



Shell Lubricants

## PREPARING FOR **API CK-4** AND **FA-4**

WHAT THE NEW CATEGORIES MEAN  
FOR YOU AND YOUR HEAVY-DUTY ENGINES

Technical brochure, May 2017











# THE AMERICAN PETROLEUM INSTITUTE (API) HAS CREATED NEW CATEGORIES OF HEAVY-DUTY DIESEL ENGINE OIL SPECIFICATIONS.

Shell has played a leading role in this process and has developed and tested next-generation low- and high-viscosity oils that will meet the new specifications without compromising oil life or wear protection. This technical brochure explores the drive behind the new categories and what they mean for you and your heavy-duty engines.





# ENABLING CHANGE FOR MODERN ENGINES

**Selecting the right oil is critical for heavy-duty-vehicle owners. There are two new categories of heavy-duty diesel engine oil specifications: both categories will reflect improved engine performance and one category is specifically intended to deliver fuel economy benefits for modern diesel engine technology.**

The API has completely redesigned heavy-duty diesel engine oil specifications. Shell has had a leading role in the new category development and, through more than 64 million km of real-world testing, has demonstrated the performance of its next-generation, low-viscosity oil formulation technology.

## EVOLUTION TO REVOLUTION

Heavy-duty diesel engine designs have evolved substantially over the last 40 years. This evolution has been driven by emission legislation and customers' requirements for efficiency and reliability. There has been significant progress. For example, high-pressure, common-rail injection systems are now widely used to improve combustion efficiency; advances in turbocharger technology have increased specific power output; and exhaust gas recirculation and aftertreatment devices, such as diesel particulate filters and selective catalytic reduction, have curbed harmful emissions of oxides of nitrogen and particulate matter (i.e., soot).

Despite this progress, there is a long way to go. Recent regulations, coupled with customers' desires to reduce the total cost of ownership, are making fuel economy the most critical driver for engine manufacturers. Advanced technologies and materials, and new operating conditions such as higher internal temperatures continue to improve engine efficiency.

But oil and engine technology go hand in hand. Engine changes place more stress on the oil, which has to lubricate, cool, clean and protect over extended oil-drain intervals.

The vehicle industry is starting to recognise that oil can help to achieve an engine's full potential for fuel economy without compromising hardware durability. As engine manufacturers create cleaner, more-fuel-efficient diesel engines, they will need a new generation of higher-performing diesel engine oils to protect them.





# WHAT ARE THE NEW API CK-4 AND FA-4 CATEGORIES?

## DEFINING THE CATEGORIES

More than a decade has passed since the last API diesel engine oil category, API CJ-4, was developed. During this time, engines have changed considerably and have improved fuel consumption and increased power outputs. New EPA and NHTSA emission legislation scheduled for diesel-powered commercial transport vehicles in 2017 requires significant improvements in fuel consumption that will help to reduce carbon dioxide emissions. These fuel consumption improvements depend on vehicle class, type and size, and include specific improvements for medium- and heavy-duty engines. This created the need for a new category of lubricant specifications, collectively called Proposed Category 11 (PC-11) during their development. The categories have been officially named by the API as CK-4 and FA-4. These oils will replace the current CJ-4 heavy-duty oils.

The API will introduce two types of heavy-duty diesel oil as part of the new categories:

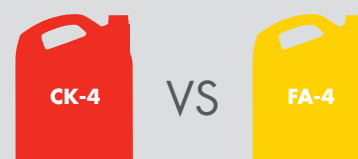
- CK-4<sup>1</sup> oils will replace today's lubricants and will be completely backwards compatible with all current diesel vehicles.

They will be designed with improved oxidation resistance, shear stability and aeration control.

- FA-4<sup>2</sup> oils will also meet these new requirements and include lower viscosity grades designed for next-generation diesel engines to help maximise fuel economy without sacrificing engine protection. These oils will have limited backwards compatibility because some older engines were not designed to operate with lower viscosity grades.

These new engine oil requirements, especially for FA-4, are a major change in the industry's approach to heavy-duty oil specifications. However, the chemical limits used in CJ-4 oils will remain in place for CK-4 and FA-4 oils.<sup>3</sup> Oil producers will therefore need expertise in formulating oils for the required performance and ensuring that they continue to deliver excellent wear protection and cleanliness—two factors that help to drive down customers' maintenance costs and prolong engine life.

## NEW OIL SPECIFICATIONS: API CK-4 VERSUS API FA-4



**CK-4** oils will have improved oxidation resistance, shear stability and aeration control, and similar viscosity grades to API CJ-4 products. They are designed to replace oils for current technologies and will have a minimum high-temperature, high-shear (HTHS) viscosity of 3.5 cP.

**FA-4** oils will have all the benefits of the CK-4 formulations, but will be formulated to have a lower HTHS viscosity (2.9–3.2 cP), which is known to provide a fuel economy benefit compared with oils having higher HTHS viscosities. As lower-viscosity oils can form thinner films, designing products for wear protection will be critical for oil formulators.

**"The CJ-4 standard has lasted well beyond the life of the typical engine category. Some of the engine tests required to qualify an oil are no longer available or no longer relevant to next-generation engines."**

Dan Arcy, Global OEM Technical Manager

<sup>1</sup>The name API CK-4 is the official name for the category, and it follows the naming convention of the API C series. This is the name that was given to the PC-11A development.

<sup>2</sup>The name API FA-4 is the official name for the category and it will align with the future ACEA F category nomenclature for fuel economy oils. The term FA-4 will differentiate them from API CK-4 oils. This is the name that was given to the PC-11B development.

<sup>3</sup>Chemical limits were introduced with the use of diesel particulate filters to reduce particulate matter.





#### ON- AND OFF-HIGHWAY

On-highway diesel emission legislation generally leads off-highway emission requirements by several years. On-highway engines are used to develop engine tests because they are typically more advanced and use less fuel than off-highway engines. Engine manufacturers will determine whether off-highway applications will use FA-4 oils.

#### NEW AND UPDATED TESTS

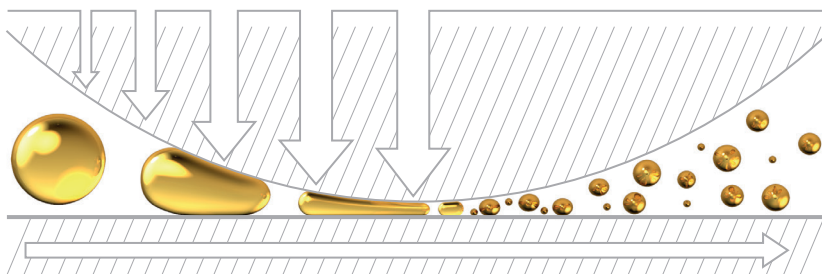
A major part of designing an oil specification is defining a set of rigorous tests that each oil formulation must pass before it goes on sale. CK-4 and FA-4 specifications will continue to use many of the current tests, but some of these tests, such as shear stability, will have more stringent limits to reflect the needs of future engine hardware. Two new tests will be introduced to ensure that next-generation oils can cope with the oxidation stability and aeration control needs of modern technology.

#### MODIFIED LIMITS FOR OIL SHEAR STABILITY

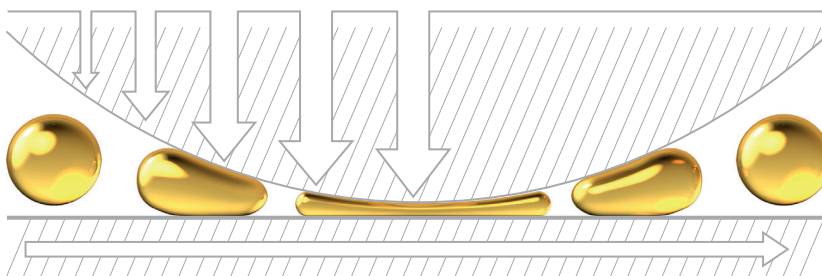
Shear stability is a measure of an oil's ability to resist being sheared (mechanically degraded) under severe stress (Figure 1). Shearing the polymer used in multigrade oils into smaller parts can reduce oil viscosity, which may result in failure to protect vital engine parts.

**CK-4 and FA-4 oils will have to meet more stringent shear stability limits.**

#### INCREASING SHEAR FORCE



**FIGURE 1a:** An engine oil with low shear stability breaks down under high stress.



**FIGURE 1b:** Superior oils maintain their viscosity even in highly loaded contacts.



### AERATION CONTROL FOR MODERN TECHNOLOGY

Aeration is the inclusion of tiny air bubbles, or foam, in the oil, which can impede its ability to cool and protect an engine (Figure 2).

The higher operating temperatures, pressures and oil flow in modern engines can increase the amount of air entrained in lubricants. Oils are also used more frequently as hydraulic fluids for valve-train actuation: a task that may be compromised by aerated oil. Consequently, it is increasingly important for oils to have excellent aeration control.

**CK-4 and FA-4 oils will have to pass a new Caterpillar engine oil aeration test.**

### IMPROVED OXIDATION STABILITY TO PROTECT HOTTER ENGINES

Oxidation is the reaction of oil molecules with oxygen. It can cause oil to degrade, thereby decreasing its life and causing potentially damaging sludge and varnish, viscosity increase and corrosive wear.

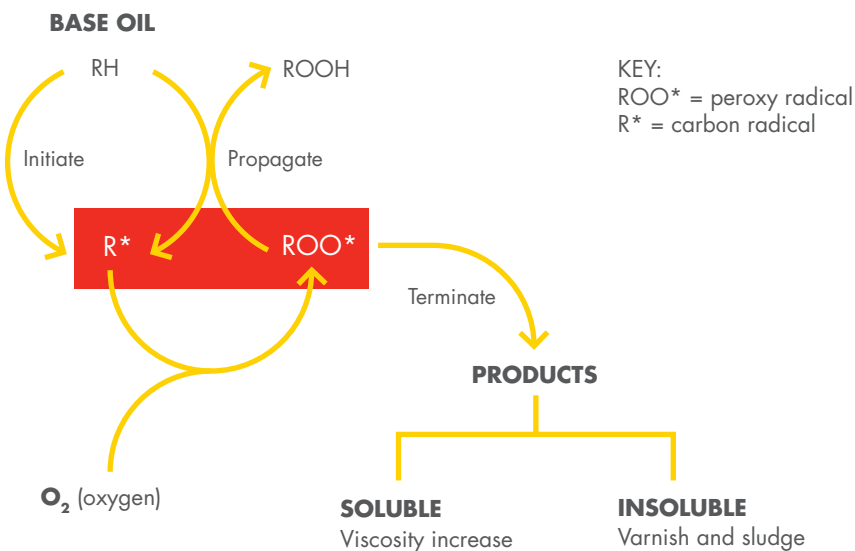
Next-generation engines are designed to operate at higher temperatures, which can greatly accelerate oxidation rates.

Selecting the right base oils and antioxidant additives can disrupt oxidation reactions and prevent the formation of harmful by-products (Figure 3).

**CK-4 and FA-4 oils will have to pass a new oxidation stability test.**



**FIGURE 2:** The formation of air bubbles in an oil formulation.



**FIGURE 3:** Engine oil oxidation occurs via a radical chain reaction with oxygen. Antioxidants slow down ageing by reacting with the radicals to disrupt degradation (red box).



## VISCOSITY AND FUEL ECONOMY

FA-4 oils will have lower viscosities for enhanced fuel economy. Even small increases in fuel economy can result in significant reductions in fuel consumption and carbon dioxide emissions. For example, every EU truck increasing its fuel economy by just 1% would see an annual reduction of over 4 million tonnes of carbon dioxide emissions, which is the equivalent of removing 23,000 trucks from the road. This would save fleet and owner operators combined an estimated \$3 million a day.<sup>4</sup>

Low-viscosity oils pump more easily and help to reduce engine friction, which can improve fuel economy. However, there are different types of viscosity measurements that contribute to an engine oil's viscosity grade. Critically, it is the HTHS viscosity (defined as an oil's resistance to flow under high stress conditions at operating temperatures) that will distinguish backwards compatible CK-4 oils from the fuel-economy FA-4 oils for modern engines.

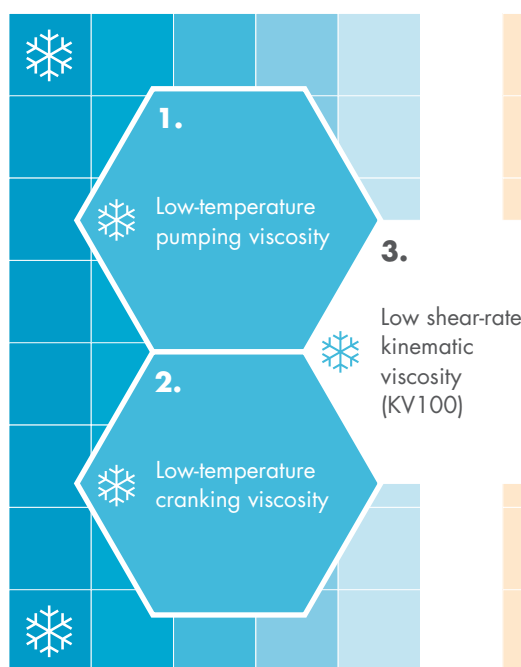
## WHAT IS HTHS VISCOSITY?

Society of Automotive Engineers (SAE) oil viscosity grades are defined by four different tests (Figure 4). Low-temperature pumping and cranking viscosities define the winter grade (for example, the 15 in 15W-40). HTHS dynamic viscosity contributes to the SAE viscosity grade definition (for example, the 40 in 15W-40). Low shear kinematic viscosity (KV100) contributes to the definition of monogrades, and provides a viscosity range for high-temperature viscosity grades in multigrade oils.

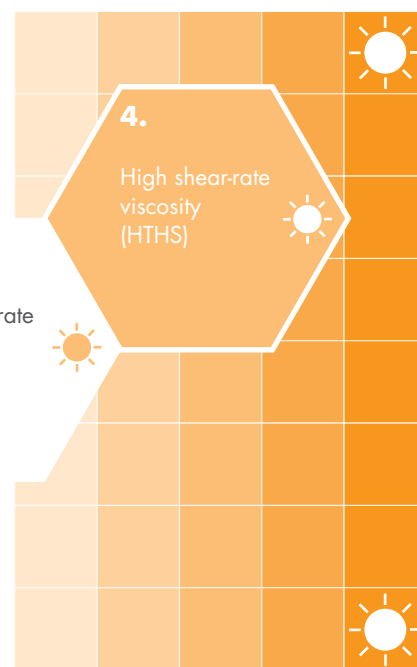
Switching to a lower viscosity grade SAE oil, for example, from a 10W-40 to 10W-30 oil, will provide modest fuel economy benefits. Even within a viscosity grade, differences in HTHS viscosity could affect fuel economy. The minimum HTHS viscosity for current XXW-30 CJ-4 and future CK-4 oils is 3.5 cP.

FA-4 XXW-30 oils will have HTHS viscosities between 2.9 and 3.2 cP, which will help to enhance fuel efficiency further. Oil companies and engine manufacturers are currently testing these products, which are designed to provide fuel economy without sacrificing engine protection, in a range of applications.

Sets SAE winter viscosity grade:  
**0W TO 25W**



Sets SAE viscosity grade:  
**08 TO 60**

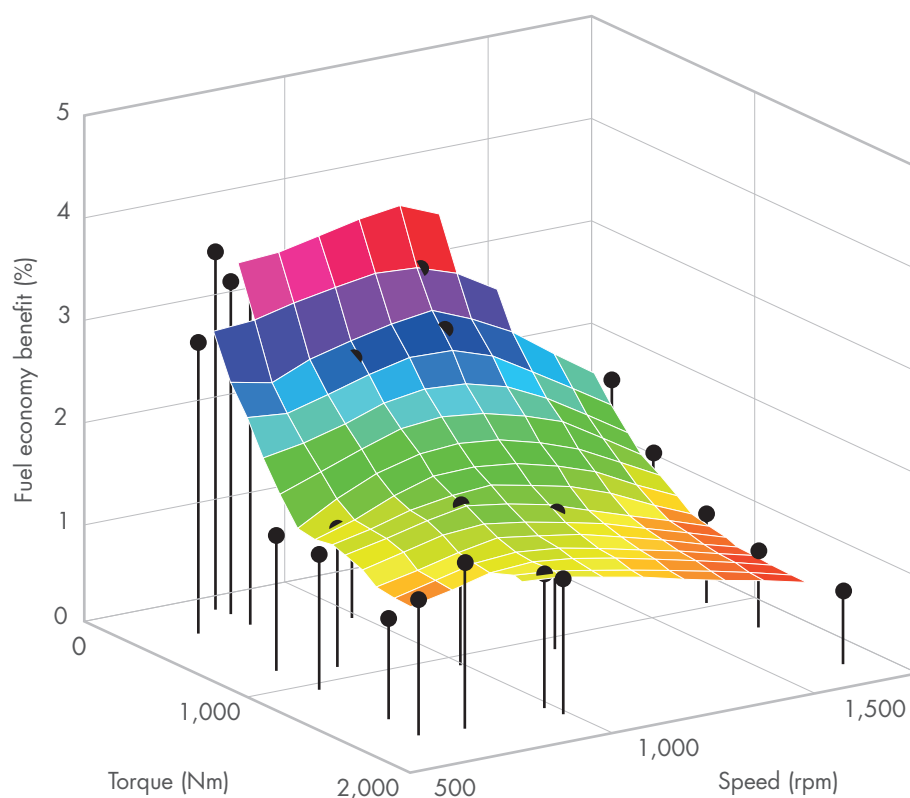


1. Resistance to pumping in cold conditions: determines an oil's ability to circulate through the engine.
2. Oil viscosity in crankshaft bearings during cold start up: determines performance of oils at low temperature.
3. Internal resistance to flow. Minimum value sets the SAE winter grade; the range determines the SAE viscosity grade.
4. Resistance to flow between narrow moving parts; mimics crankshaft and connecting rod bearing lubrication. The SAE viscosity grade specifies a minimum HTHS viscosity value.

FIGURE 4: Viscosity grade tests.

<sup>4</sup>EIA – US Energy Information Administration – 2012 On-highway fuel sales. Calculation based on 1% of 36.34 billion gallons of fuel consumed annually at \$3.00/gallon.

To measure the effect of lubricant viscosity on fuel economy, Shell has used a proprietary in-house driveline test rig. The experiments have shown that fuel economy benefits vary with engine speed and load, and, therefore, driving conditions. For example, for a specific heavy-duty engine, switching from a 15W-40 CJ-4 oil with a 3.9-cP HTHS viscosity to a 10W-30 oil with a FA-4 (2.9-cP) HTHS viscosity provides a fuel economy improvement of about 1% in high-speed high-load driving conditions and up to 4% at low-speed, low-load driving conditions (Figure 5). Manufacturers are also using this information to design modern engines, for example, downsizing the engine to improve fuel economy.



**FIGURE 5:** The fuel economy benefit of a 10W-30 oil with a FA-4 (2.9-cP) HTHS viscosity compared with a 15W-40 CJ-4 oil with a 3.9-cP HTHS viscosity in a heavy-duty diesel engine, as measured using a Shell proprietary driveline test rig.





## DEVELOPING A NEW HEAVY-DUTY DIESEL ENGINE OIL SPECIFICATION

### THE ROAD MAP TO THE NEW CATEGORIES

The road to a new engine oil category is long and complex. A three-phase process is defined in API 1509 for the development of the new category.

In Phase 1, the New Category Evaluation Team (NCET) is formed, which consists of manufacturers (EMA), oil marketers (API) and additive companies (ACC, American Chemistry Council). The focus of the NCET, through a consensus process, is to review the request and evaluate the need for a new specification.

Phase 2 consists of the formation of the New Category Development Team (NCDT) to oversee the specification and test method development, and to agree to any additional guidelines (Figure 6). The NCDT is structured with four functional work groups that report to the NCDT. Each of the four groups, consisting of API, ASTM, ACC and EMA, have specific responsibilities. In addition, ad hoc work groups from SAE and engine test laboratories are asked to participate. The NCDT works through a consensus process to develop the category.

**Shell has played a leading role in the development of the new engine oil categories: Dan Arcy, who acted as NCDT Chair, is a member of the Shell heavy-duty engine oil team.**

Phase 3 of the development is the category implementation.

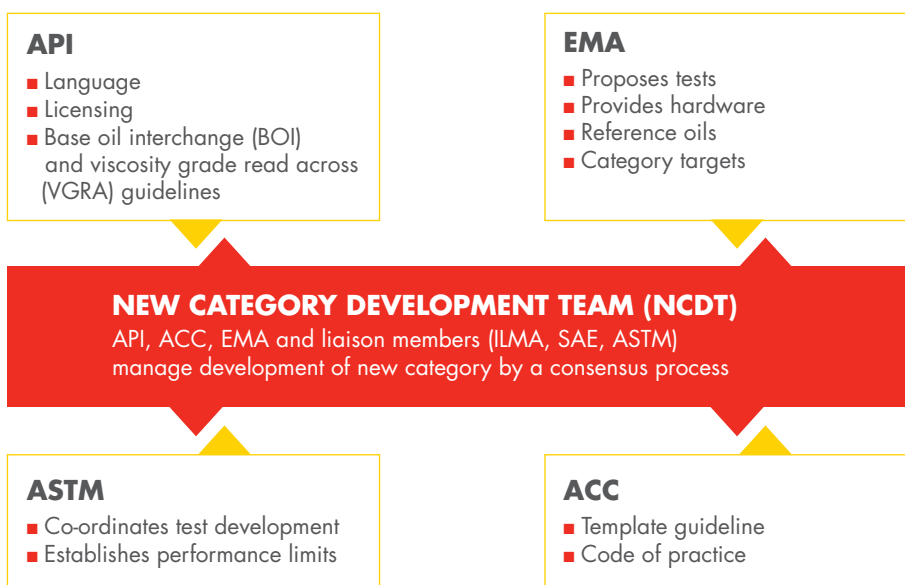


FIGURE 6: Structure of the NCDT.

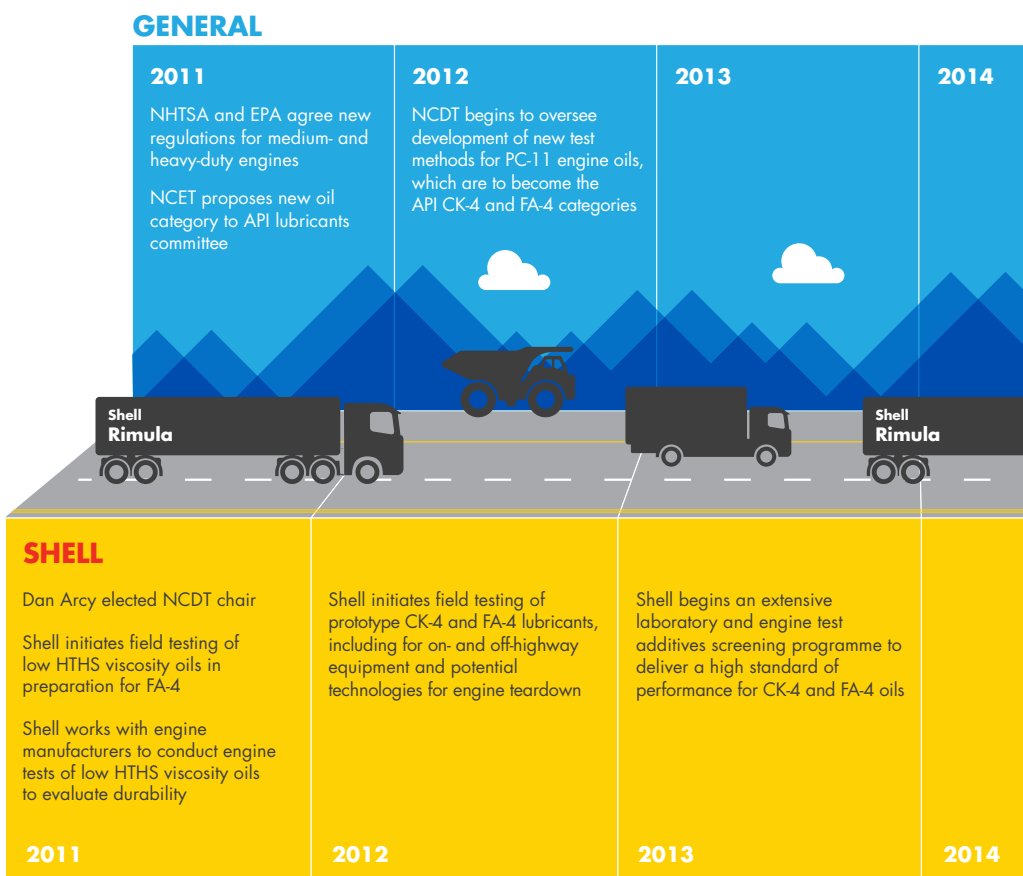
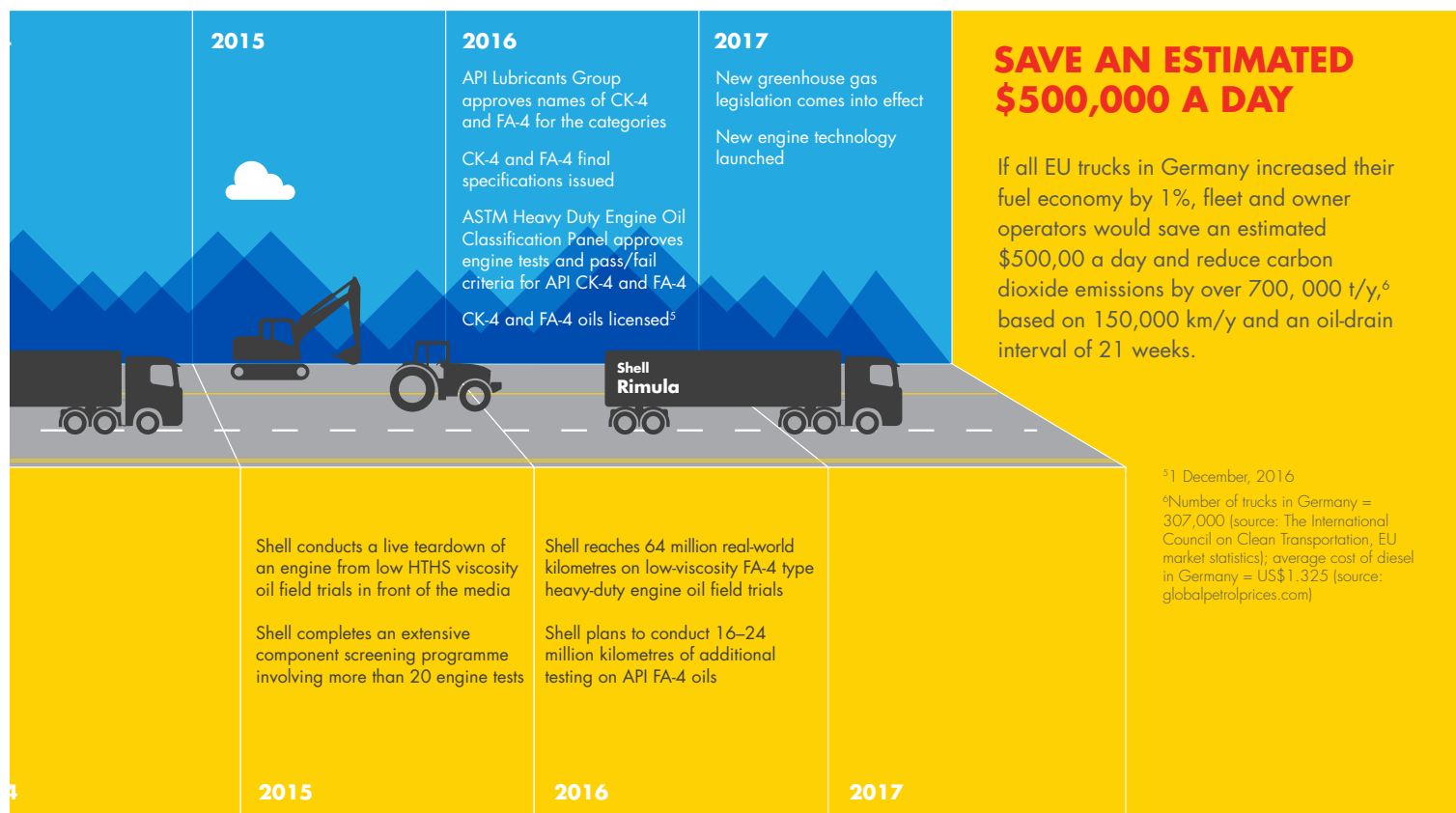


FIGURE 7: Road map of the development of CK-4 and FA-4.



**FIGURE 8:** Shell has launched [www.shell.com/rimula/ck4](http://www.shell.com/rimula/ck4) to keep customers up to date with the development of the new API category.





# LABORATORY TO ROAD: MAKING CK-4 AND FA-4 A REALITY

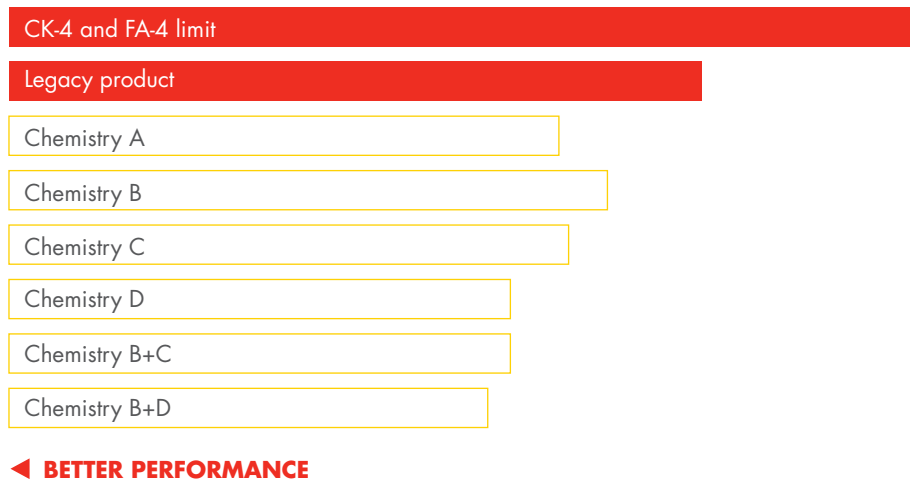
In addition to helping to lead the new category development, the Shell heavy-duty engine oil team has already been creating new oils targeted to meet the CK-4 and FA-4 specifications. The main challenges are to satisfy the stringent new performance requirements and to ensure that engine cleanliness and wear protection are maintained in future engine hardware. All this must be achieved within strict chemical limits for exhaust aftertreatment compatibility.

For CK-4 oils, optimising the oil composition for antioxidant and viscosity modifier chemistry combinations that will meet shear stability requirements is critical for success. An additional challenge for the lower-viscosity FA-4 oils is to balance these requirements with the right anti-wear components for wear protection with thinner oil films.

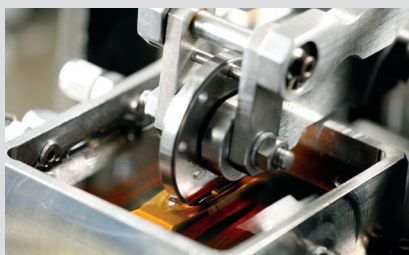
The Shell team has many decades of experience of developing high-quality products that have been tried and tested in the field. Shell has invested millions of dollars in testing and development. To date, the team has performed more than 9,000 tests using proprietary test rigs and external engine test rigs in collaboration with engine manufacturers in order to understand the CK-4 and FA-4 formulation requirements.

Lubricants are complex mixtures of base oils and additives, and getting the right balance of components requires significant expertise and extensive screening in the laboratory and on the road. Shell scientists have designed and screened prototype oils to optimise additive chemistry in combination with high-quality base oils (Figure 9). They recognise that selecting the right additive chemistry is about finding the right component combinations that will help next-generation Shell Rimula engine oils to meet and exceed the demanding targets of the CK-4 and FA-4 categories.

## WEAR PERFORMANCE OF PROTOTYPE CHEMISTRIES



**FIGURE 9:** CK-4 engine screening tests show that combinations of prototype anti-wear additives could exceed CK-4 requirements and the performance standard of a legacy product.



**FIGURE 10:** The unique slide/roll rig test, which was designed by Shell, is a good simulation of diesel engine wear tests. It is used to screen a wider range of candidate oil chemistries in a shorter time than full engine tests would enable. The best technologies are then tested further in selected engine tests.



**FIGURE 11:** The optical profilometer uses a laser as a non-destructive way to measure wear. It is enabling Shell scientists to evaluate product wear performance more precisely than conventional methods.

# GOING THE DISTANCE: 64 MILLION KM AND COUNTING

It is not enough to evaluate prototype oils in the laboratory: the real test is how they work in on- and off-road vehicles in the real world. Field trials are an integral part of the Shell engine oil technology development process. They are extensive programmes run in collaboration with customers and require scientific rigour, experience and expertise.

Shell performs millions of kilometres of real-world testing with customers (Figure 12). Between 2006 and 2015, Shell provided more than 270,000L of lubricants for use in customer field tests. A special focus has been placed on a subset of more than 50 engines, which have been thoroughly inspected. These engines received additional attention and were part of a teardown programme to inspect parts following significant distance accumulation.

A heavy-duty vehicle on the road is expected to meet 1.6 million km of life without engine failure. Although some wear is normal, higher levels can indicate durability issues.

During each trial, oil samples are taken and analysed to evaluate the oil's wear-protection and viscosity performance. Used oil analysis can also provide information, for example, about coolant leaks, which can be used for preventive maintenance.

FA-4 oils have lower viscosities, and therefore form thinner oil films, than any products currently on the market, so ensuring that they provide good wear protection is critical. Shell has assessed the wear protection performance of low-viscosity oils in the field for several years and demonstrated that low HTHS viscosity oils can deliver effective wear protection and long oil life. By the beginning of 2016, Shell had performed more than 64 million km



**FIGURE 12:** Shell real-world testing with customers. Shell has tested engines from a variety of equipment manufacturers, including Cummins, Detroit Diesel, Mack, Navistar, Paccar and Volvo.

of testing on low HTHS viscosity oil. The field trials cover all the major manufacturers' on-highway engines and in different vehicles with diverse duty cycles. Positive wear protection results have been recorded.

In addition to used oil analysis during field trials, Shell engineers teardown field trial engines, sometimes in collaboration with manufacturers and customers, to inspect and quantitatively rate engine component wear and thus evaluate the oil's ability to protect critical hardware. For trucks running on low HTHS viscosity oils, 14 engine teardowns have been performed, including two in front of the media.



### FA-4 VERSUS CURRENT TECHNOLOGY: AN 800,000-KM EXAMPLE

As part of the extensive field programme, a fleet of vehicles with 2011 Detroit DD15 engines was tested over multiple oil-drain intervals and more than 800,000 km to compare current 15W-40 and 10W-30 CJ-4 oils with a prototype (FA-4) low HTHS viscosity 10W-30 oil. In addition, in June 2015, a Detroit DD15 engine running a low HTHS oil with more than 1.2 million km was inspected and compared with a similar engine running a 15W-40 viscosity oil.

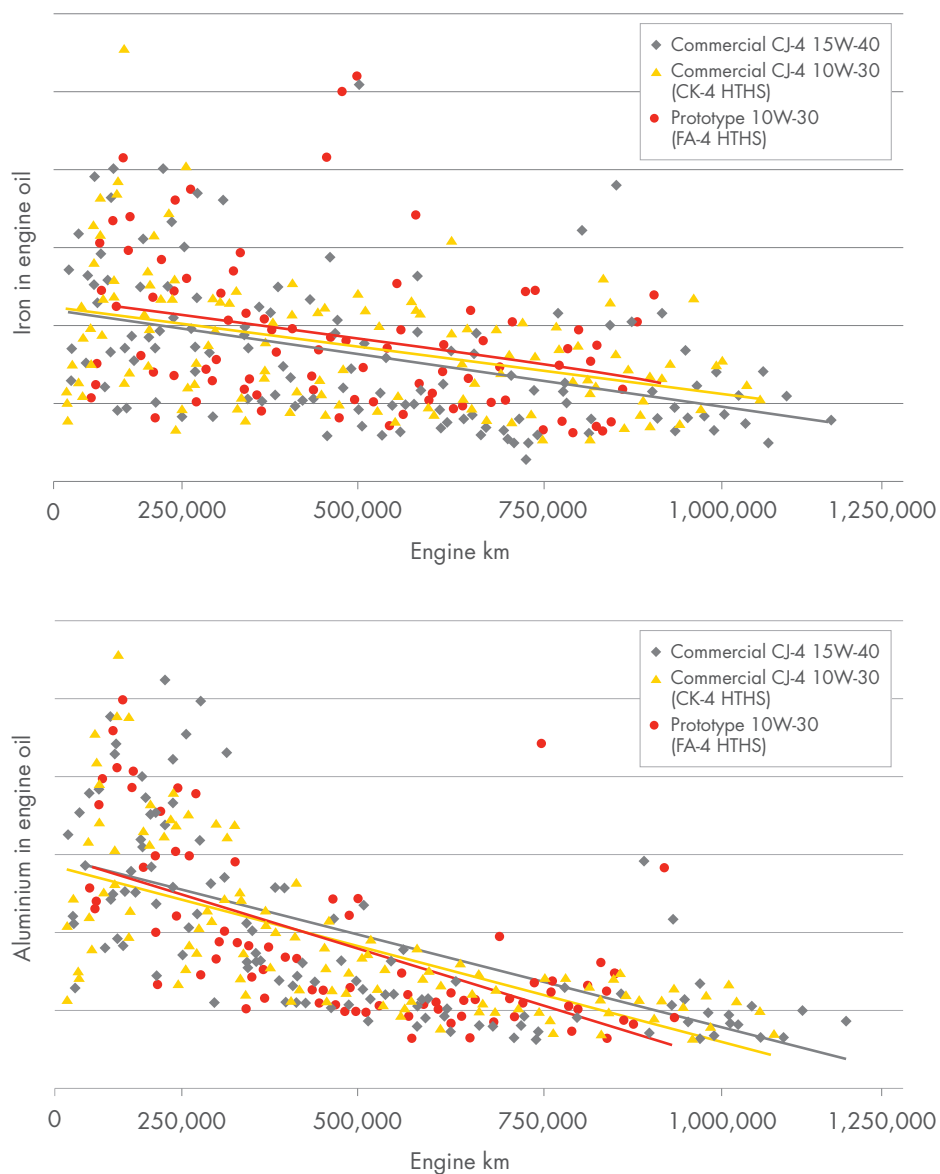
Used engine oil analysis showed that the low HTHS viscosity oil compared with the current oil, offers

- the same wear performance (Figure 13)
- similar ageing characteristics (Figure 14).

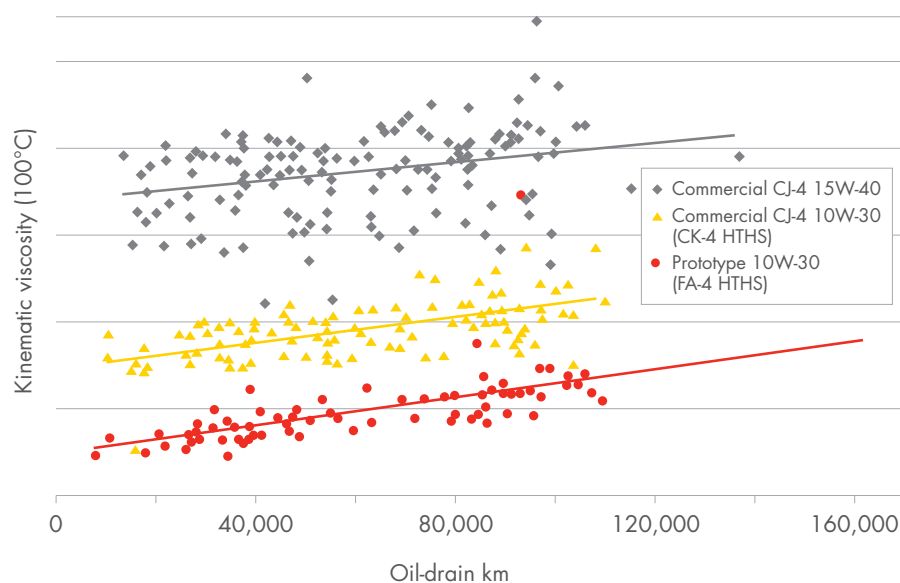
Engine teardowns show

- no discernible difference in wear performance (Figure 15).

Currently, Shell is working on the FA-4 formulation and making sure that the product not only meets but also exceeds the FA-4 specification, which has built-in fuel economy wins.



**FIGURE 13:** The wear rates for iron (top) and aluminum (bottom) were nearly identical for all three oils. In all three cases, microscopic wear particles show early break-in wear followed by a reduction to a consistent low wear rate.



**FIGURE 14:** The rate of viscosity increase throughout the oil-drain interval is similar for all three oils (shown by the similar gradient of the lines). Oxidation is a major cause of viscosity increase, which indicates oil ageing.

**"In more than 64 million km of real-world field testing, we are seeing promising performance and durability for low-viscosity FA-4 oils. Customers using Shell Rimula products can be assured that we are committed to delivering next-generation engine oils that will provide the opportunity to reduce fuel consumption without compromising the products' excellent wear protection."**

Matt Urbanak, Team Leader for Heavy Duty Engine Oil Development, Shell Lubricants



**FIGURE 15:** No discernible difference in wear was observed between engines using the prototype low HTHS viscosity oil and the two higher viscosity oils. In fact, the engine using the prototype oil had a notable lack of wear. The cam lobe, piston and wrist pin bushings pictured here were observed to be in a very good state after running for 837,499 km with the prototype oil. The contact areas of these components are critical for wear protection, as they are subjected to extreme pressures with high heat and friction.

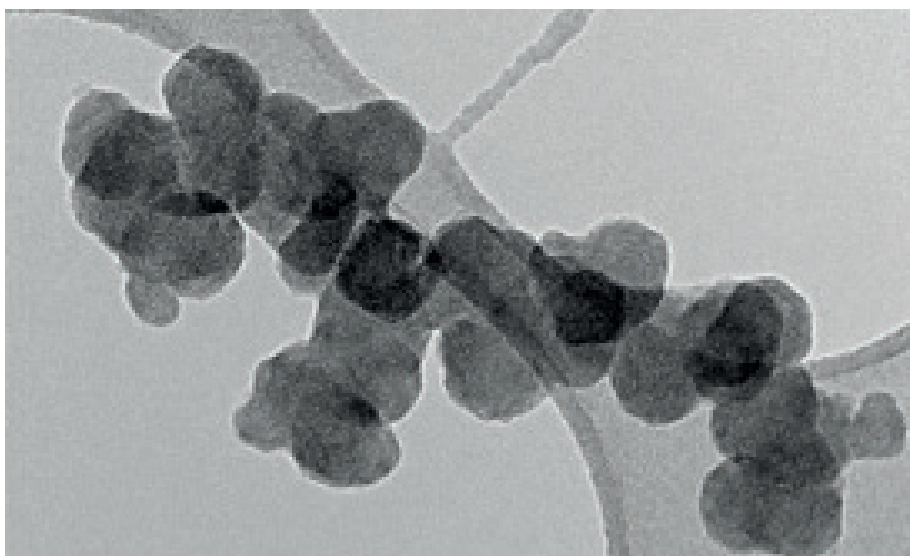


## BEYOND API CK-4 AND FA-4: LOOKING TO THE FUTURE

There is a worldwide need to improve heavy-duty engine fuel efficiency. The introduction of CK-4 and FA-4 is another milestone on the road to greater efficiency. As global fuel economy targets and the associated penalties for failing to meet them become increasingly important for manufacturers, they will turn more and more to engine oil as a critical enabling technology. Getting this right requires out-of-the box thinking and long-term technical partnerships.

### STUDYING SOOT

For example, Shell is sponsoring a PhD project at Imperial College London, UK, to further understanding of the mechanisms behind soot-induced engine wear using a range of state-of-the-art experimental techniques (Figure 16). Soot produced in diesel engines can promote wear, so it is critical to employ the correct lubricant chemistries to mitigate this issue. In addition, selecting the optimum dispersant system plays a significant role in keeping soot particles dispersed in the oil, so it is important to understand how dispersants interact with



**FIGURE 16:** Carbon-black aggregates formed during the combustion process can play a significant role in engine wear.

the anti-wear additives. The insights gained in this project, including the identification of strong-performing anti-wear and dispersant combinations, will help Shell in formulating better lubricants for current and future needs.



# CONCLUSION: CK-4 AND FA-4 WITH PEACE OF MIND

The drive for fuel efficiency comes from greenhouse gas emissions legislation and the ever-present need for successful businesses and customers to cut operating costs. Engine technology continues to evolve and engine manufacturers and regulators recognise that engine oil, along with developments in engine technology, will power the delivery of enhanced fuel efficiency.

A major milestone along the road to ever-greater fuel economy will be the launch of a new specification category API CK-4, for backwards compatible oils, and the inclusion of another category for low-viscosity, heavy-duty engine oils (API FA-4).

Shell had a leading role in the development of CK-4 and FA-4. The new specifications set more stringent shear stability limits and new tests for aeration control and oxidation stability. In addition, the new specifications for FA-4 will set low HTHS viscosities for greater fuel efficiency.

A key concern for operators is whether low-viscosity oils can reduce fuel costs and carbon dioxide emissions while providing the long oil-drain intervals and reliable engine protection required to keep down the total cost of ownership.

Extensive laboratory screening has helped Shell to formulate promising FA-4 prototype oils efficiently. Millions of kilometres of road testing have since demonstrated that engine durability is not significantly compromised through using these low HTHS viscosity oils. Fuel economy demonstrations have come through specific test protocols using highly statistical test methodologies. These oils offer the potential for significant fuel savings while matching the oil life and wear protection performance of today's leading commercially available oils.

In Europe, the Association des Constructeurs Européens d'Automobiles (ACEA) is expected to introduce new specifications aligned with API FA-4. ACEA 2018 will most likely include updates of ACEA E6 and E9 with lower HTHS viscosities, which will potentially be

## MEET THE SHELL HEAVY-DUTY ENGINE OIL TEAM



### Dan Arcy

Global OEM Technical Manager

Dan was elected chair for the API NCDT responsible for CK-4 and FA-4 after decades of involvement with API. He is also responsible for technical relationships with major equipment manufacturers in the US market.



### Matt Urbanak

Team Leader, Heavy-Duty Engine Oil Development

Matt is a leading member of the heavy-duty engine oil team. He has worked on several previous categories and is heavily involved in formulation and field trial programmes for CK-4 and FA-4.



### Howard Hill

Heavy-Duty Engine Oil Field Trial Engineer

Howard leads Shell's field trial programme in the USA and is an independently qualified engine rater. He has conducted several hundred inspections for heavy-duty engines during his 36 years with Shell.



### Dr Jason R. Brown

Global Technology Manager, Heavy-Duty Engine Oil

Jason manages the technology programme for the Shell Rimula and Shell Rotella portfolios. He has been part of the heavy-duty engine oil team for almost a decade and deeply involved in understanding formulations and leading product development. Jason is very excited about the challenge of developing fuel economy oils for the next API category.

called ACEA F8 and F11 respectively. The introduction of lower HTHS specifications to ACEA may result in the addition of new tests to reflect the changes in modern heavy-duty engine hardware. These may include a low soot wear test as well as the new Volvo T13 oxidation test.





## ENGINE TECHNOLOGY CONTINUES TO EVOLVE

AND ENGINE MANUFACTURERS AND REGULATORS  
RECOGNISE THAT ENGINE OIL, ALONG WITH  
DEVELOPMENTS IN ENGINE TECHNOLOGY, WILL  
POWER THE DELIVERY OF ENHANCED FUEL EFFICIENCY.









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