“Engine Lubricant Trends Since 1990 ”

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Acronyms

AAM: Alliance Automobile Manufacturers

ACC: American Chemical Council

ACEA: Association des Constucteurs Europeéns d'Automobiles

API: American Petroleum Institute

ASTM: American Society for Testing and Materials

ATC: Technical Committee of Petroleum Additive Manufacturers in Europe

ATIEL: Association Technique de l'Industrie Européenne des Lubrifiants

CAFE : Corporate Average Fuel Economy

CEC: Co-ordinating European Council for the Development of Performance Tests for Lubricants and Engine Fuels

CMA: Chemical Manufacturers Association (USA)

EELQMS: European Engine Lubricants Quality Monitoring System

EGR: Exhaust Gas Recirculation

EMA: Engine Manufacturers Association

EU: European Union

FEI: Fuel Economy Improvement

HDEO: Heavy duty engine oil

HDEOCP: Heavy-Duty Engine Oil Classification Panel

ILMA: Independent Lubricant Manufacturers Association

ILSAC: International Lubricant Specification and Approval Committee

JAMA: Japan Automobile Manufacturers Association

JASO: Japan Automobile Standards Organisation

JPI : Japanese Petroleum Institute

JSAE : Japan Society of Automotive Engineers

METI: Ministry of Economy Trade and Industry

OEM: Original Equipment Manufacturer

NOACK: This is the name of the evaporative test equipment used for determining oil volatility

PAJ: Petroleum Association Japan

PCEOCP: Passenger Car Engine Oil Classification Panel

PCMO: Passenger car motor oil

SAE: Society of Automotive Engineers

STLE: Society of Tribologists and Lubrication Engineers

TEOST: Thermo-Oxidation Engine Oil Simulation Test

Abstract

A review is undertaken of the important trends in engine lubricants that have taken place over the last 10-15 years. Lubricant formulations are driven by industry standard specifications, OEM requirements, and consumer needs. A review is given of the important specifications, and how these have impacted on lubricant development. The key trends are: (1) the need for improved fuel economy, (2) the need for improved oxidation stability, (3) the need for improved handling of contaminants (e.g. soot), and (4) the recent move to lubricants containing low levels of sulphur, phosphorus, and sulphated ash, for aftertreatment device compatibility reasons.

Introduction

Engine lubricant formulations change in response to changing industry standard specifications, OEM requirements and consumer needs. Industry standard specifications are often driven by legislation (in particular, legislation on vehicle emissions), which usually requires new engine technologies to be introduced. When new technologies place particular challenges on lubricant formulation, these new technologies often appear as engine tests in industry standard specifications. Industry standard specifications are set by ACEA in Europe[1,2] (although individual tests within a specification sequence are developed by CEC). In the USA, the API sets specification requirements[3] (and individual tests with the specification sequence are developed by the ASTM). In Japan the lubricant specification body is JASO. Lubricant marketers are free to choose the mix of specifications that their products meet, whether their products just meet the specifications or exceed them greatly, and are also free to develop products which meet consumer needs that are not explicitly covered by industry standard specifications.

The regional specification standards bodies (ACEA, API, JASO) are now also starting to develop global lubricant specifications. ILSAC sets specification standards that are mainly used in the US and Japan (e.g. ILSAC GF-4). Global specifications are in place for heavy duty diesel engine lubricants (DHD-1, DHD-2 and the proposed DHD-2). The whole process of developing new specifications is complex, and an attempt is made to explain the current situation in Appendix One. A good overview is also given by Caines & Haycock[4].

Since 1990, the main trends in lubricant formulation have been:

- A requirement for improved oxidative stability (for controlling deposit formation, minimising sludge formation, ensuring viscosity is controlled) as oil drain intervals and engine power outputs (and hence oil temperatures) have trended upwards.

- A requirement for improved fuel economy performance (this has been driven by legislative controls, such as CAFE in the USA, and the CO_2 emission limits that the EU has mandated for introduction in 2008 – there are also fuel economy engine tests in ILSAC and ACEA lubricant specification sequences which will be considered in more detail later).
- A requirement for improved soot handling capabilities for heavy duty diesel engine oils. Increasingly stringent legislative limits on NO_x emissions have led to increased lubricant soot levels, and since 1990 there has been a need to improve the soot handling capabilities of these oils. In Europe and the US this has led to increased dispersancy levels in the oil.
- A requirement for reduced vehicle emissions. The need for reduced tailpipe emissions from vehicles has led to the widespread introduction of aftertreatment devices (eg catalytic converters) for passenger car vehicles, and this trend is expected to spread to heavy duty diesel engines over the next few years. The OEMs clearly want lubricants to be compatible with these increasingly sophisticated devices. Currently there is much debate on whether chemical limits should be imposed on lubricant formulations to limit the amount of sulphur, phosphorus, and sulphated ash. Note that since one of the most important antiwear additives contains both sulphur, phosphorus, and contributes to the sulphated ash level, there are some interesting formulation challenges to meet these chemical limits whilst still ensuring satisfactory lubrication performance.
- A requirement for new improved additives and base oil technologies. New additive and base oil technology clearly impacts lubricant formulation – for example the appearance of Group II base oils in the US in the 1990's enabled fuel economy lubricants to be formulated at a cost effective level. Towards the latter part of this decade, the expected appearance of Gas-to-Liquid base oils will be significant for the widespread production of low sulphur lubricants.

These trends will be considered in more detail below, and where appropriate the evolution of engine tests since 1990 will be described, together with the improved lubricant performance these tests have necessitated. Some of the future challenges are also discussed.

Oxidation Stability

Engine lubricants consist predominantly of base oil (depending on performance level the base oil content will be 80-95% of the lubricant) with the remainder being lubricant additives (5-20%)[5,6]. Since the lubricant can stay in the vehicle for a long time period (a minimum of 3 months in the US, and from 6 months to 2 years for a passenger car in Europe) and operates at elevated temperatures (sump temperatures can be as high as 130°C in a passenger car under high load operation – eg towing a caravan up a steep hill - and piston temperatures can be 250°C or higher) in the presence of aggressive gases (combustion gases, NOx, high pressures etc) the lubricant formulator needs to ensure that oxidation is controlled. Figure 1 shows schematically the process of lubricant oxidation.

The base oil, which is predominantly a branched hydrocarbon, produces ketones, alcohols, esters, and (mostly) acids during the oxidation process. It is also possible that higher molecular weight products are formed by polymerisation. These oxidised products are thought to be responsible for the change in viscosity during an oil drain interval – large viscosity increases are observed when the antioxidants in a lubricant are used up. In addition to viscosity increases, the oxidation products can become precursors for sludge and deposits. Since acids are formed during the oxidation process, the Total Acid Number (TAN) of an oil will also increase as oxidation progresses. The increased acid content of the lubricant can lead to bearing corrosion. Since acids form during lubricant oxidation, the fresh lubricant contains a certain amount of “base”, which is included for the neutralisation of any acid products that are formed during oxidation. This is quantified using the Total Base Number (TBN).

Figure 2 shows the typical effects of lubricant oxidation[7] (in terms of viscosity increase, Total Base Number (TBN) decrease and TAN increase).

Since 1990, specific power outputs of engines have increased and oil drain intervals have increased. Therefore there has been a need for better antioxidant performance in engine lubricants for these reasons alone, which is why industry standard specifications are requiring improved oxidation performance. An "oil stress factor", OSF may be defined[8]. The usual definition of such an oil stress factor is:

$$OSF = \left(\frac{P}{V_D}\right)\left(\frac{ODI}{V_S}\right) \qquad \ldots(1)$$

where P is the engine power (kW), V_D is the engine displacement (litres), ODI is the oil drain interval (km) and V_S is the volume of lubricant in the sump (litres). The "oil stress factor" thus has units of kW.km/litre^2. (Note that alternative oil stress factor equations are also used, some of which take account of oil consumption rates.)

Using the above definition of oil stress factor, Figure 3 shows schematically the way in which the oil stress factor has increased over recent years. (Note that this figure is for European gasoline passenger cars, with high performing sports cars omitted.)

Figure 4 shows that one of the side effects of increased antioxidancy in passenger car engine lubricants (in response to oil specification tests and increased oil stress factors) has been, in general, cleaner engines.

There are industry standard tests designed to assess: viscosity increase of oxidised oil[9,10]; sludge formation in engines[11,12]; deposit formation and piston cleanliness[13]; acid corrosion. There are also limits on the volatility of the oil (as measured using the NOACK volatility test), which impact on the base oils which may be used (clearly if the oil is too volatile a large fraction of the lubricant could evaporate, which is undesirable).

The relevant industry standard engine tests are:

- The Sequence IIIF Engine Test[9] for viscosity increases dues to oxidation, and also deposits and piston cleanliness, cam wear and oil consumption. The test uses a 1996 Buick V6 gasoline engine, with a displacement of 3.8 litres. The test duration is 80 hours. The test uses unleaded fuel, and the sump oil temperature is 155°C. The lubricant viscosity increase (this is the increase in kinematic viscosity as measured at 40°C) has to be less than 275% for passing performance. In this test piston skirt varnish and weighted piston deposits are rated, cam and lifter wear and oil consumption are also measured (there are pass/fail limits on each of these factors. This test is used in ILSAC GF-3 and API SL specifications. Note that for ILSAC GF-2/API SJ, the Sequence IIIE engine test was used – this test was for a duration of 64 hours and pass/fail limits for the viscosity increase was 375%. Clearly the increased duration of the current test, and the tightened limits, require improved oxidation performance of the lubricant. In combination with the MHT-4 TEOST test (see below) this more stringent performance requirement has led to engine lubricants requiring higher quality base oils and/or substantial increases in antioxidant levels – by as much as 50-75%. In ILSAC GF-4, the Sequence IIIG engine test is used, and in this test the pass/fail limit on the lubricant viscosity increase (increase in V_k40) has been tightened even further to just 150%.
- In Europe, the CEC uses a pressure differential scanning calorimeter (PDSC) test[14] (the test method is CEC-L-85-T-99) for assessing lubricant oxidation. In this laboratory test the

oxidation induction time of the lubricant is measured. Conditions are: 100 psi air, no flow, 40°C for 2 minutes, 40-50°C at 5°C per minute, 50°C for 5 minutes, 50-210°C at 40°C per minute, 210°C isothermal for 120 minutes, aluminium sample pans are used, and the sample weight is 3.0±0.5 mg. Samples generally give an oxidation plot with a primary and secondary peak. The onset time for the primary peak is recorded as the oxidation induction time. For ACEA E5-02 performance this oxidation induction time has to be greater than 35 minutes.

- The Sequence VG Engine Test[11]: This test evaluates the lubricant performance in combating sludge and varnish formation under low temperature conditions (eg such as those found in "stop-go" driving cycles). The test uses a Ford 4.6 litre V8 gasoline engine (this engine is also used for US fuel economy tests) and is run for 216 hours for a range of engine speeds and loads, with the sump oil temperature varying between 45 and 100°C.
- In Europe the CEC use the Mercedes Benz M111 sludge test[12] (this engine is also used for the European fuel economy engine test). This is a test for black sludge. The engine is a 2.0 litre gasoline engine, test duration is 224 hours, engine speed varies from 750-6000 rpm, load varies from 0 to maximum, and the oil temperature varies from 37-140°C. The test method is CEC-L-53-T-95.
- For high temperature deposit formation, the TEOST MHT-4 bench test is used[15]. In this test, the amount of deposits (in mg) formed in a laboratory glassware test are assessed. For the current specification (ILSAC GF-4) the pass/fail limit is 35 mg whereas for ILSAC GF-3/API SL the pass/fail limit was 45 mg maximum. There has been some debate as to the correlation of this test to field performance – whatever the merits, the test does impact on lubricant formulation.
- In Europe, the Peugeot TU3 and TU5 tests have been used to evaluate piston deposits, ring sticking tendency and viscosity increase of lubricants (for gasoline engine oils)[10]. The TU3 engine test uses a 1.36 litre 4 cylinder single point injection (SPI) engine, the test duration is

100 hours and the oil temperature varies between 40-100°C. The TU5 test uses a 1.6 litre 4 cylinder multipoint injection (MPI) engine, with a test duration of 96 hours, and an oil temperature of 80-150°C.

- A large number of European tests are in place for assessing diesel engine oil performance (both heavy duty and passenger car diesel engines). The OM364LA test is used to look at bore polishing, piston deposits, sludge, liner wear and oil consumption (uses a DaimlerChrysler OM364LA engine – the test method is CEC-L-42-T-99). The OM602A test is used to look at cam wear, viscosity increase, bore polishing, cylinder wear, sludge and oil consumption (uses a DaimlerChrysler OM602A engine – the test method is CEC-L-51-T-98). The OM441 LA test is used to look at piston deposits, bore polishing, wear, oil consumption, valve train condition, and turbocharger deposits (uses a DaimlerChrysler OM441LA engine – the test method is CEC-L-52-T-97). The Peugeot XUD-11 test is used for assessing lubricant related piston deposits and viscosity increases (the test uses a 4 cylinder IDI, T/C, I/C 2.0 litre diesel engine – the test method is CEC-L-56-T-99), The VW 1431 test is used for piston deposits, varnish and ring sticking (the test uses a 4 cylinder T/C, I/C 1.6 litre engine – the test method is CEC-L-46-T-93). The VW 1453 test is used for piston deposits, ring sticking, and viscosity increase (the test uses a 4 cylinder T/C, I/C 1.9 litre engine – the test method is CEC-L-78-T-97 (or T-99)).
- For bearing corrosion protection, ILSAC GF-4 uses the Sequence VIII test. The pass/fail limits for maximum bearing weight loss are 26 mg (this is essentially the same as ILSAC GF-3 where the pass/fail limit was 26.4 mg). In ILSAC GF-2/API SJ specifications, however, the pass/fail limit for maximum bearing weight loss was 40 mg. Therefore the current sequence requires oils with better oxidation stability and increased alkalinity (ie higher Total Base Number (TBN)) compared to preceding sequences.
- In ILSAC GF-3/API SL (and ILSAC GF-4) there is a constraint on lubricant volatility. The volatility (as measured by ASTM D5800 using a NOACK volatility test) must be less than

15%, whereas in ILSAC GF-2/API SJ, the limit was less than 22%. Clearly this change has led to a need to use superior basestocks in lubricant formulations (particularly for the lower viscosity lubricants required for improved fuel economy performance, as discussed later). NOACK volatility limits are also used in ACEA specifications.

In addition to industry standard specifications, OEMs often use the same tests (for their own in-house lubricant specifications, often required for factory fill and service fill lubricants), but may insist on tighter limits. For example, Ford require a double length Sequence IIIF test (160 hours) or a double length IIIE test (128 hours) with a maximum viscosity increase of 200% (the corresponding limits for the single length tests are 275% maximum (IIIF) and 375% maximum (IIIE)). In addition, Ford's limit for high temperature deposits in the TEOST MHT-4 test is 30 mg (whilst the ILSAC GF-4 limit is 35 mg). Honda also required double length IIIF or IIIE tests, but in their case the maximum viscosity increase is pegged at the same level as the single length tests (275% and 375% respectively). Clearly, oils meeting the Ford requirement exceed the antioxidant requirement for minimum performance in ILSAC GF-3/API SL (and will require the use of high quality basestocks and increased antioxidant treat rates).

Finally we consider fuel sulphur levels. If fuel sulphur levels are very high (eg > 500 ppm) then there can be a detrimental effect on lubrication (in fact the API have specifications for lubricants which are used with high sulphur fuels – API CF). However, fuels with very low levels of sulphur can also cause problems. In Europe, fuel sulphur levels are currently set at 50 ppm, but there will be a move to 10 ppm levels later this decade (some EU countries are already at this level). The US is also moving to low sulphur fuel - by 1997, 95% of fuel in the US will be at the 15 ppm sulphur level, and all fuel in the US will be at this level by 2010. Sulphur in fuel can help a lubricant's antioxidancy, and reduced fuel sulphur levels can also cause lubricity problems in fuel pumps.

Clearly, the fuel and lubricant do interact with each other, although the precise mechanisms are not well understood.

Fuel Economy

The desire for countries and automotive manufacturers to reduce emissions includes CO_2 emissions that arise from burning fuel in internal combustion engines. There is a direct correlation between a vehicle's fuel consumption and the CO_2 emitted from that vehicle. The EU have set a "voluntary" target that the fleet average CO_2 emissions for manufacturers selling vehicles in Europe must be lower than 140 g/km by 2008 (this is about 25% lower than current levels). Many countries have also expressed a desire to reduce their CO_2 emissions by signing the Kyoto Agreement. Since one of the main sources of CO_2 emissions arise from the transport sector, improved fuel economy is a major target of many OEMs[16-19]. In the US, there are Corporate Average Fuel Economy (CAFE) targets that an OEM must meet, averaged over their entire fleet. The fuel consumption of a vehicle depends amongst other things on the friction that must be overcome in the engine[20-26]. Clearly this is affected by the engine design. However, friction in the engine can also be affected by lubricant viscosity. If we denote the lubricant (dynamic) viscosity by η (mPa.s), then for those parts of the engine that are lubricated hydrodynamically (this is where an oil film completely separates the moving metal surfaces) the friction varies as $\sqrt{\eta}$. For parts of the engine where there is boundary lubrication (eg the valve train) the metal surfaces can touch, and the use of surface active "friction modifier" additives (such as molybdenum dithiocarbamate, MoDTC, or organic based friction modifiers such as glycerol mono-oleates) can significantly reduce friction in these areas. Therefore, the requirement for improved fuel economy has led to lower viscosity lubricants containing friction modifier additives.

Table 1 shows typical viscosities for different lubricant SAE viscosity grades (note that the viscosity grade assigned to a lubricant is determined by SAE J300[27]).

SAE Viscosity Grade	V_k40 (cSt)	V_k100 (cSt)	Estimated dynamic viscosity at –15°C (mPa.s)
SAE 30	91.3	10.8	3950
SAE 20W-50	144.8	17.8	5870
SAE 15W-40	114.3	14.9	2940
SAE 10W-30	72.3	10.8	1900
SAE 5W-30	57.4	9.9	1090
SAE 0W-20	44.4	8.3	690

Table 1: Typical viscosities of commonly available lubricants (as classified by the Society of Automotive Engineers (SAE) J300 classification system).

In 1990 the most common viscosity grade was SAE 15W-40. This is probably still true today, on a global basis. However, an increasing proportion of SAE 5W-30 and SAE 5W-20 grades are now available in the US (SAE 5W-20 is the recommended viscosity grade for new Ford vehicles in the US, whereas the recommended viscosity grade in Europe is SAE 5W-30). Clearly these lower viscosity grades have significantly lower viscosity compared to an SAE 15W-40 lubricant. In Japan, some OEMs are now using SAE 0W-20 lubricants as factory fill oils for new vehicles. In the US and Japan the main driving force leading to lower viscosity lubricants has been the ILSAC GF-2, GF-3 and GF-4 fuel economy engine test. In Europe, since 1990 there has been a trend towards 0W (and 5W) grade lubricants (to give fuel economy benefits at low temperatures) whilst at the same time having a 30 or 40 grade specification at high temperatures (so as to give a sufficiently thick oil film under high temperature conditions). For example, VW specify SAE 0W-30 lubricants as their preferred viscosity grade.

According to SAE J300, the minimum high temperature high shear viscosity (HTHSV, in mPa.s, evaluated at a temperature of 150°C and a shear rate of 10^6 s-1) is 2.6 mPa.s for xW-20 grades, is 2.9 mPa.s for xW-30 grades (and also for 0W-40, 5W-40 and 10W-40 grades) and is 3.7 mPa.s for 15W-40, 20W-40, 25W-40, 40 grades, and also for xW-50 and xW-60 grades. (Note that for xW-10 grades there is no minimum HTHSV value defined). For ILSAC GF-3 (and also for the proposed

ILSAC GF-4 sequence) the only allowed viscosity grades are SAE 0W-20, SAE 5W-20, SAE 5W-30, SAE 0W-30 and SAE 10W-30 (note there are no such viscosity grade restrictions for API SL). ACEA also use the SAE J300 viscosity classification, but allow HTHS viscosities to be as low as 3.5 mPa.s (rather than the 3.7 mPa.s specified for the relevant viscosity grades in SAE J300).

In terms of engine tests, the first US fuel economy engine test was the Sequence VI test. This used an engine with a sliding valve train system (ie the cam slid against the follower). The test "appetite" was found to be that lower viscosity lubricants gave improved fuel economy, and friction modifiers were also important. The fuel economy improvement of candidate oils was evaluated against a 20W-30 ASTM HR reference oil. Following this, the Sequence VI-A engine test was introduced (used in ILSAC GF-2). This used a Ford 4.6 litre V8 gasoline engine (the same engine as used for the Sequence VG sludge test). The engine had a roller follower valve train system (ie the cam contacted a roller, and for the majority of operation the contact was rolling, rather than sliding). This engine was found to have an appetite for lower viscosities, but the use of a roller follower valve train meant that there was very little boundary friction in the engine, and so friction modifiers only had a small effect on fuel economy. The Sequence VI-B engine test[28] used the same engine as for the Sequence VI-A test, but operating conditions were modified to increase the proportion of boundary friction. However, the predominant way to improve fuel economy in this test is simply to reduce lubricant viscosity. For the Sequence VI-B test, the fuel economy of the test lubricant was evaluated under both "fresh" and "used" conditions (the Sequence VI-A test just measured the fuel economy benefit of the fresh lubricant). The lubricant was aged in the engine for the equivalent of 5000 miles (which is typical of a US oil drain interval), when the fuel economy of the aged oil was once again measured. The Sequence VI-B fuel economy engine test is used in both ILSAC GF-3 and GF-4.

Table 2 shows the pass/fail limits for the Sequence VI-A (for GF-2 specification) and Sequence VI-B engine tests (for both GF-3 and GF-4 specifications. Clearly, there has been a requirement for improved fuel economy performance each time the specification has been upgraded.

Viscosity grade	FEI
SAE 0W-20 SAE 5W-20	1.4% min
All other SAE 0W-x & SAE 5W-x	1.1% min
SAE 10W-x	0.5% min

Sequence VI-A pass/fail limits, as used in ILSAC GF-2

Viscosity grade	FEI1 (16 hours)	FEI2 (96 hours)
SAE 0W-20 SAE 5W-20	2.0% min	1.7% min
SAE 0W-30 SAE 5W-30	1.6% min	1.3% min
	FEI1+FEI2 ≥ 3.0%	
SAE 10W-30 and Higher	0.9% min	0.6% min
	FEI1+FEI2 ≥ 1.6%	

Sequence VI-B pass/fail limits, as used in ILSAC GF-3

Viscosity grade	FEI1 (16 hours)	FEI2 (96 hours)
SAE 0W-20 SAE 5W-20	2.3% min	2.0% min
SAE 0W-30 SAE 5W-30	1.8% min	1.5% min
SAE 10W-30 and Other grades not above	1.1% min	0.8% min

Sequence VI-B pass/fail limits, as used in ILSAC GF-4

Table 3: Pass/fail limits for the VI-A (ILSAC GF-2) and VI-B (ILSAC GF-3 and GF-4) tests. Fuel economy improvement (FEI, %) in the tests are evaluated relative to the ASTM Reference oil BC

In Europe, the Mercedes Benz M111 engine is used for the fuel economy test[29]. The test duration is 24 hours, and a combined ECE-15 (4 cycles) + EUDC driving cycle is used (Figure 5). The oil temperatures in the test are 20°C, 33°C and 75°C. No aged oil fuel economy measurement is carried out. The fuel consumption of the test oil is compared with a standard reference oil, RL-191 (an SAE 15W-40 lubricant with a HTHSV of 3.9 mPa.s). The pass/fail limit is 2.5%. It is found that this engine has both a pronounced viscosity and friction modifier effect – it is not possible to pass this test without a friction modifier for oils whose HTHSV is greater than 2.6 mPa.s.

An attempt was made recently by the CEC to develop a fuel economy engine test for aged oil fuel economy (the CEC TDG-L-089 Test Development Group)[30]. The proposed test used a Ford Duratorq 2.0 litre passenger car diesel engine using an ageing cycle that would be representative of 30,000 km of European driving. The Test Development Group found that the fuel economy evaluated in the test (compared to various reference lubricants) was linearly dependent on HTHSV, and the role of friction modifiers was found to be small (this contrasts with the M111 fuel economy test where friction modifiers are found to have a significant effect). In light of these results, no new test was introduced and the Group recommended that improved fuel economy may be achieved in this engine by simply using lubricants with lower HTHS viscosities.

In addition to bench tests, fuel economy lubricants are also evaluated on vehicles running on chassis dynamometers, running on standard driving cycles. In Europe, VW use the driving cycle shown in Figure 5, but the oil temperature at start-up is -7°C (the VW PV1451 fuel economy test). Other OEMs, eg DC, also use the same cycle but with a starting oil temperature of around 20°C. In Japan, the driving cycles are similar to the European cycles. The Japanese 11 mode cycle uses a cold start (oil temperature at start-up is around 25°C) and is used to simulate urban driving conditions, whereas the 10-15 mode cycle is used for a fully warmed up engine (sump oil temperature is approximately 100°C) and attempts to simulated urban and higher speed driving cycles. Both these driving cycles are illustrated in Figure 6.

In the US, the Federal Standard Urban Driving Cycle and the Federal Standard Highway Driving Cycle are available for use. These are more highly transient than the European and Japanese driving cycles and so will have a proportionately high fuel consumption (although they may be more realistic of real driving conditions). These driving cycles are shown in Figure 7.

An attempt has also been made by the CEC to develop a fuel economy test for heavy duty trucks (the CEC IL-87 Heavy Duty Diesel Fuel Economy Group). The Group concluded that the scope for fuel economy improvement in heavy duty diesel engines, by changing the lubricant, is small but measurable. The Group concluded that the main constraint on using lubricants to improve the fuel economy performance is ACEA's insistence that the HTHSV of heavy duty diesel engine lubricants should be greater than 3.5 mPa.s. The Group concluded that with this limit in place, it was unlikely that a bench test could be developed which had adequate reproducibility for general industry use. The Group also concluded that it would be useful if Recommended Codes of Practice were introduced, for operators who wished to conduct valid fuel economy field trials (along the lines of US guidelines for running fuel economy field trials using trucks issued by the US Truck Maintenance Council).

In terms of what impact these fuel economy tests have had on lubricants, Taylor[22] has concluded that, for the USA, the appetite of the Sequence VI-B engine test has led to the following formulation trends: A move to lower viscosity grades (SAE 5W-20 etc); The use of shear unstable viscosity modifiers (VM); The use of higher Viscosity Index (VI) basestocks; The use of effective friction modifiers; A move to lower HTHS viscosities (2.6 mPa.s); A move to lower Cold Cranking Simulator (CCS) viscosities .

Since there is a requirement for many European lubricants to achieve longer oil drain intervals than in the US, the additive treat rate tends to be higher than for many US lubricants, and as such it is difficult to formulate a "European style" long oil drain interval lubricant that also performs well in US fuel economy tests.

There is also a constraint on lubricant volatility (as measured by NOACK) in API and ACEA specifications, and so the move to lower viscosity lubricants has meant a shift towards higher quality basestocks. In the US, SAE 5W-x fuel economy grades are predominantly formulated using Group II basestocks. In Europe, 0W-x grade lubricants are formulated using polyalphaolefins (PAO). The choice of basestock clearly influences the final price of the product (PAOs are considerably more expensive than Group II basestocks).

Heavy Duty Diesel Engine Oil Soot Control

Increasingly stringent emissions legislation was introduced in the USA and Europe during the 1990's. This has resulted in radical changes in heavy duty diesel engine design, which in turn have had a significant impact on the lubricant environment, affecting the relationship between oil formulation, piston deposits, soot dispersion and wear control[31,32]. In particular, tightening of the NO_x legislation led to a widespread retardation of injection timing, which has led to increased levels of soot loading of the engine lubricant, which has been associated with increased wear levels. In addition, the drive for reduced particulate emissions has led to a large reduction in oil consumption levels. Therefore the used oil is likely to be replenished (by "top-up") less often and by smaller amounts. Hence contaminant levels have tended to increase. Increased soot levels in lubricants can lead to: soot induced oil thickening, engine sludge (in the rocker cover and sump), oil filter blocking and reduced cold-start pumpability.

During the 1990's a number of engine tests designed to test the performance of soot loaded lubricants were developed. The basic tests introduced were:

- The Mack T8 test[33] – introduced into the API CG-4 oil performance category, as a test designed to assess an oil's ability to "handle" soot. During this engine test (250 hours for API CG-4 and 300 hours for API CH-4), which uses a 12 litre Mack E7-350 horsepower diesel engine, soot is deliberately accumulated in the lubricant. The engine is overfuelled, with retarded timing of 9.5°, and an engine speed of 1800 rpm. For CG-4, when the soot level reaches 3.8% (by mass), the viscosity of the lubricant is measured, and for a passing result the oil viscosity is required to increase by less than 11.5 cSt (as measured at 100°C). For API CH-4 the same viscosity increase limit is used, together with a relative viscosity increase limit measured at 4.8% soot by mass. The Mack T-8 test led to oils with increased dispersancy and it was also found that a careful choice of base oil was needed in order to ensure passing performance. The Mack T8 test became the Mack T-8E test in CH-4 (the same test but over a longer time (300 hours) and with the viscosity increase evaluated at 4.8% soot level). In API CI-4, the Mack T-8E test is also used but there is a lower allowed relative viscosity increase at 4.8% soot (compared to API CH-4) for passing performance. A Mack T11 test (which uses a low swirl head, and low rates of EGR for 300 hours) is used in MACK EO-N and the new API CI-4 Plus specification that is currently under discussion. The passing criteria of the Mack T-11 test is a maximum viscosity increase of 12 cSt at 6% soot level. The minimum viscosity is defined after 90 cycles in the Kurt Orhahn test. (Most oils that were qualified in the Mack T-8E non-EGR with limits of 4.8% soot would fail the Mack T11 test). API CI-4 oils require even high levels of dispersancy performance than CH-4 or CG-4 oils.

- The GM 6.5 litre roller follower wear test (RFWT) forms part of the US API CG-4, CH-4 and CI-4 diesel oil performance specifications[32,34,35]. A steel tyre rests directly on individual inlet and exhaust cams and rolls over the cam surface throughout the engine's operating cycle. The engine is run at 1000 rpm and high load for 50 hours, and generates 4% of soot. The depth of the wear scar on the axle where it contacts the needle bearings is assessed. Wear has to be controlled to less than 11.4 μm for the oil to satisfy the API CG-4 peformance level. Calculations of the oil film thickness between the needle bearings and the axle, under GM6.5 test conditions, have found values of just 13 nm, much smaller than the surface roughness of the two surfaces, and roughly five times smaller than a typical size soot particle. Therefore it is likely that soot particles in the lubricant which enter the needle bearing/axle contact will make heavy simultaneous contact with the moving surfaces, and perhaps promote high levels of wear.

- The Cummins M11 crosshead wear test forms part of the API CG-4 and CH-4 oil specification tests[32,34]. The crosshead is a component of the Cummins M11 valve train system (each of the inlet and exhaust rocker arms actuate two valves with the load transferred by a simple bridge piece, known as a crosshead). In the M11 engine test the crosshead is weighed before and after each engine test and the weight loss used to assess a sooted oil's wear performance.

Figure 8 gives a visual representation of how a lubricant's performance level (with respect to soot loading) can impact on cleanliness of the rocker cover.

Soot loading levels have increased even more significantly in recent years as legislated NO_x emission have decreased even further, and OEMs have introduced technology such as Exhaust Gas Recirculation (EGR). The latest API CI-4 specification[35] was specifically designed to assess lubricant performance in engines equipped with EGR.

Work is currently ongoing for Proposed Category PC-10[36]. This new category is planned to be in place by 2007 (which is when diesel particulate traps will be required on all US diesel engines). The category aims to approve lubricants which balance after-treatment life with engine durability. In this specification, it is likely that some "chemical limits" will be imposed in addition to engine test requirements (this will be discussed in more detail in the next section).

Aftertreatment Device Compatibility

Over the last decade, legislation on the allowed emissions from vehicle tailpipes has tightened significantly. For passenger car vehicles, the emissions of concern are carbon monoxide, hydrocarbons and nitrogen oxides. Legislation is now so tight that all passenger car gasoline and diesel engines required to meet US, European and Japanese targets will use aftertreatment systems of some sort[37,38]. It should also be mentioned that in the passenger car sector emissions targets do not take any account of vehicle size. Since emission levels increase with vehicle weight, these fixed targets are more demanding for larger vehicles. Therefore “cutting edge” aftertreatment systems will be demanded by these vehicles first.

For heavy duty diesel engines, the main emissions targeted by legislation are particulates and oxides of nitrogen (hydrocarbon (HC) and carbon monoxide (CO) emissions are also limited but at present these are not challenging targets). Aftertreatment systems are not widely used in the heavy duty sector at the present time, but emissions legislation scheduled for introduction in 2005 will force their use.

There are many different aftertreatment device options.

For passenger car vehicles equipped with conventional gasoline engines (i.e. stoichiometrically fired engines), current Three Way Catalysts (TWC) can control HC, CO and NO_x emissions very well. However, these catalysts take time to warm up, and this warming up period is usually indicated by a light. Once the light is off, emissions are controlled to meet legislated limits. It is the emissions that occur during the pre light off period that dominate the total emissions level. Hence the current emphasis is on promoting quick light off, and then ensuring that the catalysts perform well over the lifetime of the vehicle. The target light off time is currently less than 15 seconds. To achieve this, options being explored include: close coupling of catalyst to engine, starter catalysts, heaters etc. For lubricants, there is pressure on the phosphorus content since phosphorus is thought to cause coating of the catalyst, affecting catalyst performance. Increasingly, there is also pressure to reduce sulphur levels in the lubricant, (note that the widespread use of aftertreatment devices in passenger car vehicles has been partly responsible for the introduction of low sulphur fuels in the

US and Europe with fuel sulphur levels less than 50 ppm, and in some parts of Europe less than 10 ppm) and questions are being asked about the contribution of sulphur from the lubricant. For stratified charge gasoline direct injection engines, which operate under ultra lean conditions (i.e. high air/fuel ratios), conventional Three Way Catalysts will not work since the NO_x cannot be reduced due to the oxygen-rich atmosphere. Therefore NO_x emerges at engine out levels considerably in excess of legislated levels. CO and HC control depends largely on the promptness of the light off time. The use of stratified charge engines will only remain viable if aftertreatment systems can be developed which will reduce NO_x to N_2 under essentially oxidising conditions. Options for such aftertreatment devices include (1) Passive NO_x control – whereby HC are accrued on a zeolite substrate during low temperature operation, creating a rich micro climate with appropriate stoichiometry, which are liberated during higher temperature operation to enable reduction of NO_x species. (2) Active NO_x control – NO is converted to NO_2 during lean operation over Pt catalyst. The NO_2 is stored on Barium storage sites embedded on the catalyst substrate, and when the Barium is saturated, the engine switches to rich operation which liberates NO_2, which is reduced in the presence of HC and CO. This is feasible because gasoline engines will run stoichiometrically. Option (1) has no known issues for lubricants – however, efficiencies are low (<30%) and there are other technical problems which makes it unlikely that these systems will see widespread use. Option (2) is complex, but has efficiency levels > 90% - however these systems require low sulphur fuels, and since fuel sulphur levels are low, attention is now being focussed on the lubricant sulphur level.

For light duty and heavy duty diesel vehicles, as mentioned before, the important emissions to control are particulates and NO_x. Unlike passenger car vehicles, emission targets are expressed in units of grams/(brake horsepower.hour), which eliminates any bias towards larger vehicles. There are many more options for aftertreatment devices for heavy duty diesel vehicles. The devices which are "starred" are sensitive to sulphur. To reduce particulate levels there are: oxidation catalysts;

simple traps; Johnson Matthey Continuously Regenerating Trap (CRT)*; Englehard regenerating trap; AEA Electrocat; Delphi NTP (non-thermal plasma). For NO_x reduction, there are the following devices: Passive NOx catalysts; Storage catalysts*; Selective Catalytic Reduction (SCR). There are also some devices which combine more than one of the above options: the Degussa GD-KAT*; Johnson Matthey SRT*.

Particulate traps are made of cordierite material with porous walls. The device can be thought of as a large number of drinking straws, which have porous walls. Half of the "straws" are open at the inlet end, and closed at the outlet end, whereas the other half are closed at the inlet end and open at the outlet end. Exhaust gases enter the device, and the gas has to diffuse through the walls before it can escape. Any particulates do not diffuse through the wall, and are kept within the trap. Clearly, the particulate trap will eventually become blocked (the engine back pressure can be monitored to give warning of when the trap is becoming blocked). These devices are effective at trapping particulates. However, it is clear that these devices may be sensitive to the amount of sulphated ash present in the lubricant. In practice, these devices will also need to regenerated quickly and relatively cheaply when they become blocked.

The Johnson Matthey Continuously Regenerating Trap (CRT) is a commercially available system that removes CO, HC and particulates. This device requires ultra low sulphur fuel to operate effectively. This device has been in widespread used in Scandinavian countries where low sulphur fuel is readily available. The device can be fitted to both new and old engines. The device captures lubricant ash, but the accumulation of ash in the device is not sufficient to cause a rise in back pressure. After every 100,000 km, the trap is simply turned around, and this clears ash out of the system. These devices have been used successfully in Scandinavia, on trucks using standard lubricants.

For NO_x reduction, the Siemens SCR (Selective Catalytic Reduction) SiNO_x system uses urea to remove NO_x from the exhaust gas. The main issue for this system is that a separate tank of urea is needed on the truck (the specific urea consumption amounts to about 4% of fuel consumption). Also there clearly needs to be an infrastructure to ensure the supply of urea. A urea tank of 45 litres would have a range of roughly 3000 km. This route is preferred by European OEMs. This system does not require the use of low sulphur lubricants, but there may be issues arising from the need to provide a urea infrastructure to customers, and how urea is handled.

The Degussa GD-KAT is a combined particulate and NO_x control device. It consists of a Pre-cat, (which reduces CO, HC and particulates) a Hydrolysis cat (which removes some NO_x), a Reduction cat (which removes more NO_x) and an Oxidation cat (which removes NH_3 – produced from the use of urea in the Hydrolysis cat).

In conclusion, there are a large number of aftertreatment options for passenger car and commercial vehicles. Some of these systems are thought to be sensitive to lubricant sulphur level and lubricant sulphated ash level[39,40]. In addition, for Three Way Catalysts (TWC) used on conventional gasoline engines, there is evidence that phosphorus from the lubricant forms a coating on the catalyst. However, direct links between these inferred sensitivities and a reduction in aftertreatment systems performance have not yet been made.

Despite this, in forthcoming industry standard lubricant specifications, chemical limits for sulphur, phosphorus and sulphated ash are being discussed.

In ILSAC GF-4, for example, the following limits are used:

	Phosphorus limit (% mass)	Sulphur limit (% mass)
All grades	0.06 min, 0.08 max	-
0W, 5W grades	-	0.5% max
10W grades	-	0.7% max

Table 4 : Chemical limits for ILSAC GF-4 (introduced in January 2004)

Note that in Table 4, there is both a minimum phosphorus limit, and a maximum. Some OEMs, during the ILSAC GF-4 negotiation process, wanted a minimum limit to ensure maintenance of engine durability.

For ACEA E6–2004, and JASO DH-2, Table 5 gives the limits on sulphated ash, phosphorus and sulphur that have been imposed for engine oils used with exhaust after-treatment system.

	ACEA E6	JASO DH-2
% Sulphated Ash	1.0	1.0
% Phosphorus	0.08	0.12
% Sulphur	0.3	0.5

Table 5: Chemical limits (maximum values) on sulphated ash, phosphorus and sulphur for ACEA E6 and JASO DH-2 engine lubricants

Clearly, there is some conflict between the chemical limits that may be imposed for aftertreatment compatibility and the lubrication demands of modern engines. For good antiwear performance, the most cost effective and reliable additive is ZDTP (zinc dialkyl dithiophosphate) which contains both ash, sulphur and phosphorus. For heavy duty diesel engines equipped with EGR (Exhaust Gas Recirculation), oils with higher Total Base Number (TBN) are needed to neutralise the strong acids that are likely to be formed – most additives used to increase TBN will contribute to the lubricant sulphated ash level. For long oil drain intervals, both for passenger car and heavy duty vehicles, increased levels of dispersant and detergent will be needed, the latter contributing to ash levels. In addition, of course, at present most base oils contain sulphur. There is currently great activity ongoing to find low sulphur, low phosphorus and low sulphated ash additives which give good antiwear performance, and good dispersancy/detergency performance.

The other major issue is that most industry standard specifications assume that an oil which meets the latest specification is "backward compatible" with previous specifications. If chemical limits are imposed, it is almost inevitable that they will be tightened in the future in line with emissions legislation limits. There may come a point at which backward compatibility may not be possible, which would mean different lubricants depending on the engine and aftertreatment technology.

The Impact of New Base Oil and Additive Technologies

Whilst lubricant performance requirements, as dictated by specification tests, have changed over the last 15 years, so have the range of base oils and additives that are available to the lubricant formulator.

Many US ILSAC GF-3 lubricants made use of Group II base oils. These base oils had the right mix of volatility and viscosity grade to formulate fuel economy lubricants for ILSAC GF-3. These base oils are manufactured by the further hydroprocessing of conventional base oils

In the future, there is the prospect of large volumes of zero sulphur, low volatility base stocks manufactured from gas[41]. These "Gas-to-Liquid" base oils may enable some of the sulphur limits to be met for future passenger car and heavy duty diesel vehicles. (These base oils are likely to have VI's in excess of 130, pour points lower than -40°C and volatilities (as measured by NOACK) less than 10%).

In addition to base oil developments, many new additives have been used over the last 15 years. For fuel economy applications, MoDTC has been widely used as a friction modifier. More recently, however, there has been a move to organic friction modifiers (since they will not contribute to the sulphated ash level of the lubricant) such as GMO (glycerol mono-oleate).

New dispersant PMA (polymethacrylate) viscosity modifiers have appeared[42], which appear to be surface active VI improvers, and these additives have found use in some engine oil applications.

Clearly, in light of the chemical limits that are being proposed for future lubricant specifications, there is much activity ongoing to develop low ash, low sulphur and low phosphorus containing additives[43,44] (especially anti-wear and friction modifier additives).

Future Challenges

The major challenge for the future will be to continue to develop lubricants which adequately lubricate engines with higher power outputs, operating at higher temperatures, with longer oil drain intervals, and which are compatible with aftertreatment devices.

As mentioned previously, compatibility with aftertreatment devices is currently being addressed by chemical limits being placed on sulphur, phosphorus, and sulphated ash. Lubricants which may meet future specifications, which meet these chemical limits, may also need to be backward compatible with older vehicles. This will become an increasingly difficult challenge when chemical limits are tightened.

Conclusions

The main trends in engine lubricants over the last 10-15 years have been elucidated. We have emphasized the requirement for lubricants with better antioxidancy, better dispersancy and detergency, improved fuel economy performance and which are compatible with aftertreatment devices.

These requirements are checked with appropriate industry standard (and OEM) engine and bench tests. Today's lubricants perform at a far higher level than those of 10-15 years ago.

At the same time, it should be noted that the most modern technology only represents a small fraction of the passenger car and truck parc. It is necessary not just to adequately lubricate new technology, but also the older technology engines which are still on the road. For this reason, the ability for lubricants which meet new specifications to also be backward compatible with older specifications is extremely important, and it will be a challenge to continue to do this if and when chemical limits on sulphur, phosphorus and sulphated ash (designed for the protection of aftertreatment devices) are tightened.

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Appendix One: Lubricant Specifications

Europe

Figure A1 illustrates schematically the European Industry Structure for developing lubricant specification tests.

The Coordinating European Council (CEC) develops specific lubricant test procedures, taking inputs from lubricant marketers (represented by ATIEL), additive companies (represented by the ATC), and automobile and truck manufacturers (represented by ACEA).

CEC develops and maintains performance tests which permit the development of engine fluids – fuels, lubricants and coolants. Tests for crankcase lubricants are developed for use within the ACEA sequences and are required to satisfy stringent statistical criteria related to their use.

ACEA, ATIEL and the ATC are collectively known as the "AAA". The AAA meet to debate the need and shape of future ACEA oil performance specifications. PCMO and HDEO threads are handled in parallel task forces. All three trade groups speak through spokesmen and strive to present pre-agreed positions developed within their own organisations. Attendance is limited and determined by agreement within each trade group. There is no formal voting system – agreement is reached by discussion, with ACEA holding the upper hand. Meetings take place at quarterly intervals.

ACEA oil performance standards are ensured via EELQMS (the European Engine Lubricants Quality Monitoring System). This is a voluntary system entered into by "reputable or responsible" oil marketers and additive companies. EELQMS has two significant parts: the ATIEL and ATC Codes of Practice which govern the way test programmes supporting ACEA oil performance claims must be organised, recorded and reported. Both codes are maintained to ensure that the rules remain consistent with the current suite of tests.

Within ATIEL, ATC and ACEA, each trade group contains several task forces and committees which debate and develop strategic positions on current topics. These positions are then used in dialogue between AAA and other external bodies. Current topics of mutual interest include: Base oil sulphur and aftertreatment compatibility, base oil interchange and viscosity grade read across, the structure of legacy and future ACEA sequences, the shape and scope of CEC, and waste oils.

There are three ACEA Sequences meeting the needs of gasoline, light duty diesel (LDD) and heavy duty diesel (HDD) engines. Within each Sequence are several Performance Categories meeting different performance needs. Table A1 summarises these performance categories.

Gasoline	LDD	HDD
A1	B1	-
A2	B2	E2
A3	B3	E3
(A4)	B4	E4
A5	B5	E5

Table A1: ACEA Performance Categories

A1 and B1 cover fuel economy lubricants (the reason why there isn't a fuel economy performance category for heavy duty diesels was discussed in the section on fuel economy). A2, B2 and E2 are baseline quality. A3, B3 and E3 are higher quality lubricants, A4 and B4 are performance categories for direct injection passenger car engines (A4 is reserved but is currently unused – i.e. there is currently no performance category for direct injection gasoline engine lubricants). A5 and B5 are performance categories that combine both high oil drain interval performance and fuel economy. E4 addresses the needs of German heavy duty diesel engines. E5 meets the needs of most emission controlled heavy duty diesel engines with high levels of soot.

These Sequences were updated in 1996, 1998, 1999 and 2002. Note that the ACEA Sequences allow for a tiered lubricants market in Europe. This contrasts with the situation in the USA. Further details of specific tests within the ACEA Sequences, and the consequence for lubricant formulation, were discussed in the paper.

Finally, we should comment that the linkage between engine technology, emissions legislation and performance specifications has in the past been somewhat hazy, but is tightening as more sophisticated aftertreatment systems are developed and emissions legislation becomes more restrictive. Current ACEA discussions are focussed on ACEA E6 – the next generation HDEO with low levels of sulphated ash, phosphorus and sulphur.

USA

Figure A2 shows schematically the American Industry Structure for developing lubricant specification tests.

Each of the groups shown in Figure 2 are involved in the development of engine oil performance specifications. Different approaches are taken in the HDEO and PCMO arenas.

In developing a performance category for PCMO the ILSAC/Oil "Gang of Six" (General Motors, Ford, DaimlerChrysler, Shell, Valvoline, CIBA) agree a need for a new performance category and provide high level steering. The ASTM then develops specific tests for the performance category. Test coordination is carried out via the PCEOCP, with one task force per test. The ILSAC/Oil "Gang of Six" agree limits for the specific tests within the performance category, and finally the API agrees the consumer language describing the new performance category. Table A2 shows the different API performance categories, and the year in which they were introduced. Note that API performance categories are backward compatible, and so an oil meeting the latest API specification will meet any of the preceding specifications. Table A3 shows the timetable of the ILSAC specifications, which are related to recent API ‘S’ specifications.

API Specification	Comments
SA	Obsolete. For older engines. Use only when specifically recommended by manufacturer
SB	Obsolete. For older engines. Use only when specifically recommended by manufacturer
SC	Obsolete. For 1967 and older engines
SD	Obsolete. For 1971 and older engines
SE	Obsolete. For 1979 and older engines
SF	Obsolete. For 1988 and older engines
SG	Obsolete. For 1993 and older engines
SH	Obsolete. For 1996 and older engines. Valid when preceded by current C categories
SJ	Current. For 2001 and older automotive engines
SL	Current. For all automotive engines presently in use. Introduced July 1, 2001. SL oils are designed to provide better high-temperature deposit control and lower oil consumption. Some of these oils may also meet the latest ILSAC specification and/or qualify as Energy Conserving

Table A2: Details of the API “S” sequences for passenger car gasoline engine oils

ILSAC Specification	Year of Introduction	Comments
GF-1	1996	
GF-2	1997	Includes Sequence VI-A Test
GF-3	2001	Includes Sequence VI-B Test
GF-4	2004	Includes Sequence VI-B Test with tighter limits

Table A3: Details of the ILSAC “GF” sequences for passenger car gasoline engine oils

For HDEO lubricants, an API New Category Evaluation Team agrees a need for a new performance category, and provides high level steering. The ASTM develops specific tests for the performance category, and test co-ordination is via the HDEOCP. The ASTM assigns a task force to each test, and agrees test limits. Finally the API develops the consumer language for the new performance category. Table A4 summarises the API HDEO performance categories, and the year that they were introduced. In common with the API PCMO specifications, the HDEO specifications are also backward compatible. (Note that during the development of a new performance category, a different name is used. For example, during the development of the new API CI-4 HDEO performance category, the draft specification was referred to as PC-9 during development.)

API Category	Description	Year
CA	Mild/Moderate Duty	1940's - 1950's
CB	Mild/Moderate Duty & Low Quality Fuels	1949
CC	Moderate to Severe Duty	1961
CD	Moderate to Severe Duty & Low Quality Fuels	1955
CD-II	Severe Duty Two-Stroke	
CE	Wide Service Range	1983
CF-4	On-Highway Heavy Duty Truck Applications	1990
CF	Indirect Injected Diesel Engines & Low Quality Fuels	1994
CF-2	Severe Duty Two Stroke	1994
CG-4	Severe Duty On- and Off-Highway	1994
CH-4	Severe Duty for 1998 Emissions Standards	1998
CI-4	For Diesel Engines Using Cooled EGR	2002

Table A4 : API "C" Sequences for Heavy Duty Diesel Engine Oils

Most US meetings have an open attendance. Although formal membership is monitored, most meetings have many guests, and can be unwieldly. All decisions are made by consensus – voting memberships are allocated to preserve a balance between the OEM and Oil & Additive communities (eg the ILSAC/Oil "Gang of Six" above).

API and ILSAC oil performance quality is ensured via EOLCS (the Engine Oil Lubrication Classification System) in tandem with the ACC Code of Practice). Together, these comprise a voluntary system followed by "reputable and responsible" oil marketers and additive companies. They govern how test programmes supporting API and ILSAC performance grades must be organised, reported and recorded. Both documents are maintained to ensure that the rules remain consistent with the current suite of tests. EOLCS also describes the API Licensing system – its symbols and their usage.

To increase consumer awareness and assurance about their products, API operate a licensing system. Oil marketers can apply to the API for a license for a particular product. Having provided satisfactory documentary evidence and paid a license fee, the marketer is allowed to use the API "donut" on their oil. By licensing only the most recent categories, the API encourages consumers to use the latest products.

The linkage between emissions legislation, engine technology and performance specifications in the US is much tighter than that in Europe. All recent performance category developments have been associated with a specific tranche of US emissions legislation. Current discussions are focused on: ILSAC GF-4 and its companion specification API SM – covering the needs of passenger cars designed to meet Tier II emissions, and API PC-10 targeted at heavy duty vehicles designed to meet the 2007/10 emissions standards and capable of sustaining aftertreatment system performance (this category will presumably be called API CJ-4 when it is introduced).

Japan

Figures A3 and A4 show schematics of the Japanese industry structure.

There are currently 21 JASO oil specifications and 18 JPI lubricant test methods.

Global Specifications

Increasing globalisation of passenger car and truck markets are leading to a need to develop global specifications. This has been particularly apparent for heavy duty engine lubricants. The first attempt at a global specification was “Global DHD-1”. This specification was driven by ACEA, EMA and JAMA, thus representing the European, the US and Japanese markets. The engine tests in this specification are a mixture of existing European, US and Japanese engine tests, accompanied by bench tests (which for example address issues such as seal compatibility).

This initial global heavy duty specification is due to be upgraded in 2007, to DHD-2.

There are also moves to introduce a global light duty diesel specification, DLD-1.

OEM Specifications

In addition to industry standard specifications, some of the major OEMs, such as DaimlerChrysler, Ford, VW, GM, Cummins, MAN, have their own requirements. Some of these requirements are based on industry standard engine tests, but with tighter limits (e.g. Ford's requirement for a double duration Sequence IIIF performance for example), whereas some tests are specific to the OEM (e.g. the VW RNT test). The variety of test requirements can be quite bewildering, and there is insufficient space here to comprehensively list all the different OEM requirements.

Figure Captions

Figure 1: Schematic mechanism of lubricant oxidation

Figure 2: The effect of lubricant oxidation on viscosity, Total Base Number (TBN) and Total Acid Number (TAN) for three different oils. The data above was generated in a laboratory screener test designed to mimic the Sequence IIIE engine test

Figure 3: Schematic indication of the way in which the oil stress factor is increasing (this Figure is © BP/Castrol 2004)

Figure 4: Effect of antioxidant treat rate on engine cleanliness: Antioxidant treat rate ranges from high-good-average (left to right)

Figure 5: Driving cycle used for the CEC M111 fuel economy engine test

Figure 6: Japanese driving cycles

Figure 7: US driving cycles

Figure 8: The impact of oil performance level on rocker cover sludge in a Cummins heavy duty diesel engine

Figure A1: Schematic of European industry structure for developing lubricant specification tests

Figure A2: Schematic of US industry structure for developing lubricant specification tests

Figure A3: Schematic of the interactions within the Japanese lubricants industry (acronyms defined at beginning of paper)

Figure A4: Schematics of Japanese lubricant industry structure

Figures

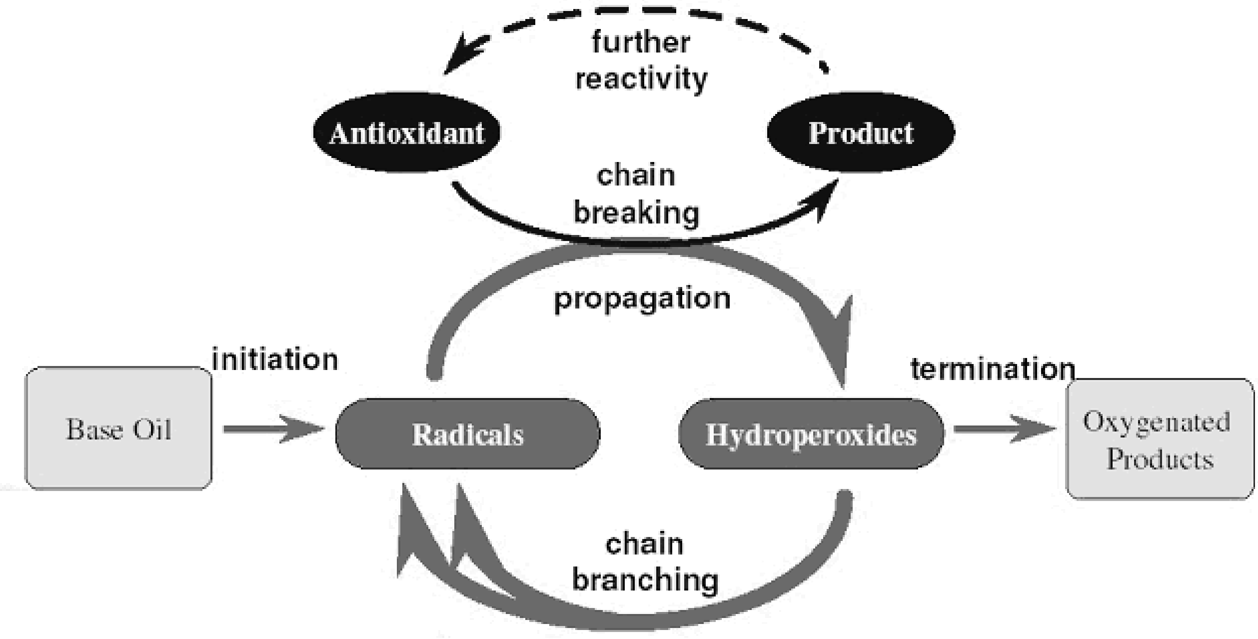
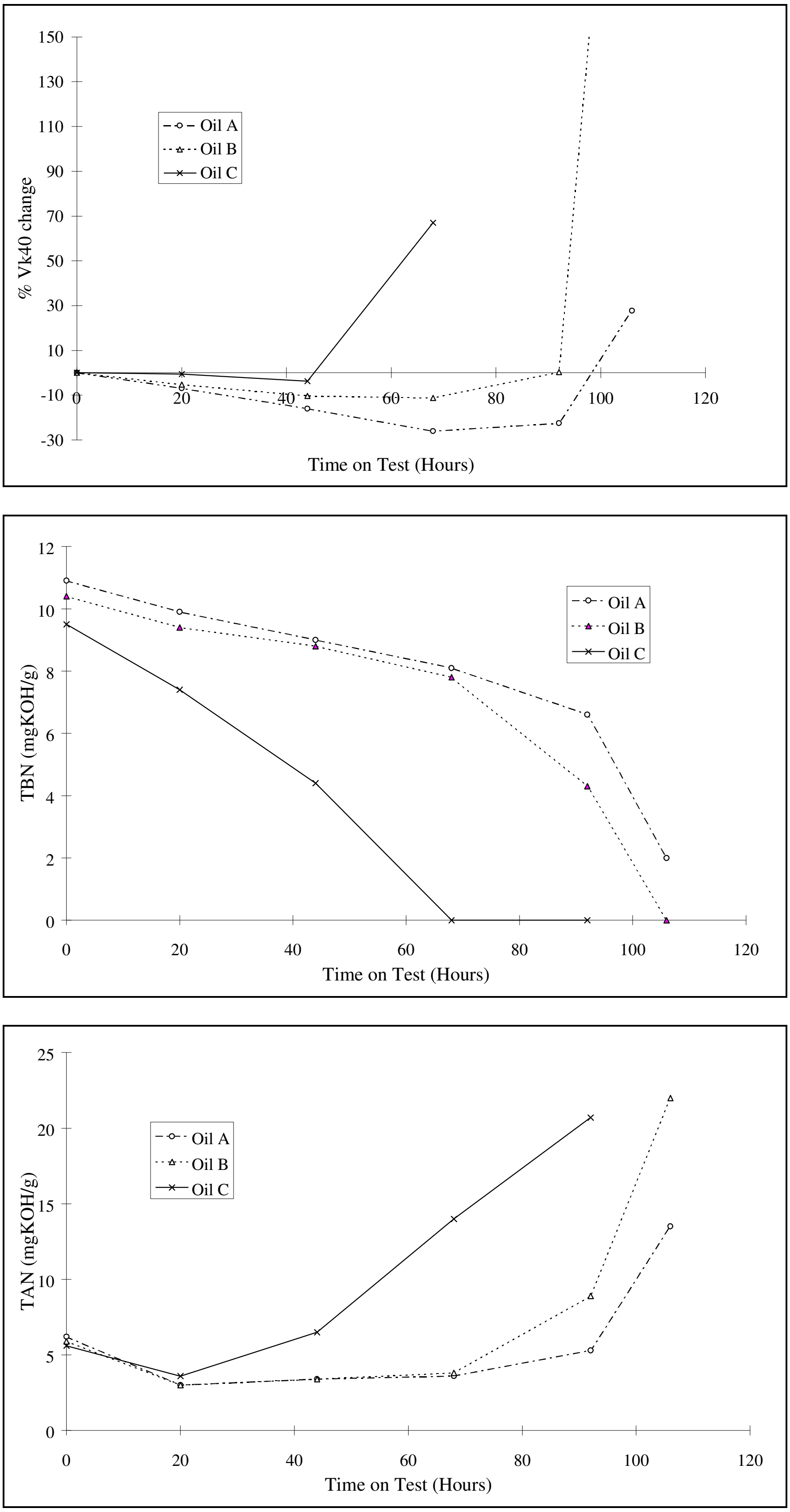


Figure 1



% Vk40 change
Oil A
Oil B
Oil C
Time on Test (Hours)
TBN (mgKOH/g)
Oil A
Oil B
Oil C
Time on Test (Hours)
TAN (mgKOH/g)
Oil A
Oil B
Oil C
Time on Test (Hours)

Figure 2

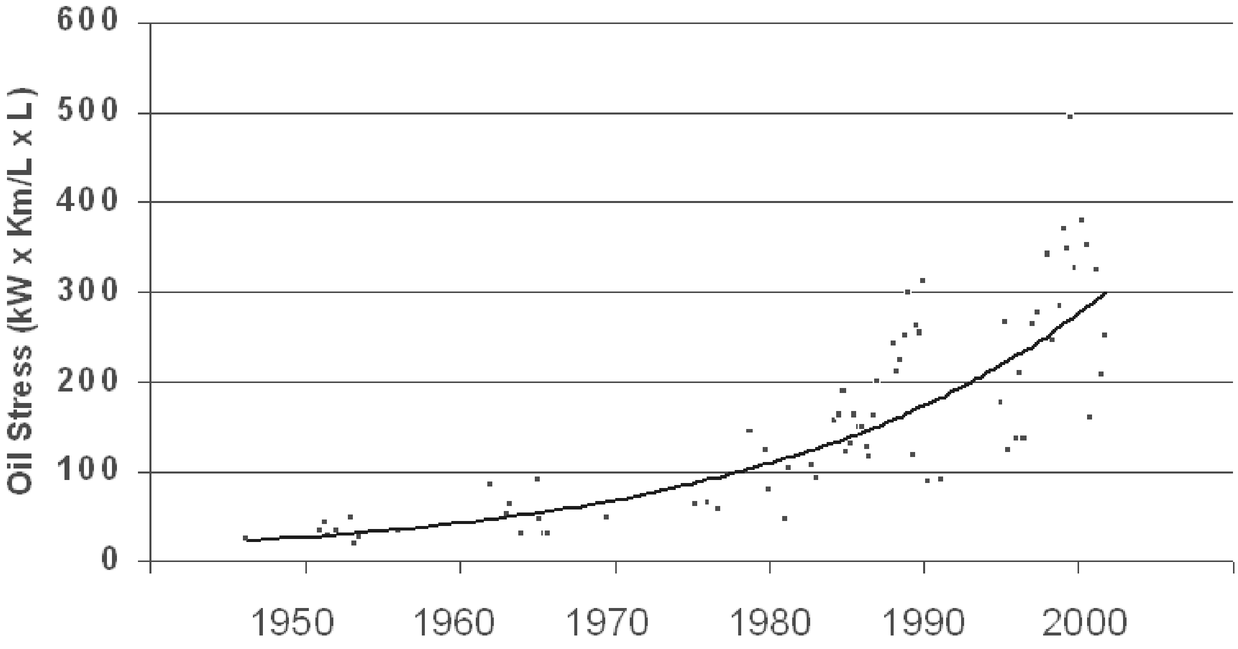

Oil Stress (kW x Km/L x L)
600
500
400
300
200
100
0
1950
1960
1970
1980
1990
2000

Figure 3

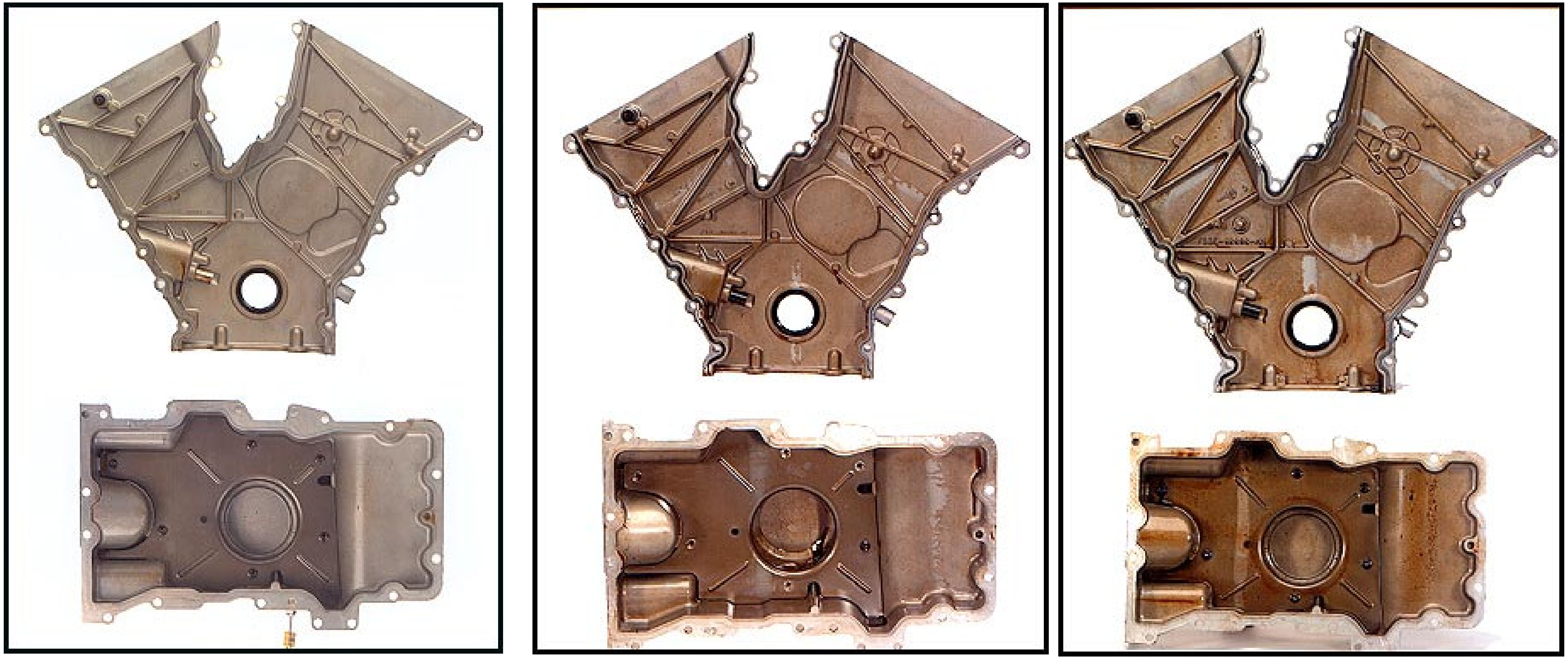


Figure 4

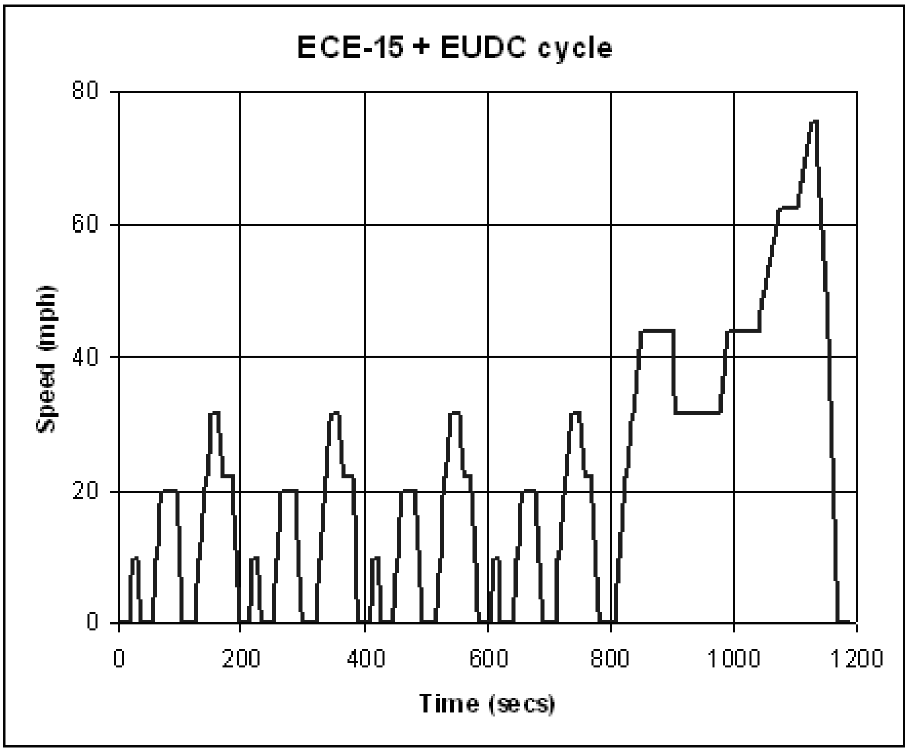


Figure 5

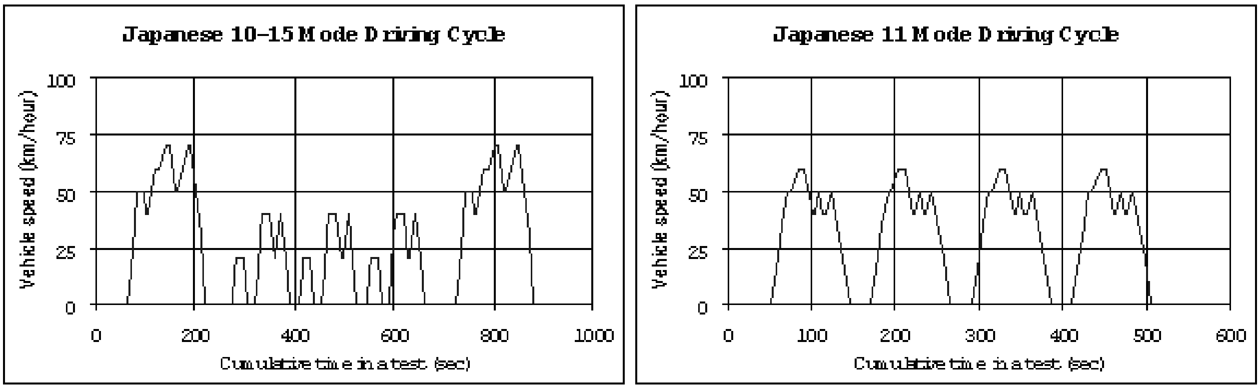


Figure 6

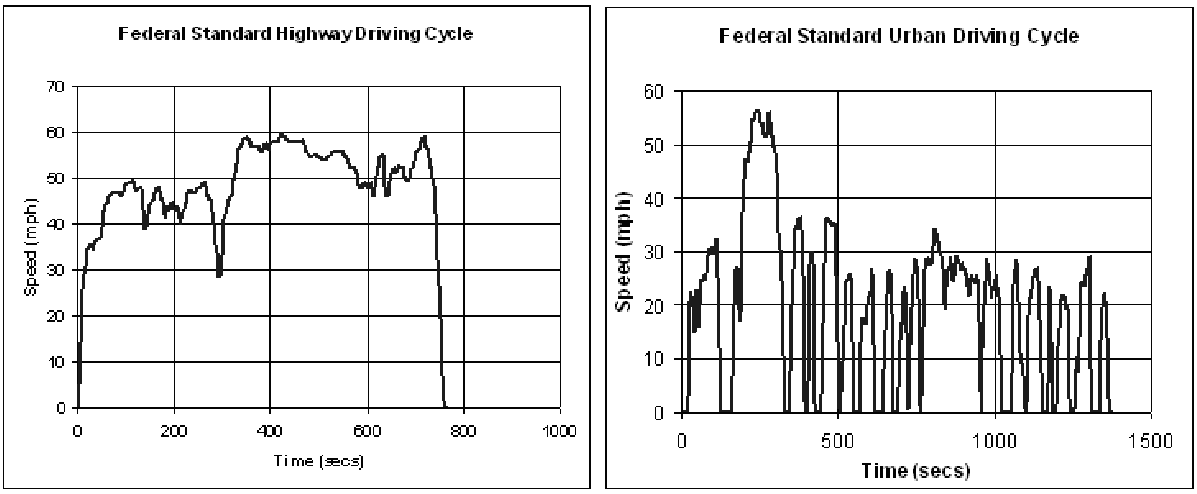


Figure 7

API CF-4 oil
48,000 km oil drain

API CG-4 oil
81,000 km oil drain

API CH-4 oil
81,000 km oil drain

Figure 8