8% of E/P additive.

Oil	KV @100 °C mm²/s	VI	KV @EOTT mm²/s	EOTT °C
Mineral	3.40	101	3.05	107.7
Mineral	3,93	103	3.36	110,5
Mineral	3,93	103	3.36	110,5
Mineral	5.44	105	4.34	113.3
Mineral	10.76	95	6.51	124.6
Mineral	12.26	97	7.38	124.0
Mineral	26.67	144	11.34	135.0
PAO	3.97	126	4.72	89.6
PAO	5.81	137	6.11	97.2
PAO	7.81	137	7.95	99.1
PAO	12.51	154	10.23	110.0
Ester	2.37	126	2.60	92.5
Ester	3.31	145	3.82	90.1
Ester	9.41	192	8.13	108.3
Ester	10.11	189	7.36	118.6
Ester	10.40	185	7.57	118.3

Table 1: End of Test Temperature (EOTT) and viscosity

We also calculated the viscosity of the oils at EOTT using the MWW equation [8]. The complete results are detailed in Table 1 and illustrated in Figure 2.

Figure 2 confirms that within the range of viscosity studied for a given oil type, the higher the viscosity, the higher the End of Test Temperature (EOTT) and the frictional loss in the ARKL test. This finding is consistent with those reported by Wienecke [2].

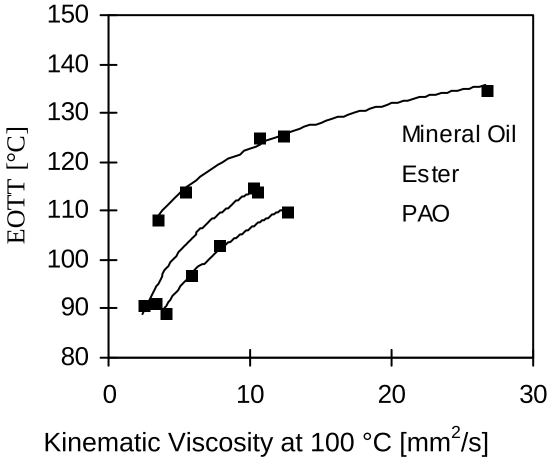


Figure 2: End of Test Temperature (EOTT) for different types of base stocks

The results show that oils having the same kinematic viscosity at 100 °C but of different type can produce very different EOTTs. There seem to be a correlation between the VI of the oils and EOTT when comparing PAO and mineral oil of the same kinematic viscosity at 100°C: The higher the VI, the lower EOTT. This finding is consistent with that reported by Wienecke et al. [2]. They observed that hydro-cracked mineral oils having a higher VI operate at a lower equilibrium temperature than conventional mineral oils.

INFLUENCE OF VI IMPROVER

We evaluated five different VI Improvers in a PAO 4 and a 150SN mineral oil: Two polyalkyl-methacrylates of different molecular weight, a low molecular weight OCP, a low molecular weight PIB and, an oligomer of PAMA and alpha-decene. Each blend was evaluated five times.

4.1 VI Improvers in PAO 4 and 150SN

The concentration of each VI Improver was adjusted to obtain a kinematic viscosity of about 13 mm²/s at 100°C. However, as shown in Table 2, the viscosity indices of the test oils are very different.

VI Improver	KV 100°C mm²/s	VI	EOTT °C	KV EOTT mm²/s	DV 10^6/s at EOTT mPas
PAO 4	4.0	126	89.6	4,7	4.0
PAO 40	12.5	154	110	10.2	8,2
OCP	13.0	175	106.6	11.6	8.6
PAMA 1	12.9	219	106.4	11.5	8.4
PAMA 2	13.2	183	110.8	10.5	8.9
PAMA/ α decene	13.0	168	110.0	10.7	9.3
PIB	12.8	150	120.4	8.7	6.9

Table 2: Results of VI Improvers in PAO 4

Base Stock or VI Improver	KV 100 °C mm²/s	VI	EOTT °C	KV. at EOTT mm²/s	DV 10^6/s at EOTT mPas
150 N	5.4	105	113.3	4.3	3.4
Mineral	13.0	105	126.0	7.7	5.5
OCP	13.1	146	120.0	8.8	6.7
PAMA 1	13.3	171	117.0	9.6	7.2
PAMA 2	12.8	148	117.0	9.2	7.5
PAMA/α decene	12.9	141	117.5	9.1	7.3
PIB	13.1	120	129.5	7.2	6.0

Table 3: Results of VI Improvers in 150N

The addition of a VI Improver results in an increase of the EOTT, with the highest increase in EOTT is observed with the PIB based oils having the lowest VI of the test blends.

For all the PAO 4 based oils except that based on PIB, the EOTT is significantly lower than for those based on 150SN mineral oil having the same kinematic viscosity at 100°C.

We have seen that the PIB based formulations having the lowest VI lead to the highest EOTTs. Figure 4 illustrates the relationship between the VI and the EOTTs of the formulations, including an additional formulation using a extremely low molecular weight PIB in 150N giving a VI of only 97 and EOTT of 138ºC.

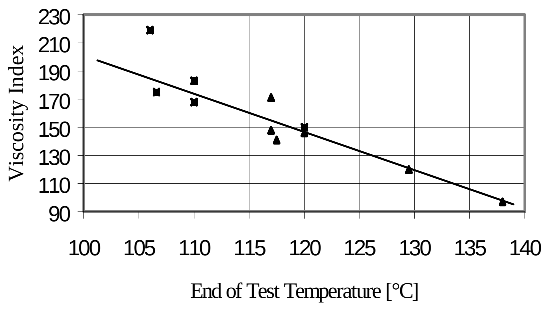


Figure 4: Correlation between Viscosity Index and EOTT (■ Formulations in PAO 4; ▲ Formulations in 150N)

5 EFFICIENCY: EXPERIMENTAL

5.1 FZG efficiency test

The test rig is a modification of the well known FZG gear test usually used for determination of scuffing, pitting and other kinds of wear. In order to compare gear oils in matters of gear efficiency, VW modified the rig and proved successful the correlation to transmission tests [6, 7]. The test measures the torque loss which the drive motor brings into the gear system to sustain the rotation using a torque meter installed between the motor and the transmission gear.

5.2 Test Program

The target of this study was to differentiate oils at conditions that are close to the MVEG (Motor Vehicle Emissions Group) test cycle, the relevant governmental test for evaluating fuel economy of passenger cars in Europe. For the MVEG test cycle, an OEM measured an increase of temperature from an initial temperature of 20°C, to 44°C at the end of the test cycle. We analyzed torque and speed of the engine fuel economy test M 111, which is based on the MVEG test using a Daimler Chrysler car. The torque ranges between 0 and 150Nm and the speed between 900 and 3070 rpm with a weighted mean value of 1600 rpm. Our FZG tests were thus conducted at constant temperatures of 20°C and 44°C and at constant rotation of 1600 rpm with applied torques between 0 and 302 Nm.

In order to investigate the influence of VI Improvers on transmission efficiency, we formulated three gear oils having the same kinematic viscosity at 100°C and containing the same DI package. The first was a monograde SAE 90, while the other two were multigrade fluids using different VIIs, but containing the same amount of PAO 4: a PAMA based formulation, that gives a SAE 75W-90 and a PIB based formulation, that gives only a SAE 80W-90 because of poorer low temperature viscosity.

	SAE 90	SAE 80W-90	SAE 75W-90
VI Improver	none	PIB	PAMA
PAO 4 %	none	18	18
Mineral Oil %	93.5	55.5	58.5
DI package %	6.5	6.5	6.5
VI	94	128	172
KV100°C mm²/s	17.5	16.7	17.5
EOTT (ARKL)	126ºC	125 ºC	120 ºC

Table 4: Formulations for efficiency testing

Evaluating these fluids in ARKL, we find EOTTs of the test oils show the differences we have seen earlier: The PAMA based formulation has the lowest EOTT. Because of its PAO content and higher viscosity index, the PIB containing formulation has a slightly lower EOTT than the mineral oil.

Evaluating these same 3 fluids in the FZG efficiency test ranks the test oils in the same way as the ARKL test but with different distances between the test oils (figure 6 and 7).

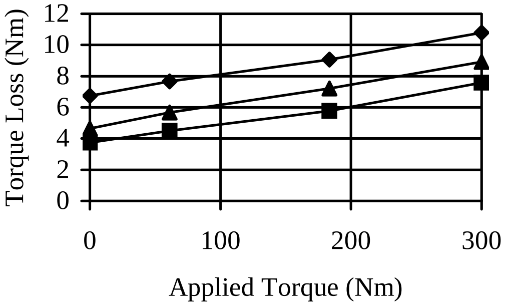


Figure 6: Torque loss of test oils at 20°C

(◆SAE 90, ▲SAE 80W-90, ■SAE 75W-90)

Because of higher viscosity, the torque loss is higher at lower temperature. With increasing applied torque the torque loss increases, but the distance between the test oils is independent of applied torque.

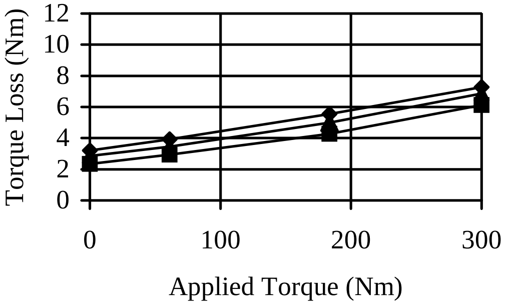


Figure 7: Torque loss of test oils at 44°

(◆SAE 90, ▲SAE 80W-90, ■SAE 75W-90)

The efficiency gain of the VII-improved formulations versus SAE 90 is shown in figures 8 and 9.

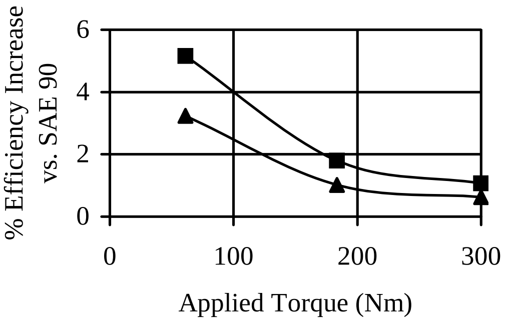


Figure 8: FZG transmission efficiency improvement vs. SAE 90 at 20°C (▲SAE 80W-90, ■SAE 75W-90)

The efficiency increase grows as applied torque decreases. At 20°C the efficiency increase is three times higher than at 44°C. Within the multigrades, the PAMA-based SAE 75W-90 leads to an efficiency increase about twice that of the PIB based SAE 80W-90.

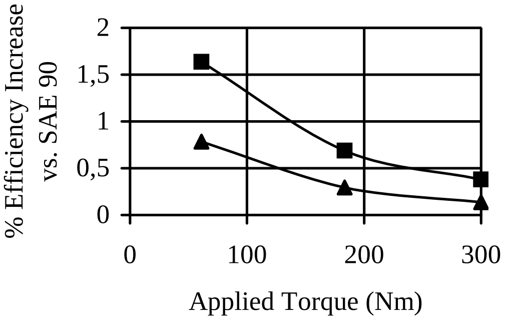


Figure 9: FZG transmission efficiency improvement vs. SAE 90 at 44°C (▲SAE 80W-90, ■SAE 75W-90)

Like EOTT in the ARKL test, the torque loss measured in the FZG efficiency test correlates with viscosity index (VI, Figure 10). Oils with a lower VI have a higher viscosity at lower temperatures resulting in a higher torque loss.

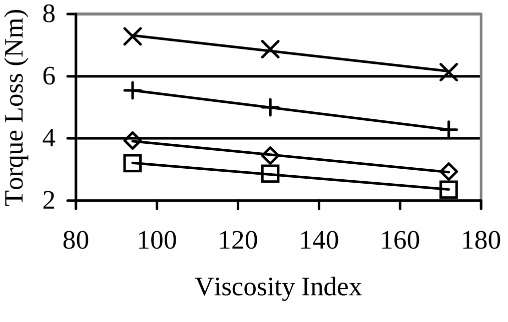


Figure 10: Correlation of Viscosity Index with torque loss in FZG test (Applied Torque: ☐ 0 Nm, ◇ 61 Nm, + 183 Nm, × 302 Nm)

7 CONCLUSIONS

For a given base stock type, the higher the viscosity at 100 °C, the higher the EOTT in the ARKL test. For a given kinematic viscosity at 100 °C, PAOs give a lower EOTT than an ester, which, in turn, produced a lower EOTT than a mineral oil.

Addition of a VI Improver to PAO 4 and to a mineral oil of grade 150 N results in an increase in EOTT. However, the level of EOTT increase depends on the nature of the base stock used for the blend. EOTT correlates in a first approximation with the VI of the formulation.

VI Improved oils that exhibit a high EOTT have also a low kinematic and dynamic viscosity at EOTT. The PIB based oils had a significantly higher EOTT and lower viscosity at EOTT than any of the other test oils.

Compared to a monograde gear oil SAE 90 having the same KV100 and formulated with the same DI package the use of multigrade oils lead to increased transmission efficiency. Compared to PIB, the use of PAMA as VII in the multigrades lead to doubled efficiency increase in the temperature range of the MVEG test cycle. Selection of a high VI PAMA-based gear lubricant should improve fuel economy by 1-2% when compared to lower VI formulations based on PIB or mineral oil. Torque loss in FZG test correlates well to the VI of the oils tested.

REFERENCES

[1] Depue R.T; Johnson D.E : *The Effect of Gear Additive Chemistry on Hypoid Gear Axle Efficiency under High Torque, Low Speed Conditions.* Maziva Symposium. Croatia. October 1997.

[2] Matsuo K.; Yoshida A.; Obata F.: *Antiwear Performance of Modern Industrial Gear Oils.* Lubrication Science (1) 51 0954-0075.

[3] Bisht R.P.S; Singhal S.: *A Laboratory Technique for the Evaluation of Automotive Gear Oils of API GL-4 level.* Tribotest Journal 6-1, September 1999.

[4] PV 1454: *Getriebeöle: Prüfung der Temperaturentwicklung im Axialrillenkugellager-Temperatur-Adapter* (Entwurf). 08/1998. VW. Wolfsburg.

[5] Wienecke. D.; Kluge. R.; Engelen. H.; Becker. V.: *Einfluß der Art und Zusammensetzung des Schmieröles auf das Temperaturniveau*. Tribologie + Schmierungstechnik 45 (1998) 5-7.

[6] PV 1456: Getriebeöle: Prüfung des Wirkungsgradeinflusses von Getriebeölen (Entwurf). 11/1997. VW. Wolfsburg.

[7] Wienecke. D.; Kluge. R.: Einfluß der Art und Zusammensetzung von Schmierölen auf die Verlustleistung in PKW-Schaltgetrieben. Tribologie + Schmierungstechnik **46** (1999) 4-13.

[8] N. MacCoull. *Lubrication*. The Texas Company. New York. 1921. p 85.

[9] Gunsel S.; Korcek S.; Smeeth M. ; Spikes H.A.: *The Elastohydrodynamic Friction and Film Forming Properties of Lubricant Base Oils*. STLE transaction Vol. 42 (1999), 3, 559-569.