Article

Contribution of Viscosity Index Improver to Fuel Economy

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Abstract

The demands on the automotive Industry to deliver improved fuel economy are long standing and continuing. A common and cost effective way to improve the fuel economy is to optimize the viscosity-temperature profile of a lubricating oil by employing a Viscosity Index Improver (VII). In this paper, we investigated the impact of the viscosity of engine lubricating oils on fuel economy and the influence of the VII in tuning the viscosity-temperature profile of the oil to maximize the fuel economy effect without compromising the protection under conditions of high temperature and high shear. We introduced novel comb type VIIs which have been specifically developed to provide the optimized viscosity-temperature profile required to give this balance. The way how these novel comb type VIIs were compared to more conventional VIIs in terms of the lubricating oil viscosity-temperature performance and also the resulting benefit in fuel economy are illustrated. We highlighted a recent study on a SAE 0W-16 oil, which is already of low viscosity, and further viscosity modification of what is already a quite efficient lubricating oil are less pronounced in terms of measurable influence on fuel economy.

Keywords

viscosity index improver, lubricant, fuel economy, NEDC test cycle, friction modifier

1 Introduction

Lowering the engine oil viscosity grade is universally employed to improve fuel economy in transport vehicles such as passenger cars. However, this must be done in conjunction with hardware modification and design improvements to ensure durability is still maintained at this lower viscosity especially under severe operating conditions. Reduction of engine oil viscosity grade is in large part dependent on the use of better-quality base oils. These allow lower viscosity while maintaining other key properties of the lubricating oil such as oxidative and thermal stability. A key aspect here is NOACK volatility and this often requires attention. Base oil selection needs to avoid oils which include lighter components which will be lost from the engine by evaporation [1]. Lower viscosity base-oils have low viscosity at intermediate temperatures such as 40°C and 60°C which is beneficial for fuel economy. The downside is the lower viscosity at high temperature such as KV 100°C, and in particular the HTHS 150°C, are very important for engine hardware protection. If not correctly controlled, low viscosity values in terms of HTHS 150°C may result in poor protection leading to reduced engine life and even more immediate engine damage. The situation can be alleviated with the inclusion of a viscosity index improver (VII) as this will increase the fluid viscosity at higher temperatures. However, the desirable effect of the VII in increasing HTHS 150°C while having less influence on lower or intermediate temperature viscosity values is greatly dependent on the chemical type of VII selected. A high performance VII is one that gives high viscosity increase at high temperature whilst at the same time giving low or preferably zero viscosity increase at low temperature.

This situation has prompted many activities in developing new engine oil VIIs in recent years. Rather than simply being an additive to provide viscosity increase at minimal cost, VIIs have been designed to specifically deliver the HTHS 150°C required for hardware protection, while allowing the viscosity at lower intermediate temperatures to stay as low as possible. It is important to consider these intermediate temperatures because the engine oil often operates at these temperatures making the viscosity here particularly important. Lower viscosity at these intermediate temperatures means less fluid friction, less churning loss and less energy wasted during engine operations. To support this, there are a number of published studies showing the benefit and correlation of lower intermediate
temperature viscosity to fuel economy, but the correlation may be somewhat test condition dependent [2-9]. In this paper, we are going to demonstrate the fuel economy performance of several VIs of different chemistries ranging from conventional hydrocarbon to novel comb type. We will examine their differing influence on formulation viscometric performance and then the resulting chassis dynamometer evaluation of fuel economy.

2 Experimental approach

2.1 Study 1: SAE 0W-20 vs 5W-30

In this first study, we looked at the fuel economy effect of different VI types in a lower viscosity engine of SAE 5W-30 and 0W-20 grades in a smaller capacity engine vehicle. Here as a reference we also compared to the SAE 5W-30 oil specified for this vehicle. The formulation details of all the oils are shown in Table 1. Viscometric properties were measured following the ASTM method as described in the table. The method to measure HTHS viscosity at 80°C is not mentioned in the table because this method is not standardized in ASTM, but we measured the viscosity with a same manner as HTHS 150°C and HTHS 100°C, using a tapered bearing simulator viscometer at 80°C. All the SAE 5W-30 and 0W-20 test oils were formulated to the same HTHS 150°C of ~ 2.9 and ~ 2.6 mPa·s respectively as the primary targets except for the one containing hydrocarbon VII considering the need to meet the KV 100°C and stay-in-grade, therefore the HTHS 150°C ends up higher at 3.12 mPa·s. The oils are formulated using DI package meeting API SN/GF-5 performance with API Group III base oils.

To investigate the fuel economy performance of test oils, we conducted chassis dynamometer testing at the ISP test lab, located in Salzbergen, Germany. Information on the test cycle and vehicle used are shown below. Reference fluid, oil A, was tested before and after each test oil to confirm the repeatability of this testing.

Table 1 Formulation table for SAE 0W-20 and 5W-30 oils

<table>
<thead>
<tr>
<th>Fluid Tag</th>
<th>Method</th>
<th>&quot;Reference&quot; oil A</th>
<th>oil B</th>
<th>oil C</th>
<th>oil D</th>
<th>oil E</th>
<th>oil F</th>
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<tbody>
<tr>
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<td>Comb I</td>
<td>Hydrocarbon</td>
<td>Comb II</td>
<td>Comb III</td>
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<td>Grp III</td>
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<td>Grp III</td>
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<tr>
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<td>ASTM D445</td>
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</table>

As with Study 1, fuel economy performance of test fluids were evaluated by chassis dynamometer testing at the ISP test lab, located in Salzbergen, Germany. Information on the test cycle and vehicle used are shown below. Reference fluid, oil G, was tested before and after each test oil to confirm the repeatability of this testing.

2.2 Study 2: SAE 0W-16

Following the Japanese OEMs’ trend to push towards ultra-low viscosity in engine oils, our recent study was focused on the SAE 0W-16. We selected a vehicle which has some history of being used for fuel economy testing by the OEM, and the commercial genuine oil, oil G, as reference which has a KV 100°C ~7.0 mm²/s. All our candidate SAE 0W-16 oils were formulated with the same hydrocarbon VII, same chemistry comb VIs, same Group III base oil as well as the same API SN/GF-5 package. All the SAE 0W-16 formulated oils except oil H included 700 ppm molybdenum type friction modifier to see if this might give further fuel economy. The difference between oil I, oil J, oil K and oil L, aside from the friction modifier inclusion, are their VII types. Methods used to measure viscometric properties of all test fluids and the obtained values are described in Table 2. Although ASTM method is not mentioned for HTHS 80°C in Table 2, the same method as HTHS 150°C and HTHS 100°C was used to measure this viscosity.

As with Study 1, fuel economy performance of test fluids were evaluated by chassis dynamometer testing at the ISP test lab, located in Salzbergen, Germany. Information on the test cycle and vehicle used are shown below. Reference fluid, oil G, was tested before and after each test oil to confirm the repeatability of this testing.

FE test cycle : NEDC
Vehicle model : Toyota Engine 1.8 TS VVT-i
Fuel type : Petrol
Fuel system : Multi-point fuel injection
Turbocharged : No
Power : 98 kW

3 Results and discussion

3.1 Study 1: SAE 0W-20 vs 5W-30

Study 1 in this paper covers the low viscosity grade engine oils along with a small size test vehicle. The chassis dynamometer test results for all oils (oil B, oil C, oil D, oil E and oil F) are shown in Fig. 1. In this study, oil A having the viscosity grade of an SAE 5W-30 was used as the reference oil. Each of these oils was tested three times except for oil A, which had three repetitive runs before and after every oil candidate. The purpose of multiple repetitive runs on the reference oil is to ensure that there will be no shift in the baseline and no outliers

Table 2  Conventional HTHS and Viscosities

<table>
<thead>
<tr>
<th>Fluid Tag</th>
<th>Method</th>
<th>&quot;Reference&quot; oil A</th>
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to the test measurements. A total of 18 test results were plotted in Fig. 2 and the repeatability as calculated was ±0.3% with a confidence level of above 95%. As we look in more detail at Fig. 1, the percent fuel economy gains from oil B, which is SAE 5W-30 grade similar to the reference oil, was merely +0.28% which fell below the test repeatability level. By changing the VII to the novel comb type, oil C demonstrated a jump in the fuel economy level with a value of +0.84%. To further challenge ourselves in achieving an even more significant level of fuel economy gain, we proceeded to formulate to lower SAE grade of 0W-20. This idea came through from many reports in the past that lowering the SAE grade viscosity of an engine oil itself can provide a substantial amount of fuel economy benefit [7, 10, 11].

The results from all the SAE 0W-20 oils were rather staggering and this includes the conventional hydrocarbon type VII. Nevertheless, the novel comb type VIIs still clearly show advantage over the hydrocarbon type in their fuel economy performance all in comparison to the same SAE 5W-30 reference oil. The percent fuel economy gains from oil D, oil E and oil F are +1.20%, +1.33% and +1.70% respectively. However, it is worth noting that all the comb VIIs used in the formulated oils give unique rheology profiles which resulted in the differences to their individual formulation viscometric properties.

Next, when we looked at all the formulated oils regardless of either the SAE 5W-30 or 0W-20, several notable properties, as shown in Table 1 under the experimental approach section, are their decreasing KV 40°C and HTHS 80/100°C values which go in the complete opposite direction as the percent fuel economy gain. In short, this means that the lower those values are in an oil, the higher the fuel economy gain it receives. Figure 3 clearly shows the correlation between those two properties against the fuel economy performance of oils B, C, D, E and F for better

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**Table 2** Formulation table for SAE 0W-16 oils

<table>
<thead>
<tr>
<th>Fluid Tag</th>
<th>Method</th>
<th>&quot;Reference&quot; oil A</th>
<th>oil H</th>
<th>oil I</th>
<th>oil J</th>
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<td>MoDTC</td>
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<tr>
<td>Base oils</td>
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<td>Grp III</td>
<td>Grp III</td>
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Japanese Society of Tribologists (http://www.tribology.jp/)
understanding. In fact, this observation is aligned to some past reports pointing to the similar trend that these properties are potential good fuel economy indicators [5, 12, 13].

3.2 Study 2: SAE 0W-16

In this study, we wanted to further understand about the potential benefit a VII could deliver in terms of fuel economy especially in a very low viscosity engine oil like a SAE 0W-16. The trigger point that drove us to look into this was the fact that when formulating an ultra-low viscosity engine oil, the inclusion of a VII tends to be significantly lower regardless of the chemistry type. The key role of a VII in altering the formulated oil viscometrics can be negatively impacted which eventually led to smaller differentiation in the magnitude of their KV 40°C and HTHS 80/100°C. Same as Study 1, the reference fluid, oil H, was run twelve times to ensure that there is no drift of the baseline. Results in Fig. 4 shows that there was no baseline drift and no outlier.

The fuel economy test result obtained from the initial test oil ran (oil H) in comparison to the reference oil (oil G) was unexpected. This oil was formulated alongside the novel comb polymer where the critical viscometric properties such as KV 40°C and HTHS 80/100°C, which are also good fuel economy indicators, were all lower compared to the reference oil (see Table 2). Results in Fig. 5 revealed that oil H achieved a percent fuel economy gain of merely +0.07% which is lower than the test repeatability calculated to be ±0.12% within a confidence level of above 90%. After some consideration, we decided to include a friction modifier of the molybdenum type (MoDTC) at a level of 700 ppm based on past studies. It was reported that a Mo-containing friction modifier has some potential in delivering improved fuel economy in low viscosity engine oils [14-16].
Following that, a series of SAE 0W-16 oils were formulated alongside the Mo-containing friction modifier and they are oil I, oil J, oil K and oil L. The main difference among these oils are the VII type included into their respective formulation. Their fuel economy results are shown in Fig. 5. Taking oil H and further adding the friction modifier to get oil I has significantly improved the fuel economy performance where the NEDC test result was a +0.67% gain over the reference oil. Next, we proceeded to formulate oil J using the hydrocarbon VII plus the same friction modifier. This was done to investigate the effect of market general VII towards the fuel economy performance level in the presence of friction modifier. When we looked at the KV 40°C and HTHS 80/100°C of oil J, they tend to be much higher compared to oil I. Based on the finding in Study 1 as well as past reports, we anticipate that oil J is likely going to deliver a poorer fuel economy gain here. In line with our expectation, oil J unveiled a lower percent fuel economy gain with value of +0.38%.

As we gained more confidence from the fact that the inclusion of a molybdenum friction modifier in addition to VII holds significant importance to achieve better fuel economy, we have continued to explore this direction using two other newly developed comb VIIs. In this paper, they are named as comb IV and comb V. These two polymers are specially designed to achieve even lower KV 40°C and HTHS 80/100°C when formulated into the ultra-low viscosity engine oil (see Table 2) all at the same HTHS 150°C level of ~ 2.3 mPa·s meeting the SAE 16 viscosity grade requirement as specified under SAE J300. The two new oils generated from these comb polymers are oil K and oil L. As we anticipated, both oils showed further improvement in the fuel economy test results where oil K and oil L individually demonstrated +0.77% and +0.90% gains respectively. Overall, the results from the entire study were encouraging enough even though we had some challenges at the beginning due to the poorer fuel economy performance from oil H.
In search of an explanation to the NEDC test results from Study 2, we further analyzed the data at a more in-depth level and discovered new information that may support our following arguments about the poorer fuel economy performance as shown in oil H. The NEDC test is separated into 3 connective cycles and they are the ECE 1-2 cycle, ECE 3-4 cycle and EUDC cycle. The ECE 1-2 and 3-4 cycles represent the urban driving condition at lower speed whereas the EUDC as the name implies, is the representative of the extra urban driving condition at a much higher speed. Figure 6 provides an illustration of the entire test cycle for easier understanding. Additionally, during the NEDC test of these ultra-low viscosity oils, the engine oil sump temperature was recorded to gradually rise from approximately 21°C at the beginning of the test and reaching up to about 95°C when it finally passed through all three test cycles.

When we analyzed the data from the ECE 1-2 and EUDC test cycle individually, it was noticeable that the ECE 1-2 cycle showed lower engine oil sump temperature ranging from 21°C to 56°C while the EUDC cycle was from 80°C to 95°C. This is clear that the ECE 1-2 cycle runs cooler whereas the EUDC cycle runs hotter. Following this observation, it has led us to believe that under the cooler operating temperature, the engine oil remains viscous that the boundary or even mixed lubrication regime does not predominate, and this was also shown from the average oil viscosity recorded at 25 mPa·s. The lubrication regime is still mainly viscosity controlled and this can be clearly seen from the fuel economy gain exhibited by oil H (+0.70%) over the reference oil (oil G) in the ECE 1-2 cycle as shown in Fig. 7. On top of that, when oil H was treated with the MoDTC, it generated oil I which gave additional fuel economy gain at the level of +1.20% by referencing it to oil G.

Moving over to the hotter test cycle as mentioned earlier, the oil viscosity recorded during this test cycle revealed a significant drop to the level of approximately 6 mPa·s. In the non-friction modified oil H, the fuel consumption recorded an increase which also translates into -0.40% poorer fuel economy performance. Conversely, the friction modified oil I exhibited a fuel economy improvement of up to +0.50% over the reference oil as a result of lower oil viscosity and improved mixed and boundary lubrications due to the presence of a friction modifier. Information regarding the fuel consumption and percent fuel economy of oil H, oil I and the reference oil are shown in Fig. 8.

We learned from Study 2 that the ratio of hydrodynamic versus other lubrication regimes can be engine and test cycle specific. Therefore, the tendency of fuel economy could be

![Fig. 6 New European Driving Cycle (NEDC)](#)

![Fig. 7 Oil H and Oil I fuel economy performance on ECE 1-2 cycle (part of NEDC)](#)

![Fig. 8 Oil H and Oil I fuel economy performance on EUDC cycle (part of NEDC)](#)
different in the new WLTP test cycle even when we test it using the exact same fluids as investigated earlier. These aspects have been considered and will form the basis of our future work related to engine oil fuel economy testing.

4 Conclusion

In this paper, we have studied the impact of engine oil viscosity on fuel economy performance and then also the connected VII influence on the engine oil viscometrics. The conclusion from our studies are as follows:

- Within a given SAE viscosity grade, differences in the fluid viscometric properties have a direct impact on the engine oil fuel economy outcome.
- Novel comb polymer gives lower KV 40°C at any given SAE viscosity grade compared to the conventional hydrocarbon type VII.
- KV 40°C and HTHS 80/100°C are two key performance indicators toward engine oil fuel economy.
- Inclusion of a Mo-containing friction modifier significantly helps with the fuel economy performance of an ultra-low viscosity engine oil, especially under mixed or boundary lubrication regime due to the synergistic effect alongside a VII.
- Fuel economy engine oils can be made achievable by a choice of VII and friction modifier combinations.

Acknowledgments

We would like to thank ISP test lab for running the tests and providing the results as well as the application lab team at Evonik who have greatly contributed to this work.

Definitions, Acronyms, Abbreviations

VII – Viscosity Index Improver
KV – Kinematic Viscosity
HTHS – High Temperature High Shear
SAE – Society of Automotive Engineers
API – American Petroleum Institute
ILSAC – International Lubricant Standardization and Approval Committee
OEM – Original Equipment Manufacturer
NEDC – New European Driving Cycle
EUDC – Extra Urban Driving Cycle
UDC – Urban Driving Cycle
FEI – Fuel Economy Improvement
WLTP – Worldwide Harmonized Light Vehicles Test Procedure
MoDTC – Molybdeneum Dithiocarbamate

References