

The Impact of Lubricant Viscosity and Additive Chemistry on Fuel Economy in Heavy Duty Diesel Engines

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ABSTRACT

The heightened interest level in Fuel Economy for Heavy Duty Diesel Engines the industry has seen over the last few years continues to be high, and is not likely to change. Lowering the fuel consumption of all internal combustion engines remains a priority for years to come, driven by economic, legislative, and environmental reasons.

While it is generally assumed that lower viscosity grade lubricants offer fuel economy benefits, there is a lot of confusion about exactly what drives the fuel economy benefits. Fuel Economy claims in trade literature vary over a broad range and it is difficult for the end user to determine what to expect when a change in lubricant viscosity is adopted for a fleet of vehicles in a certain type of operation. This publication makes an attempt at clarifying a number of these uncertainties with the help of additional engine test data, and more extensive data analysis.

In addition, a more extensive explanation is given for the impacts of base oil viscosity index, VI improver shear stability, and blend targets for the finished oil. All of these factors are part of the design parameters of a finished lubricant. With a better understanding of those parameters, lubricant blenders can optimize the viscosity characteristics of their lubricants for improved fuel economy.

INTRODUCTION

Now that tailpipe emissions of Particulate Matter (PM) and Oxides of Nitrogen (NO_x) have been reduced to near zero levels, improving fuel economy in heavy duty diesel engines is one of the most important challenges of the coming years. Rising fuel costs and emerging on- and off-highway fuel economy regulations of diesel engines, starting to take effect as early as 2015 (1), are having a profound impact on the direction of lubricant research in the industry. As of the time of writing this paper, a U.S. medium and heavy duty truck fuel economy regulation proposal has been made by the National Highway Traffic Safety Administration (NHTSA) and the Environmental Protection Agency (EPA) to the Obama administration (2,3). Exact details of the proposal are not known. The U.S. Office of Management and Budget are reviewing the proposal and will announce regulations by the end of 2010. It is anticipated that progressively more severe truck vehicle regulations will be implemented from 2014 to 2017 with the 2017 regulations to be "technology forcing" (i.e. requiring new technologies that are not being used commercially today). An overview of these developments is included in Table 5 in the Appendix. Japan already has defined regulations in place that are based on engine dynamometer tests and will become more severe in 2015. Other regions and countries such as Europe and China are adopting a combination of

vehicle CO₂ regulations and the use of biofuels to reduce greenhouse gas emissions.

Earlier studies (4) have been focused on developing a better understanding of the impact of operating conditions on fuel economy in a heavy duty diesel engine. In addition, the impacts of the lubricant's viscosity grade, base oil type, VI improver type, and performance additives have been evaluated. The data indicate that the predominant impact on diesel engine fuel economy, as it relates to a truck in on-highway type operation, is the high temperature lubricant viscosity.

While the impact of moving to lower viscosity grades has been well established, there still is uncertainty over which critical viscometric parameters determine the fuel efficiency of an on-highway truck. In an attempt to clarify this issue, a further study was conducted to evaluate the viscosity related parameters of experimental oils that impact an engine-based fuel economy test. The correlation analysis points toward certain parameters that represent the viscosity of the oil after it has been exposed to shear, as the most informative parameters for the prediction of fuel economy improvement potential for trucks in line-haul operation.

RECAP OF PREVIOUS WORK

Work has been conducted in a Volvo D12D Fuel Economy engine test (4). This test tool is an industry standardized engine test where specific fuel consumption is measured for each of the thirteen different operating conditions of the ESC 13 Mode Test. Each mode is run for about 7 minutes, enough to measure the stabilized fuel consumption. The 13 Mode sequence is repeated five times, and the average per mode is calculated from the second through the fifth measurement for each mode.

The thirteen conditions are represented in Figure 1, where they are shown in the order they are run. The test on the lubricant of interest is preceded by, and followed by, a test on a 15W-30 Reference Lubricant. The final test result is calculated from those three measurements, as the difference between the candidate oil and the average of the reference oil tests before and after the candidate test. The calculated differences are then multiplied by a set of weighting factors for the thirteen individual modes and added up for a final test result that gives a fuel economy improvement (FEI), expressed as a percentage improvement relative to the reference lubricant. Two different sets of weighting factors are used, one that provides an FEI percentage that is representative for vehicles driving in hilly terrain, and one representative for vehicles driving on flat roads. Figure 2 shows a set of the official Volvo D12D FE test results for lubricants with different SAE Viscosity

Grades. The presented data suggest that the high temperature viscosity determines the outcome of the test to a greater degree than the low temperature viscosity.

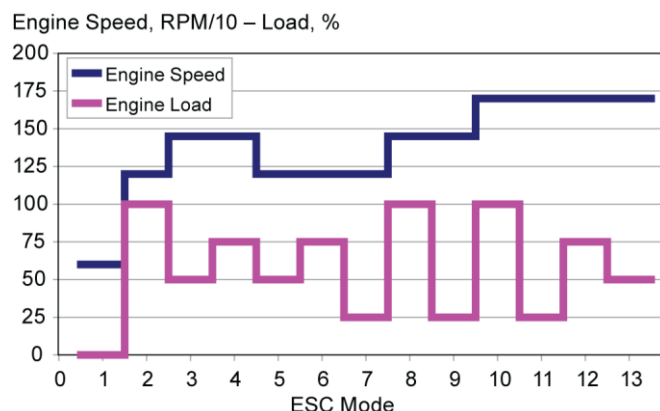


Figure 1 - Speed and Load Sequence During the Volvo D12D FE Engine Test

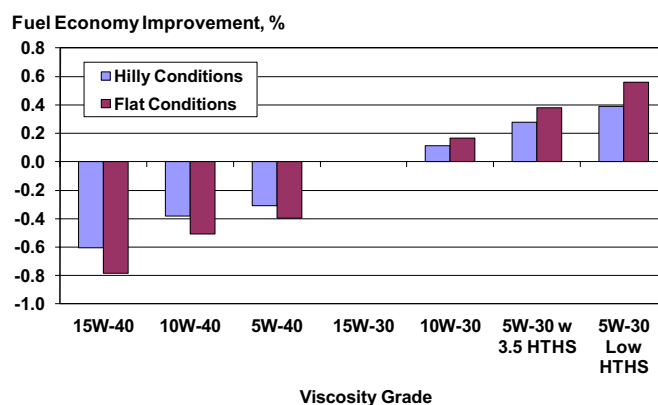


Figure 2 - The Official Volvo D12D FE results for Different Viscosity Grades

In previously reported work, it was indicated that there is a strong relationship between the magnitude of the observed difference and the speed/load of the 13 modes of operation. A parameter called the Quasi Stribeck Number was introduced and was defined as the engine speed divided by the engine load percentage. Table 1 lists the operating conditions for the Volvo D12D FE engine test and the corresponding Quasi Stribeck Numbers for the thirteen modes. If the improvement or degradation of the Specific Fuel Consumption (SFC) relative to the 15W-30 Reference Lubricant is plotted as a function of the Quasi Stribeck Number, the thirteen datapoints form a linear dependency describing the fuel economy improvement as a function of the operating condition. The slope of this line formed by the thirteen

datapoints for a given lubricant is a measure of its average fuel economy improvement. As this approach uses all thirteen datapoints, it is a better approximation of the FEI benefits than the official Volvo D12D FE number, which is heavily biased toward a select number of the thirteen modes by the proprietary weighting factors. Using this approach for the representation of the test results for the same set of lubricants as seen in Figure 2 (minus the low HTHS 5W-30 lubricant), yields the graph displayed as Figure 3.

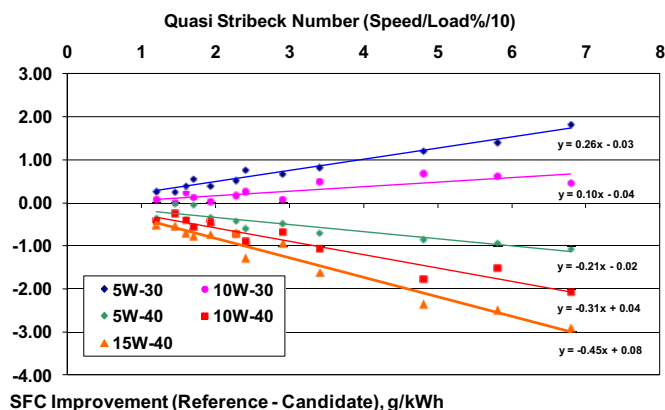


Figure 3 - The SFC Improvement for Different Viscosity Grades

Table 1 – Volvo D12D FE Test Conditions

Mode No.	Speed (rpm)	Load (Nm)		Quasi Stribeck Number
		(%)	(Nm)	Speed/Load%/10
1	600	0	0	—
2	1200	100	2250	1.2
3	1450	50	1130	2.9
4	1450	75	1695	1.9
5	1200	50	1125	2.4
6	1200	75	1690	1.6
7	1200	25	560	4.8
8	1450	100	2260	1.5
9	1450	25	565	5.8
10	1700	100	1930	1.7
11	1700	25	480	6.8
12	1700	75	1450	2.3
13	1700	50	965	3.4

The next paragraph describes a search for the lubricant viscosity measurement that best correlates with the FEI of a lubricant. The assumption is that if such a method can be identified, it may tell more about what viscometric parameter is critical for FEI optimization, and from that,

a set of guidelines for lubricant development can be derived.

CORRELATION ANALYSIS

For the correlation analysis, a larger set of test results, that included the results shown in Figure 3 plus a group of additional test results, was used. The included lubricants were blended with different blend targets for the viscosity, used different base oils, and different VI Improvers. Lubricants that were formulated with friction modifier additive technology were excluded to make sure that the correlation analysis focused on the physical aspects of controlling friction in the engine. Chemistry aspects, if included, would introduce more variability.

Figure 4 represents the correlation that was found between the slope of the Specific Fuel Consumption Improvement line (SFCI-slope) and the cold crank simulator (CCS) viscosity at -20° C. The R^2 is only 0.45, which indicates that this viscometric characteristic does not correlate well with the SFCI-slope of the lubricants. This is an expected conclusion as the engine that is used for the test is fully warmed up when the fuel consumption measurements are taken, and the lubricant temperature during the test is just over 100° C during the test.

The correlation between SFCI-slope and Kinematic Viscosity at 100° C is shown in Figure 5. It is immediately obvious that the correlation is a lot better with an R^2 of 0.64. However, especially for the higher viscosities, there is a wide range of SFCI-slopes visible, suggesting that this viscosity parameter does not accurately describe the viscosity characteristics that determine the engine's friction behavior.

As the engine does expose the lubricant to very high shear levels in contacts such as the ring / liner interface, valve train contacts, and gear sets, it is an obvious next step to look at the correlation with High Temperature High Shear viscosity (HTHS). Figure 6 shows the result of this comparison, and indeed the R^2 is now 0.78, a clear improvement over the previously discussed correlations. The preliminary conclusion therefore is that for a fuel economy prediction based on the lubricant viscometrics, a combination of high shear and high temperature during the viscosity measurement is necessary.

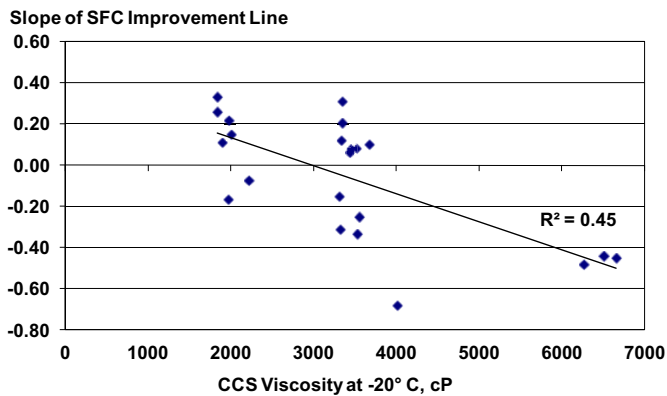


Figure 4 - SFCI-slope versus CCS Viscosity

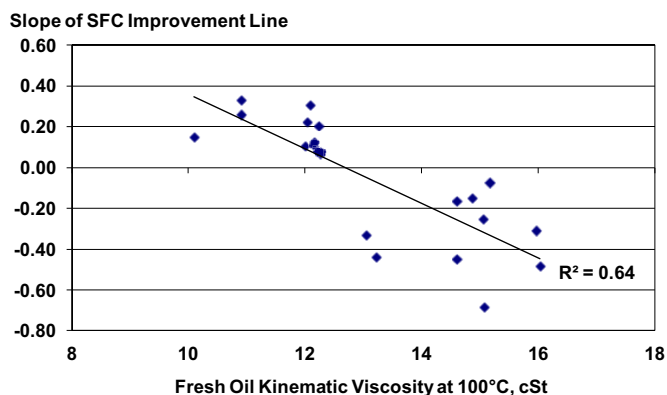


Figure 5 - SFCI-slope versus Fresh Oil Kinematic Viscosity

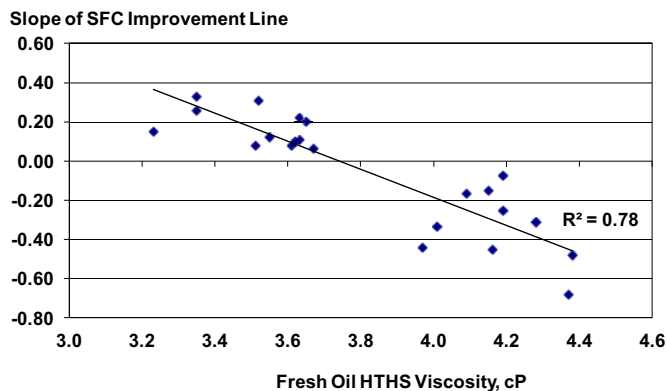


Figure 6 - SFCI-slope versus Fresh Oil HTHS Viscosity

It is obvious from the above paragraphs that shear plays a major role in conditioning the lubricant in the engine. The internal friction in the engine, which is thought to be

the leading factor in lubricant related fuel economy improvements, seems to relate to the condition of the lubricant after it has been subject to shear. This brings up the question of what shear level is the appropriate level to apply to a fresh lubricant in order to predict its fuel economy improvement impact. The HTHS method shears a lubricant to a level of 10^6 sec^{-1} , which is thought to be a shear level causing only temporary viscosity loss. Kinematic viscosity measurements taken before and after a sample is subjected to the HTHS measurement will yield the same result. There are however methods that apply even more shear to a lubricant sample than the HTHS method does. One of those methods is the Bosch Shear Test, also called the Kurt-Ohrban Shear Stability Test (5). In this test, the lubricant is cycled through a fuel injector. As the lubricant passes through the small openings in the injector, the larger molecules are cut into smaller molecules, with a resulting permanent drop in the Kinematic Viscosity. The 90 cycle version of the test was chosen as this is the version of the test that is now most commonly used for heavy duty diesel engine lubricant requirements, and is assumed to best represent real world shear levels.

Figures 7 and 8 show, respectively, the Kinematic Viscosity and the HTHS Viscosity of the lubricants after they have been run in the Bosch Shear Test for 90 Cycles. The Kinematic Viscosity in this case just accounts for the permanent shear loss, where the HTHS measurement accounts for both the permanent shear loss in the Bosch Shear Test as well as the temporary shear loss in the HTHS measurement. The R^2 for both correlations is almost the same, 0.91 and 0.92. This would suggest that the permanent shear loss represents what happens in the engine in the contacts with very high shear loads. The friction in the engine though is mostly hydrodynamic friction in contacts that experience shear loads equal to or lower than the shear loads in the HTHS Viscosity measurement.

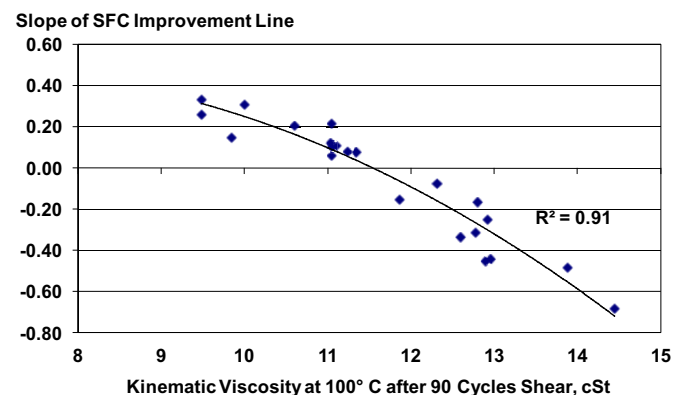


Figure 7 - SFCI-slope versus Kinematic Viscosity after 90 Cycles Bosch Shear Test