

Field and Bench Study of Shear Stability of Heavy Duty Diesel Lubricants

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ABSTRACT

Global environmental and economic concerns of today's world dictate strict requirements for modern heavy duty engines, especially in emissions, noise control, power generation, and extended oil drain intervals. These requirements lead to increased stresses imposed on lubricants in modern heavy duty engines. At the same time, the original equipment manufacturers (OEMs) desire additional fuel economy from the lubricating oil, requiring the use of lower viscosity lubricants to minimize frictional losses in the engine. These lower viscosity oils are subjected to increased stresses in the engine and need to provide robust performance throughout their lifetime in order to protect engine parts from wear and damage. One of the most important lubricant qualities is to maintain viscosity throughout the drain interval and thus provide continuous engine protection. Multi-grade engine oils contain polymeric viscosity modifiers that can be mechanically sheared in the high shear environment of the engine with a resulting drop in viscosity. We evaluate the viscosity behavior of the oils formulated with various viscosity modifiers and the corresponding engine wear in modern Heavy Duty Diesel (HDD) engines in a field trial. The correlation between mechanical shear in the engine and that in the bench test is confirmed. The effect of shear on kinematic viscosity at 100 °C (KV100) and high temperature high shear viscosity at 150 °C (HTHSV150) of both high and low viscosity oils is analyzed.

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INTRODUCTION

Since the introduction of multi-grade engine oils enabled by the use of the polymeric viscosity modifiers, shear stability of the engine oils has been questioned and tested [1, 2, 3]. Bench tests were developed to simulate the mechanical degradation of the polymer in typical service conditions in the most relevant engine designs of the time [3, 4]. At the same time, significant efforts have been made towards understanding of mechanical degradation of the polymeric additives in automotive lubricants [5, 6]. Although significant progress has been made on testing, development and understanding, the ongoing question of how to correlate the bench tests to field performance still remains, due to both the development of modern engines and changes in specifications.

The requirements for modern heavy duty engines in emissions, noise control, power generation, and extended oil drain intervals drove changes in the modern engine design. For example, the injector design moved from Hydraulic Electronic Unit Fuel Injectors (HEUI) to Common Rail Diesel injection systems with solenoid valve equipped injectors. Current emission compliant heavy duty diesel engines are equipped with Selective Catalytic Reduction (SCR) and produce less soot than pre-2010 diesel engines. Also modern diesel engines feature high contact ratio gears for the purpose of noise

reduction. The changes in engine hardware lead to increased stresses imposed on lubricants in modern heavy duty engines, which may also lead to changes in the correlation of the bench tests to the performance of lubricants in the field. In the absence of systematic field data, the initial evaluation of engine oils was usually performed in a bench test such as the Shear Stability by Diesel Injector Apparatus or Kurt Orbahn test (KO) (ASTM D6278) and KRL test (CEC L-45-A) [6]. KO has been used as the predictor of the shear stability performance in engines since it was first developed. Good correlation between the KO test and field performance has previously been established for earlier engine designs using oils with OCP viscosity modifiers [3]. As engine conditions have changed and become more severe, the correlation between the KO test and modern engine performance needs to be re-examined. The KRL test, which is a more severe test compared to the KO test, has traditionally been used to predict the shear stability of transmission fluids. In some cases it is able to reduce multi-grade (non-Newtonian) oil containing certain types of polymeric additives to their Newtonian viscosity in a relatively short period of time. In fact, it is known that Brightstock (considered Newtonian or near Newtonian fluid) can lose viscosity due to severe shear effect in the KRL test [7]. In a recent paper, it was shown that the KRL test even at 4 or 8 hours was not able to correlate to the field trial data due to its extremely severe shear

conditions [6]. Thus, understanding of field performance of multi-grade oils in these modern engines and finding the correlation to a bench test for predicting oil shear stability is an important step in lubricant development and engine protection.

The introduction of new specifications in both North America and Europe raises additional concerns about the shear stability of lubricants and the correlation between bench test and field performance. Fuel economy is one of the major driving forces for new specifications. The original equipment manufacturers (OEMs) desire improved fuel economy from lubricating oils by use of lower viscosity grades to minimize frictional losses in the engine. These lower viscosity oils are expected to withstand sometimes severe ageing processes in the engine and provide robust performance throughout their lifetime in order to protect engine parts from wear and damage in the engine. The bench tests used for predicting the engine performance needs to address both the traditional and the low viscosity requirements.

In this paper we present data from a field test using modern engines with high contact ratio gears. The oils evaluated in the field trial include SAE 15W-40 and SAE 10W-30 multi-grade oils formulated with various viscosity modifiers. The performance of these lubricants was assessed through wear metal content, total base number (TBN) retention, low temperature pumpability (MRV TP-1), and both kinematic viscosity at 100 °C (KV100) and high temperature high shear viscosity at 150 °C (HTHSV150) of the lubricant at end of drain and at intermediate sampling intervals. A good correlation between mechanical shear in the field and viscosity loss in the Kurt Orbahn test at 90 cycles is established for both SAE 15W-40 and SAE 10W-30 grades. In addition, the OEMs' concern about using lower HTHS viscosity oils for enhanced fuel economy is addressed by analyzing the effect of shear on KV100 and HTHSV150 of low viscosity oils with SAE xW-30 grade.

MATERIALS AND TESTING METHODS

Oil Samples

Field trial oils, SAE 15W-40 and SAE 10W-30, were blended using API CJ-4 additive technology and API Group II base stocks. The VM type and SSI are summarized in [Table 1](#). The SAE 15W-40 oils with HSD 1, HSD 2, OCP 2, and OCP 4 were blended to equal KV100 of 15.5 mm²/s, while the SAE 10W-30 oils with HSD 1, OCP 1 and OCP 2 were blended to KV100 of 11.5 mm²/s.

Table 1. Type and properties of the VMs in the field trial and the KO test.

VM Type	SSI	Description
HSD 1	20	Star, styrene-diene
HSD 2	4	Star, styrene-diene
OCP 1	35	Linear, semi-crystalline
OCP 2	35	Linear, amorphous
OCP 3	25	Linear, amorphous
OCP 4	25	Linear, semi-crystalline

To address the potential limitations of the low viscosity oils proposed in the PC-11B specification, oils in SAE 10W-30, 5W-30, and 0W-30 grades were blended with target HTHSV150 of 3.05 mPa·s, and tested in the Kurt Orbahn tests described below. The oils were blended with an experimental PC-11 additive technology using API Group II, Group III and Group IV base stocks for SAE 10W-30, 5W-30, and 0W-30, respectively. Three representative VMs were selected for this study, HSD 1, OCP 2 and OCP 3.

Field Trial

The field test was conducted using a fleet equipped with 2009 emissions-compliant Mack CHU613 trucks running MP8 engines with ultra-low sulfur diesel fuel. The MP8 features 415 HP to 485 HP and has torque, with ratings from 1,540 to 1,700 lb.-ft. It has a single overhead cam with ultra-high-pressure fuel injection. The combination of low soot generation, high shear conditions, as well as fuel dilution qualifies these engines in this application as severe for oil viscosity stay-in-grade requirements. All the trucks had a similar service type. The oil drain interval for this study was an extended drain service of 35,000 miles. For this type of service, Mack would have recommended 25,000 miles. The drain data from the field is the average of drains from at least two trucks and two drains from each truck. In addition, oil samples were also collected at 7,500, 15,000, 25,000 miles. The samples were analyzed for wear metals, soot content, fuel dilution, TBN retention, MRV TP-1, KV100, and HTHSV150. The analytical methods used to characterize each parameter are listed in [Table 2](#).

Table 2. Methods used for analyzing the used oil samples from the field trial.

Parameters	Testing Methods
Wear metals	ASTM D5185
Soot	ASTM D5967
TBN	ASTM D4739
MRV TP-1	ASTM D4684
Fuel dilution	ASTM D3524
KV100	ASTM D445
HTHSV150	ASTM D4683
CCS	ASTM D5293

Shear Stability by Diesel Injector Apparatus (Kurt Orbahn test)

Kurt Orbahn (KO) tests were run according to the procedure in the ASTM methods D6278 and D7109. In addition, the KO tests were run using the same procedure for various number of cycles and the samples were collected after different numbers of cycles, including 10 or 15, 30, 60, and 90. Both the kinematic viscosity (ASTM D445) and the HTHS viscosity (ASTM D4683) were measured for the fresh oils and the oils sheared in KO tests for the specified number of cycles.

RESULTS AND DISCUSSION

Field Trial

The SAE 15W-40 and SAE 10W-30 oils using API CJ-4 additive technology were tested. Table 3 includes the viscometric properties of the fresh oils tested in the field trial. The SAE 10W-30 oils were blended to between 3.4 and 3.5 mPa·s. The results of the used oil analyses from different trucks and different drains were compared and found to be similar and without statistical outliers. The analytical results of the used oils from the intermediate sampling and the final drains were averaged. The average TBN, soot level, MRV TP-1, and wear metals of the drained oils are shown in Table 4 (for SAE 15W-40 oils) and Table 5 (for SAE 10W-30 oils).

Table 3. Summary of the viscosity properties of the fresh oils used in the field trial.

	SAE 15W-40 grade			
	HSD 1	HSD 2	OCP 2	OCP 4
KV100 (mm ² /s)	15.6	15.79	15.73	15.73
CCS (mPa·s)	6040	6370	6540	6680
HTHSV150 (mPa·s)	4.06	4.28	4.2	4.24
MRV TP-1 Apparent viscosity (mPa·s)	24,900	22,100	23,700	23,600
MRV TP-1 Yield stress (Pa)	<35	<35	<35	<35

Note: CCS viscosity of the oils was measured at -20 °C; MRV TP-1 was measured at -25 °C.

	SAE 10W-30 grade		
	HSD 1	OCP 1	OCP 2
KV100 (mm ² /s)	11.53	11.52	11.38
CCS (mPa·s)	6730	6690	6770
HTHSV150 (mPa·s)	3.41	3.49	3.42
MRV TP-1 Apparent viscosity (mPa·s)	22,200	21,100	20,600
MRV TP-1 Yield stress (Pa)	<35	<35	<35

Notes: HTHSV150 was targeted below 3.5 mPa·s. CCS viscosity of the oils was measured at -25 °C; MRV TP-1 was measured at -30 °C.

The viscosity change in the field trial mainly includes the contributions from oil shearing and fuel dilution. The amount of soot generated in these engines (1-2% maximum) which is well dispersed in the oil because of the use of the API CJ-4 additive technology, produces negligible viscosity increase. In general, the viscosity increase due to soot in the oil depends not only on the content but also on how well this soot is dispersed. The

analysis of the Mack T-11 historical data for the oils with the additive packages providing API CJ-4 level of performance showed that the viscosity increase was about 0.2mm²/s per one percent of soot in the region of 1 to 2.5% soot loading. The oil thickening due to oxidation is also believed to be negligible due to low oxidation levels (10-15% maximum). To understand the influence of oil shear stability, the KV100 was corrected for the fuel dilution observed in the field trial. Fuel dilution correction factors were determined by measuring the KV100 of the fresh oils with addition of diesel fuel up to 10%. The low sulfur diesel fuel used in the field trial was used in determining the fuel dilution correction. A logarithmic correlation was found between the KV100 loss and the percentage of fuel added to the fresh oil. As used oils from the intervals and drains have different fuel dilution, measured by gas chromatography (GC, ASTM D3524), different factors calculated from the logarithmic correlation were applied to the used oil samples. The HTHSV150 values were not corrected for fuel dilution. Fuel dilution is expected to play less of a role at higher temperatures due to the light fractions boil off. In addition, measuring viscosity of the diesel mixtures at 150°C can pose safety risk. Figure 1 shows the KV100 after fuel dilution correction of the SAE 15W-40 oils formulated with various viscosity modifiers sampled in the field trial. Although there is a significant drop in kinematic viscosity for all VMs, all of the oils stay in grade at drain.

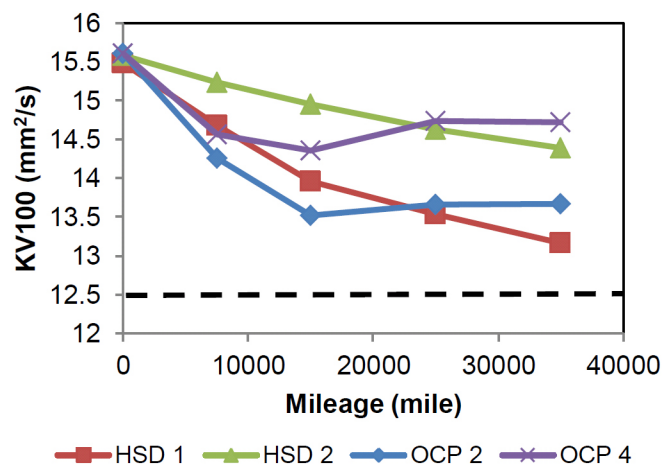


Figure 1. Average KV100 for the SAE 15W-40 grade used oils over the entire drain in the field trial. Note: the dotted line is the stay-in-grade limit.

The average HTHSV150 of the same SAE 15W-40 field oils is shown in Figure 2. The oils were blended to similar KV100, thus the initial HTHSV150 values were different for different VMs. All of the oils undergo similar but small drops in HTHSV150 and comfortably stay in-grade at the final drain.