Viscosity matters

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Without lubricants motor vehicles would not exist. Motor oil, automatic transmission fluid, hypoid gear oil, power steering fluid are all equally essential for reliable vehicle operation.

Motor oil is a vital part of the internal combustion engine. Without oil, the engine will not run. This fact was understood at the very beginning of the century-long history of the automobile. Benz Patent Motor Car, which was outed to the public in 1886 and is usually regarded as the first production vehicle powered by a four-stroke internal combustion engine, used a rather alien drip-feed lubrication and a grease cup. However, the first true mass-produced automobile, the famous Ford Model T launched in 1908, already used a splash oiling system which is conceptually similar to what we see in modern cars, except that both the engine and the transmission of Model T shared the same oil.

Since the internal combustion engine is so critically dependent on oil, the need for standardization of motor oil was quickly realized. In fact, it was in 1911 that the first classification of motor oils was adopted by the newly grounded Society of Automotive Engineers (SAE). That first SAE classification – the so-called Specification No 26 – ranked motor oils based on specific gravity, flash and fire points. More viscous oils were "heavier" and had higher flash and fire points. Ever since then motor oils are still sometimes referred by weight, although from 1923 oil viscosity began to be used as the basis for all future SAE specifications. The latest SAE J300 specification was adopted in 2015 and looks as follows:

SAE J300 - ENGINE OILS 2015

SAE Grade	Cold Cranking MAX Viscosity cP @Temp, °C	Pumpability Max Viscosity cP @ Temp, °C	Viscosity @ 100°C		HT/HS @ 150°C Min cP
			Min cSt	Max cSt	
0W	6200 @ -35	60,000 @ -40	3.8	NA	NA
5W	6600 @ -30	60,000 @ -35	3.8	NA	NA
10W	7000 @ -25	60,000 @ -30	4.1	NA	NA
15W	7000 @ -20	60,000 @ -25	5.6	NA	NA
20W	9500 @ -15	60,000 @ -20	5.6	NA	NA
25W	13000 @ -10	60,000 @ -15	9.3	NA	NA
8	NA	NA	4.0	<6.1	1.7
12	NA	NA	5.0	<7.1	2.0
16	NA	NA	6.1	<8.2	<2.3
20	NA	NA	6.9	<9.3	2.6
30	NA	NA	9.3	<12.5	2.9
40	NA	NA	12.5	<16.3	See note
50	NA	NA	16.3	<21.9	3.7
60	NA	NA	21.9	<26.1	3.7

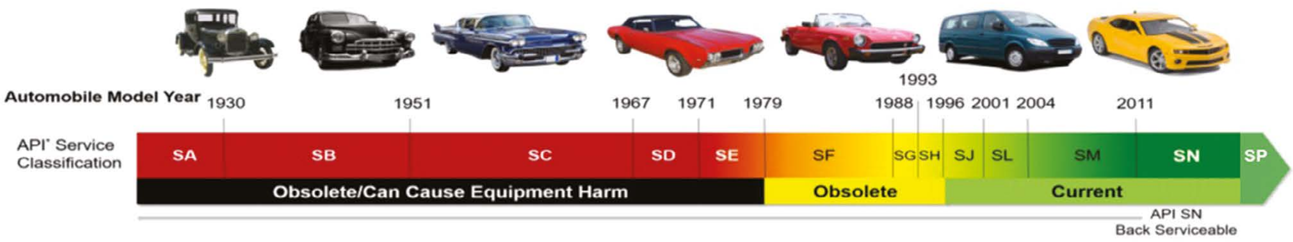
NOTE: 3.5cP for 0W-40, 5W-40 & 10W-40 grades, 3.7cP for 15W-40, 20W-40, 25W-40 & 40 grades. Penrite define "70" engine oils as above 26.1cSt at 100°C & "30W" as less than 13,000cP at -5°C.

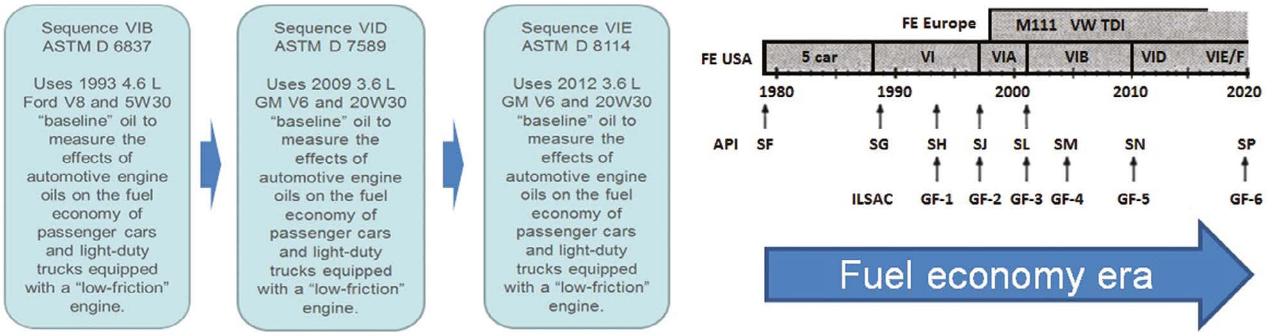
The new viscosity grades introduced with this latest revision are 8, 12 and 16. Their introduction reflects the general trend towards broader use of low-viscosity oil as this leads to improved fuel efficiency. There exists a simple empirical relationship between the HTHS of motor oil used and fuel economy (FE) of the internal combustion engine[i, ii]

$$FE = \frac{3.7 - HTHS}{3.7} \times 15\%$$

showing the fuel economy achieved compared to a legacy 15W-40 motor oil with HTHS 3.7 cP. Thus, a change from 15W-40 to 5W-20 will bring you an approximate 5% improvement in fuel economy, and moving further down to 0W-8 you will gain additional 5%.

The evolution of fuel economy motor oil





Since the 1980s, the fuel economy requirement is included in many engine oil performance specifications, such as ILSAC, and stands behind the introduction of new service categories, such as API SN-RC, API FA-4, ACEA A5/B5, ACEA C5, and future ACEA A7/B7, C6, F8, F11 categories.

The same trend can be tracked in individual OEM specifications. For instance, the newer Ford WSS-M2C948-B specification demands higher fuel efficiency than the older WSS-M2C913-C specification. Similarly, Daimler MB 229.52 oil is more fuel efficient than MB 229.51. This forces lubricant manufacturers to formulate products with the lowest possible viscosity for a given SAE viscosity grade and more broadly use synthetic base oils not only due to their superior performance but also due to their better consistency properties compared to mineral oils.

Mirroring this move, SAE J306 specifications for gear oils have also been updated this year specifying the new viscosity grades for transmission fluids and automotive gear oils.

SAE J300 specifies four different types of viscosity: kinematic viscosity at 100°C (KV100), maximum permissible viscosity for cold cranking (CCS) and cold temperature pumpability, and high-temperature high-shear (HTHS) viscosity; while SAE J306 is limited to only three of them since HTHS is irrelevant for gear operation. Hence, one can firmly state that viscosity does matter!

SAE J306 Standard

SAE Viscosity Grade	Maximum Temperature for Viscosity of 150,000 cP (°C)[1]	Kinematic Viscosity at 100°C (cSt)[2] Minimum[3]	Kinematic Viscosity at 100°C (cSt)[2] Maximum
70W	-55	3.8	-
75W	-40	3.8	-
80W	-26	8.5	-
85W	-12	11.0	-
65	-	3.8	<5.0
70	-	5.0	<6.5
75	-	6.5	<8.5
80	-	8.5	<11.0
85	-	11.0	<13.5
90	-	13.5	<18.5
110	-	18.5	<24.0
140	-	24.0	<32.5
190	-	32.5	<41.0
250	-	41.0	-

[1]Using ASTM D2983 [2]Using ASTM D445 [3]Limit must still be met following CEC L-45-A99, Method C (20h)

Oil viscosity is one important quantifier of its fitness for purpose. In a firing engine, all moving parts ride on an oil film. Any incidence of unlubricated metal-metal contact may have catastrophic consequences and has to be avoided at any cost. For oil to do its job, it has to be delivered to the critical lubrication points at precisely the right time. Oil flow through the oil channels – or galleries – in the engine is largely determined by its kinematic viscosity, that's why KV100 is the first thing to look at when choosing the right oil. However, you should also be able to start your car in winter. As temperature drops, motor oil is getting more and more viscous, eventually turning into a soap-like solid substance. If this happens, you won't be able to crank your engine. That's why SAE J300 also specifies CCS and low-temperature pumpability and J306 specifies the coldest temperature the oil can be used. Finally, under high engine load, the oil temperature in bearings may increase to 150-200°C, and at the same time, very high shear forces tend to shred oil molecules into smaller fragments. As a result, oil viscosity drops. To guarantee adequate lubrication of bearings under such harsh conditions, SAE J300 defines the minimum HTHS viscosity for each viscosity grade.

If viscosity is too high, the oil may fail to arrive in time and drive away heat quickly enough. However, using thicker than recommended oil isn't fatal: after all, this happens each time you start a cool engine. If viscosity is too low, it's far more dangerous: oil will flow away too easily and fail to build sufficient pressure. This will cause rapid wear of bearings, piston/ring scuffing, seizure, and other critical problems. You will also almost certainly see increased oil consumption.

Many vital subsystems in the engine are critically dependent on oil pressure, for instance, hydraulic timing chain tensioners and variable valve timing (VVT) systems. If the oil pressure is low, these systems may start to malfunction: the chain tensioners will fail to build up enough pressure to eliminate chain slack, and the cam phasers will fail to advance the cam normally. This will offset the engine timing, which in its turn will affect engine performance, fuel economy and emissions, and will eventually turn on the Check Engine light.

Today, nearly all automotive motor oils are "multigrade,"since they provide adequate performance both in cold and hot climates. Multigrade oils are described by two figures, like this: SAE 10W-40. The first figure – 10 followed by "W" – refers to the low-temperature performance. Basically, it says that, in winter time, this oil behaves like a legacy SAE 10W winter grade: it should let you crank your engine at -25°C and it won't lose its ability to flow at temperatures down to -30°C. The second figure, 40, says that in summer, the same oil behaves like a legacy SAE 40 monograde: it has KV100 in the range 12.5 to 16.3 cSt and HTHS viscosity minimum 3.5 cP.

The greater the difference between the second and the first figures, the broader multigrade it is. The broadest multigrades of today, such as 0W-40, 5W-50 and 10W-60, feature a VI around 180, though it is possible to boost the VI even further, up to 200-220. A high VI is a welcome feature since a high VI oil shows less variation in viscosity with temperature. However, the actual spectrum of benefits depends on how this high VI was attained, as there are many pitfalls.

Let's consider an example of how polymeric VI boosters are used in practice. Assume, you have got 150N API Group II base oil with KV40 = 28 cSt and KV100 = 5.2 cSt (VI = 109). If you add 15% olefin copolymer (OCP) type of VI improver, such as Paratone 8006, you will end up with a polymer-thickened product with KV40 = 83 cSt and KV100 = 12 cSt (VI = 140). So, the VI has increased from 109 to 140. How can you decipher that this is a polymer-oil blend and not a polymer-free 600N oil? The first thing to check is the flash point: polymer-thickened oils will have nearly the same flash point as the original base oil (150N, FP 220°C), which is much lower than the flash point of an equiviscous polymer-free base oil (600N, FP 270°C). The second useful check is the evaporative loss: polymer-thickened oils will exhibit nearly the same evaporative loss as the original base oil (150N, 15 wt.% Noack) which is much higher than the evaporative loss of an equiviscous polymer-free base oil (600N, 2 wt.% Noack).

The conclusion from this example is that polymer thickening and VI boosting should be used with care: though it helps you easily tune product viscometrics, some other vital properties may be overlooked. Excessive use of polymers may compromise shear stability – that's why SAE J300 defines the HTHS range for each viscosity grade, and why commercial VII additives are characterized by shear stability index (SSI). Other common problems are oxidative thickening and gelation in used oils.

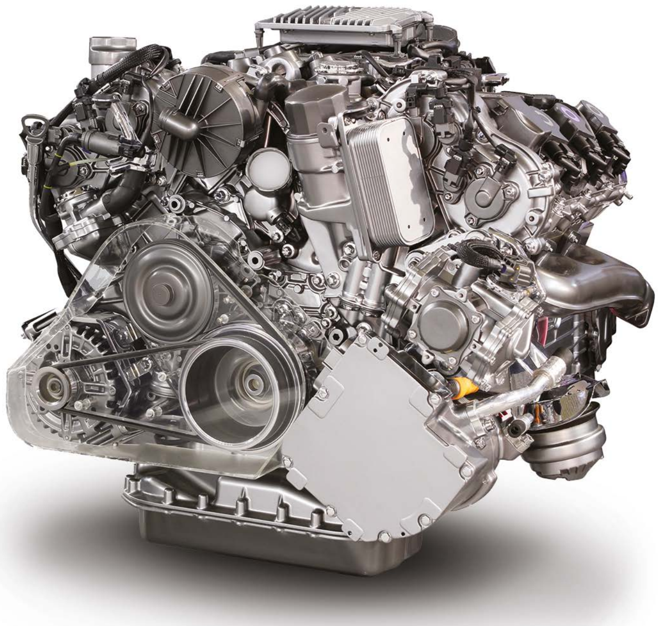
There are substantial differences between the various classes of VI improvers in terms of efficiency, shear stability, solubility, and of course, price. For instance, olefin-copolymer (OCP) and polyisobutylene (PIB) VI improvers have nowadays become a "plain-vanilla" type of VI improvement technology, with a primary focus on value-engineered products, while styrenic and polyalkyl methacrylate (PAMA) VI improvers are increasingly used in top-tier products. This fact proves that the viscosity data referred to in the SAE J300 still do not paint the whole picture: you can match all four viscosity readings and still see differences in product performance. This is because conventional viscometry says nothing about, for instance, chemical stability of VII molecules, their possible interactions with other ingredients of lubricant formulations, their effect on the extensional rheology of oil, which is essential for splash lubrication, or non-Newtonian rheological behaviour of polymer-containing lubricant films, which has an effect on oil film strength and lubricity.

Even though the theoretical understanding of the VII action of various polymer classes and their effect on the lubricant tribology has advanced enormously, experience remains the best teacher in this largely empirical field.

Nowadays, thinner oils are actively promoted to improve fuel economy. Keep in mind, however, that in a running engine, crankcase lubricant is always to some extent "diluted" by fuel. The degree of fuel dilution depends on the engine type and driving conditions. Stop-and-go city traffic is one adverse scenario most people are not even aware of. In the worst cases, oil may contain as much as 10-15% of fuel. Another adverse scenario is high-speed driving, such as stock car racing, where rich air-fuel mixtures are deliberately used to cool engines.

As a result of fuel dilution, motor oil easily goes one grade down: you start with a 5W-30 oil and soon find it diluted to a 5W-20 level. Oil also becomes thinner when the engine is heavily loaded and runs hot, for instance, while towing a trailer.

Some manufacturers tend to incorporate a greater safely margin in their formulations, setting the v100 target just in the middle of the respective viscosity grade and HTHS well above the permissible minimum value. Others try to push their products to the edge to max up fuel economy benefits. For instance, a 5W-40 with KV100 = 14.5 cSt will withstand 4-5% fuel dilution without falling off grade. A similar 5W-40 "enhanced fuel-economy" product with KV100 = 13.0 cSt will fall off grade already at 2% fuel dilution. Hence, in general, you are always safe to go one grade higher than the one recommended by your engine manufacturer, but never use thinner oils than recommended.



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www.bizol.com

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[i] *B. Zhmud, Motor oil, fuel economy, and real driving emissions in the era of E-mobility, STLE Annual Meeting & Exhibition, Nashville, USE, May 19-22, 2019.*

[ii] *B. Tatievski, B. Zhmud, "Fuel Economy Engine Oils: Scientific Rationale and Controversies", in Proc. 20th International Colloquium Tribology, Stuttgart, Germany, January 12-14, 2016.*