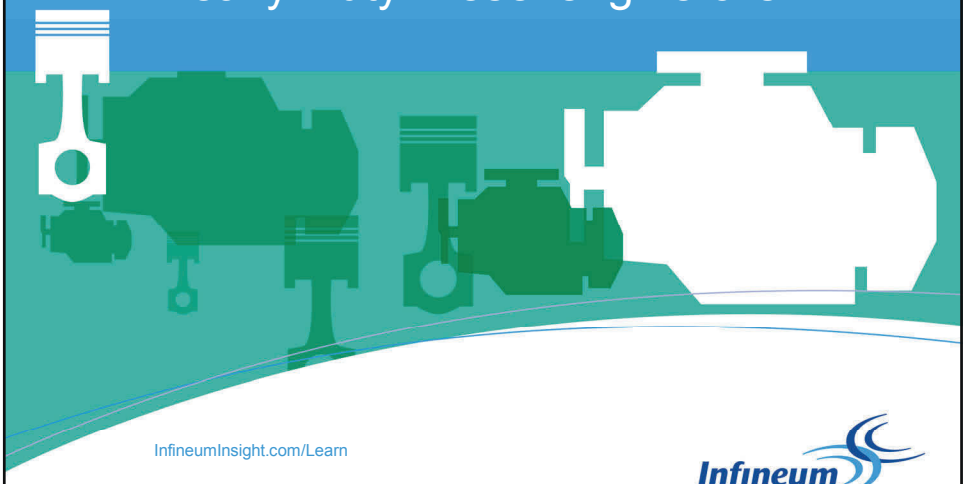
Performance you can rely on.

Heavy-Duty Diesel engine oils



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Topics in Heavy-Duty Diesel engine oil section

- Definition of HDD lubricants
- Typical Properties of HDDEO
- Function of HDDEO additive components
- Factors affecting HDD formulation
- Evolution of Heavy-Duty Diesel specifications

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Definition of Heavy-Duty Diesel engine oils

- Historically, meets API 'C' (Commercial) Category requirements: API CH-4, CI-4, CI-4 PLUS, CJ-4 or CK-4
  - Now, includes API 'F' Category requirements: API FA-4
- For use in on-road and off-road equipment and heavy-duty truck applications
- For use in diesel engines that operate under "severe" conditions:
  - Operate continuously at or near peak power output
  - Cyclic operation

Typical properties of HDDEO

Typical Properties	HDDEO	PCEO
*Additive Package, % mass	10 to 20	7 to 12
SAE Viscosity Grades	SAE 15W-40, 10W-30, 10W-40, 5W-40, 5W-30	SAE 0W-20, 0W-30, 5W-20, 5W-30, and 10W-30
HTHS Viscosity, mPa•s	3.0 to 4.2	2.6 to 3.1
TBN, mg KOH/g	8 to 12	7 to 9
Sulfated ash, % mass	0.9 to 1.3	0.8 to 0.9
Shear Stability Index of VM	25 to 35	25 to 50
Oil Drain Intervals, miles	Up to 75,000	Up to 10,000

*Current quality levels

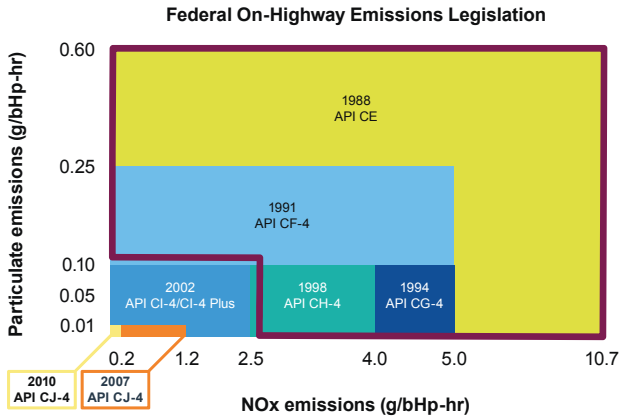
Function of typical HDDEO additive components

Component	Typical Type	Property/Function	Engine Test Stressing Property
Dispersant	Conventional, EGR Dispersant	+ Diesel Cleanliness + Soot & varnish control, soot dispersancy + Filter plugging + Valve train wear	+ 1M-PC, 1K, 1N, 1P, 1R, C13 + VG, IIIF, VIII, M11-HST, T-8, T-11 + M11-HST, M11-EGR, ISM + M11-HST, M11-EGR, RFWT, ISM, ISB
Metal Detergents	Ca or Mg based sulphonates, phenates, salicylates	+ Diesel detergency + Cyl./ring wear control + Rust Control	+ 1M-PC, 1K, 1N, 1P, 1R, C13 + T-9, T-10, T-12, M11-EGR, ISM + BRT
Antioxidants	ZDDP, phenolic, aminic, metal and/or sulfur based	+ Oxidation + Bearing wear	+ IIIF, IIIG, T-9, T-10, T-12, T-13 +VIII, T-9, T-10, T-12
Anti-wear agents	ZDDP, metal based	+ Valve train and cyl./ ring wear control	+ IIIF, IIIG, VG, RFWT, M11-HST, M11-EGR, T-9, T-10, T-12, ISM, ISB
Viscosity Modifier	OCP, Styrene Isoprene	+ High temp. viscosity + Dispersancy	+ 6V92TA, T-9, T-10, T-12 + T-8, M11-HST, M11-EGR, T-11, ISM, ISB

Factors affecting formulation of Heavy-Duty engine oils

- Engine design, operation and exhaust after treatment systems to meet exhaust emissions regulations
- Diesel fuel sulfur level
- OEM requirements for service fill and or factory fill
- SAE J300, API 1509 EOLCS, ASTM D4485 and ACC Code of Practice
- Oil company logistical considerations
- Additive technology (Detergent Inhibitor package, VM, PPD)
- Military specifications
  - No longer a significant driver of quality
- Real-world performance

Changes in diesel engine hardware



1988 – 2002
Combustion efficiency

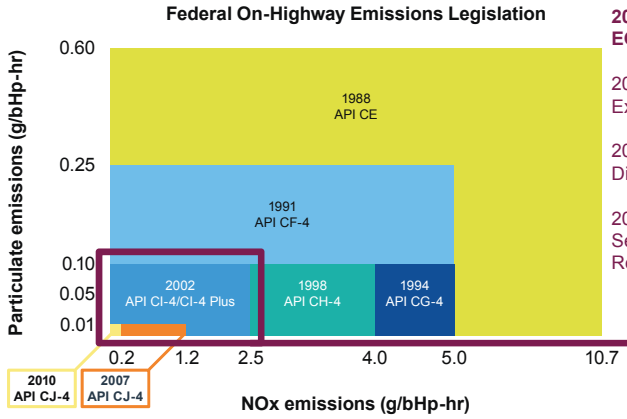
Retard injection timing

Combustion chamber design changes

- Ever tightening emissions regulations drives evolution of engine hardware
- Have achieved near zero exhaust emissions for Class 8 On-Highway vehicles

Performance you can rely on.

Changes in diesel engine hardware



2002 – 2010
EGR + After treatment

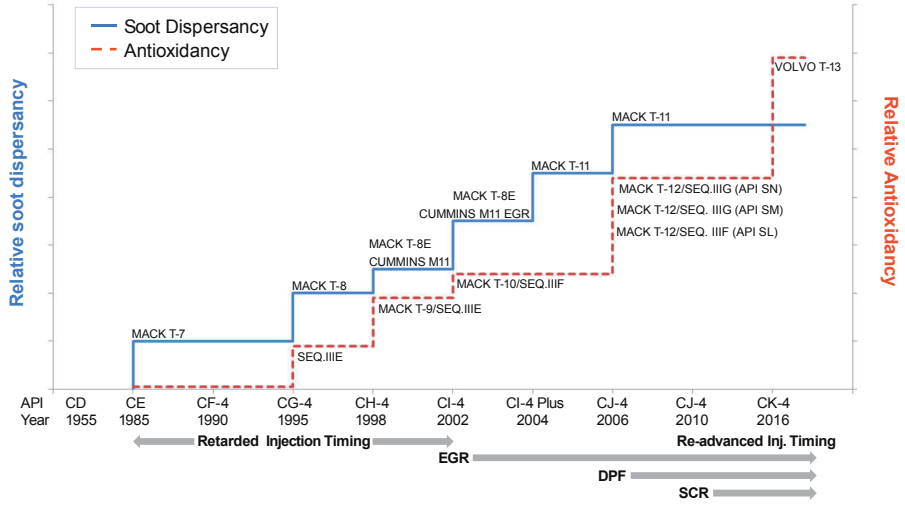
2002 EGR
Exhst. Gas Recirculation

2007 DPF
Diesel Particulate Filter

2010 SCR
Selective Catalytic Reduction

- Ever tightening emissions regulations drives evolution of engine hardware
- Have achieved near zero exhaust emissions for Class 8 On-Highway vehicles

Evolution of Heavy-Duty engine oil specifications



API CI-4 & CI-4 PLUS: Introduction to EGR

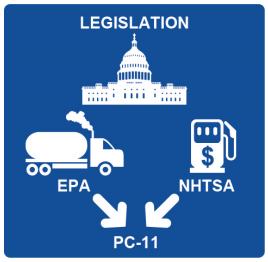
- Soot from EGR equipped engines soot was more difficult to disperse than non-EGR engines
  - Oils required a new dispersant specifically for EGR equipped engines
- EGR operation increased thermal load on vehicle cooling system
  - Oils required improved oxidation stability for higher operating temperature
- Test data suggested higher levels of TBN were needed
- If SOx, NOx and water vapor condense, sulfuric and nitric acids can form
  - Aluminum intake manifold can be attacked by acids and generate aluminum oxide (sandpaper), which is drawn into engine resulting in ring and liner wear
- API CI-4 engine test conditions established to minimize EGR condensation
- In June 2003, EMA formally requested an upgrade to API CI-4 category
- Following months of negotiation, agreement to an 'API Supplement' CI-4 PLUS was reached in April 2004
  - Mack T-11 (EGR soot handling test)
  - 90 cycle Kurt Orbhan (improved shear stability)

API CJ-4: Chemical constraints

- In 2007 HD engine emissions limits began phased-in reduction to reach 1/10th of October 2002 limits on NOx and PM
  - Requires exhaust after treatment (DPF, SCR)
  - On-highway diesel sulfur reduced from 500 ppm to 15 ppm
- Lack of performance test for after treatment compatibility drove chemical limits for Sulfated Ash, Phosphorus and Sulfur (SAPS)
  - SASH (sulfated ash) ≤ 1.0%(m)
  - Phosphorous ≤ 0.12%(m)
  - Sulfur ≤ 0.4%(m)
- Introduced four new tests to ensure protection of new technology
  - Cummins ISM (replacement for M11-EGR)
  - Cummins ISB (new valve train wear test)
  - Caterpillar C13 (multi-cylinder test for piston deposits and oil consumption)
  - Mack T-12 (replacement for T-10)
- API licensing started October 15, 2006

API CK-4 & FA-4: Oxidation & Fuel Economy

- New fuel economy and greenhouse gas rules began phased implementation in 2014 with full effect in 2018
  - Reduce CO2 by 270 million tons and save 530 million barrels of oil
- At the June 2011 ASTM meeting, the EMA issued a formal request for a new API performance category to help meet these new regulations
- Areas requested for improvement versus API CJ-4
  - Shear stability
  - Oxidation
  - Aeration
  - Bio-diesel compatibility (eventually dropped)
  - New lower viscosity oils to help deliver fuel economy performance
- API first license date was December 1, 2016



API CK-4 & FA-4: Why 2 API oil categories?

API CK-4

More Robust API CJ-4
Recommended by all OEMs
Full backward compatibility

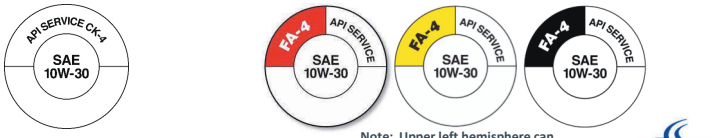
SAE xW-30 and xW-40
HTHSV > 3.5 mPa•s
API CK-4, ACEA E

API FA-4

Robust CJ-4 at lower viscosity
Some OEM's opted out
Not backward serviceable

SAE xW-30
HTHSV: 2.9 – 3.2 mPa•s
API FA-4, New ACEA F

API CK-4 has the same durability requirements as API FA-4 to minimize risks associated with the new lower viscosity fuel economy grades



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API CK-4 & FA-4: Test requirements

- Combination of New and Carry forward tests from API CJ-4

	Test	Performance Parameters	Fuel Sulfur
Legacy Tests	Caterpillar C13	Piston Deposits, Oil Consumption	15 ppm
	Caterpillar 1N	Aluminum Piston Deposits, Oil Consumption	500 ppm
	Cummins ISB	Valve Train Wear	15 ppm
	Cummins ISM	Valve Train Wear, Filter Plugging, Sludge	500 ppm
	Roller Follower Wear Test	Roller Follower Pin Wear	500 ppm
	Mack T-11	Soot Induced Viscosity Increase	500 ppm
	Mack T-11A	Sooted Oil Low Temperature Pumpability	500 ppm
	Mack T-12	Ring/Liner Wear parameters only	15 ppm
	Kurt Orbhan 90 cycle	Shear Stability Bench Test	No Fuel Used
New	Volvo T-13	Oxidation	15 ppm
	Caterpillar C13 Oil Aeration Test (COAT)	Oil Aeration	15 ppm

- Add OM 501LA, OM 646LA and Volvo D12D (or their replacements), and the DD13 Scuff test for OEM specifications

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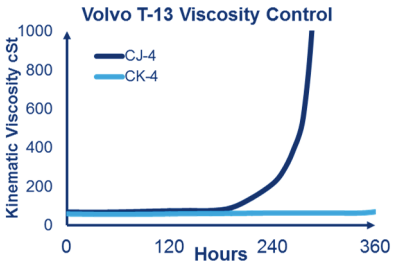
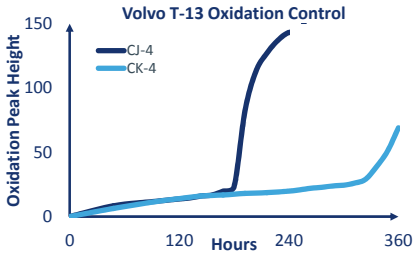
API CK-4 & FA-4: Improving oxidation

ASTM D8048 (Volvo T-13 Oxidation Test)

- 13L Mack MP8 diesel engine
- 360 hours steady-state test
- Oil temperatures:
  - 130°C main gallery
  - 140°C sump
- API CK-4 & FA-4 Limits:
  - T-13 FTIR Oxidation Peak Height: 125 max
  - KV 40C % increase (300-360 hr): 75% max
- **Drove more anti-oxidants into oil**
  - **Largest increase of any API oil category!**

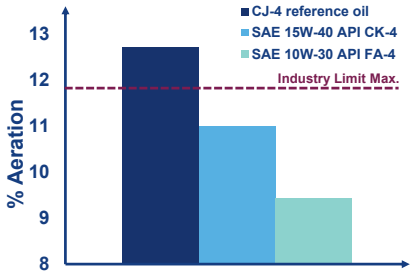


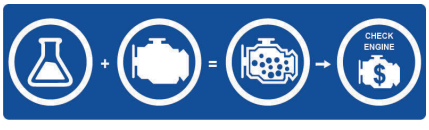


API CK-4 & FA-4: Improving aeration

ASTM D8047 (Caterpillar-C13 Oil Aeration Test)

- 13 L diesel engine
- 50 hours duration
- Aeration is measured real time via a Micromotion meter which measures oil density
- API CK-4 & FA-4 Limits:
  - Average % aeration 40-50 hrs: 11.8% max
- **Drove rebalance of additives, promotes lighter SAE viscosity grades**





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Other current HDD performance categories

OEM specifications

OEM	Specification	Base Industry Specification	Differences
Caterpillar	ECF-1-a	CH-4	+ Caterpillar 1P; SASH restrictions
	ECF-2	CI-4/CI-4 PLUS	+ Caterpillar C13; SASH restrictions
	ECF-3	CJ-4	None
Detroit Diesel	DFS 93K215	CH-4	+ Mitsubishi 4D34T4; - Mack T-9 + Mack T-10; + OM501LA
	DFS 93K214	CI-4 PLUS	+ OM501LA
	DFS 93K218	CJ-4	+ OM501LA; + OM646LA
	DFS 93K222	CK-4	+ OM501LA; + OM646LA +DD13 Scuff
	DFS 93K223	FA-4	+ OM501LA; + OM646LA +DD13 Scuff

Performance you can rely on.

Other current HDD performance categories

OEM specifications

OEM	Specification	Base Industry Specification	Differences
Mack	EO-N	CI-4	enhanced Mack T-10, T-8E, Cummins M11-EGR, Seq. IIIF requirements
	EO-N Premium Plus '03	CI-4PLUS	enhanced Mack T-11, T-10, Cummins M11-EGR, Seq. IIIF requirements
	EO-O Premium Plus	CJ-4	enhanced Cummins ISM, ISB, and Mack T-12 performance; + Volvo D12D; + Seq. IIIG
	EOS-4.5	CK-4	enhanced Cummins ISM, ISB, Mack T-12 and Volvo T-13 performance; + Volvo D12D

Other current HDD performance categories

OEM specifications

OEM	Specification	Base Industry Specification	Differences
Cummins	CES 20078	CI-4PLUS	+ Seq. IIIF wear; + Mitsubishi 4D34T4; + min TBN
	CES 20081	CJ-4	enhanced Cummins ISM, ISB, and Mack T-12 performance
	CES 20086	CK-4	enhanced Cummins ISM, ISB, Mack T-12 and Volvo T-13 performance
	CES 20087	FA-4	enhanced Cummins ISM, ISB, Mack T-12 and Volvo T-13 performance

Military HD specs

- Combine diesel and gasoline engine tests with transmission tests
- MIL-PRF-2104K
  - 2104K is roughly equivalent to 2104J + adds SCPL “Single Common Powertrain Lubricant” grade (all-season lubricant providing extended drain intervals and reduced fuel consumption)
  - 2104J is roughly equivalent to API CI-4 + Base oil viscosity and SASH limits replace DD 2-stroke test which is no longer available
  - 2104H is roughly equivalent to API CI-4 + DD 2-stroke test 6V92TA
  - 2104G is roughly equivalent to API CG-4 / CF + DD 2-stroke test 6V92TA
  - All require partial Caterpillar TO-4 and Allison C4 testing requirements but not full approvals
- No longer a significant factor in heavy duty diesel engine oil formulation

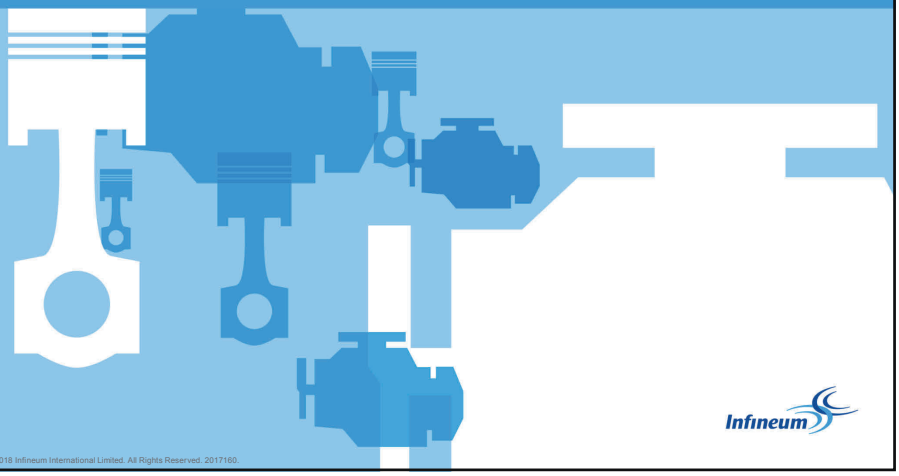
Summary of diesel engine oil performance criteria

- Low-temperature sludge control is not critical
- High-temperature soot dispersion was important for wear control, but is less so for low soot modern diesel engines
- Ring sticking must be controlled to prevent hone loss
- Valve train wear protection is significant, especially for new lower viscosity FA-4 oils
- Fuel sulfur levels can contribute to excessive ring and liner wear
- Incorporation of EGR tests in API CI-4 dramatically changed formulation evolution
  - Increased TBN, dispersant and antioxidant requirements
- Chemical constraints of API CJ-4 protected modern exhaust after treatment systems
  - Reduced TBN, inclusion of supplemental anti-wear additives
- Anti-oxidancy is key performance parameter with the introduction of the Volvo T-13
  - Significant increase in anti-oxidant levels

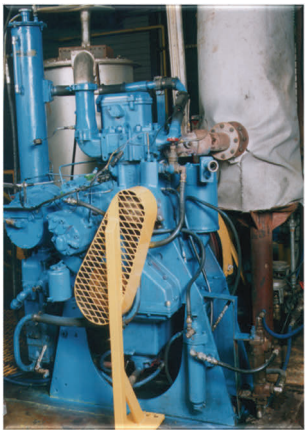
Summary

- HDD lubricants meet API ‘C’ or ‘F’ category requirements and are formulated to be extra robust for diesel engines that operate under “severe” conditions
- Historically have had higher levels of detergency, dispersancy, and antiwear components and have been formulated to higher SAE viscosity grades than typical passenger car oils
- Continued tightening of emission limits (NOx, Particulates, GHG) have a significant impact on diesel engine design and operation, fuels and lubricant formulation
  - Drives evolution of heavy duty diesel engine oil specifications
  - Focus has been on improving soot handling and oxidation performance
  - Addition of EGR significantly impacted HDD formulation
  - Chemical limits with introduction of API CJ-4 limited use of some key components, but CJ-4 is the most robust API HD category ever developed
  - API CK-4 and FA-4 HDD oils were developed with significantly more oxidation performance, improved aeration and shear stability as well as a new subcategory of lower viscosity oils to meet fuel consumption and GHG Phase I regulations

Appendix



Caterpillar 1N and C13 tests

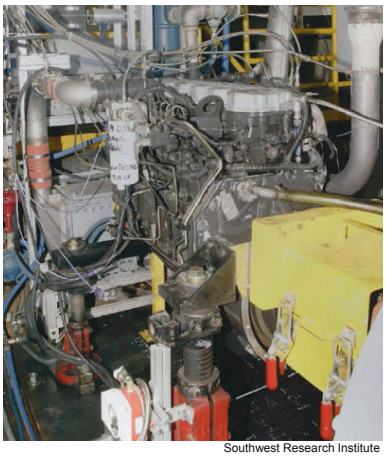


Cat 1N

Southwest Research Institute

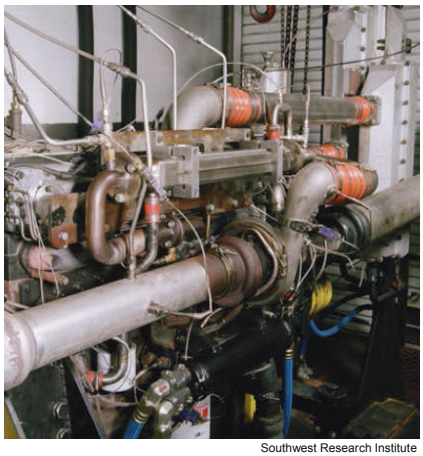
Cat C13

Cummins ISB and ISM tests



Southwest Research Institute

Cummins ISB



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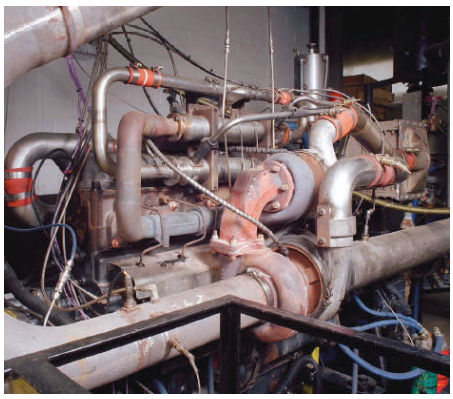
Cummins ISM

Mack T-11 and T-12 tests



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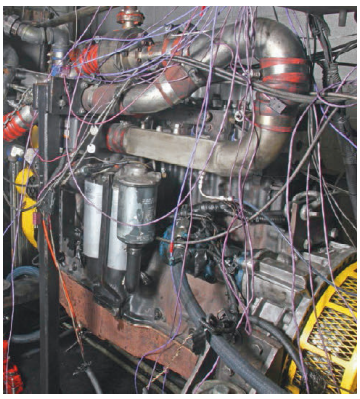
Mack T-11



Southwest Research Institute

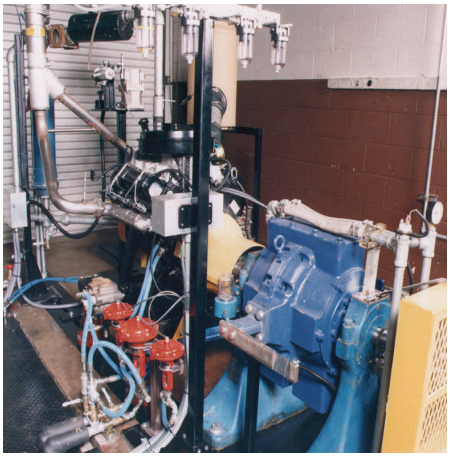
Mack T-12

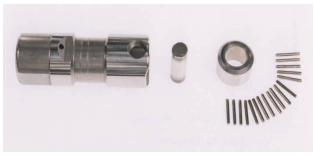
Volvo T-13 test

Southwest Research Institute

Volvo T-13

Roller follower wear test





API Categories for Diesel Engines

DIESEL ENGINES (Follow your vehicle manufacturer's recommendations on oil performance levels)

Category	Status	Service
CK-4	Current	API Service Category CK-4 describes oils for use in high-speed four-stroke cycle diesel engines designed to meet 2017 model year on-highway and Tier 4 non-road exhaust emission standards as well as for previous model year diesel engines. These oils are formulated for use in all applications with diesel fuels ranging in sulfur content up to 500 ppm (0.05% by weight). However, the use of these oils with greater than 15 ppm (0.0015% by weight) sulfur fuel may impact exhaust aftertreatment system durability and/or oil drain interval. These oils are especially effective at sustaining emission control system durability where particulate filters and other advanced aftertreatment systems are used. API CK-4 oils are designed to provide enhanced protection against oil oxidation, viscosity loss due to shear, and oil aeration as well as protection against catalyst poisoning, particulate filter blocking, engine wear, piston deposits, degradation of low- and high-temperature properties, and soot-related viscosity increase. API CK-4 oils exceed the performance criteria of API CJ-4, CI-4 with CI-4 PLUS, CI-4, and CH-4 and can effectively lubricate engines calling for those API Service Categories. When using CK-4 oil with higher than 15 ppm sulfur fuel, consult the engine manufacturer for service interval recommendations.
CJ-4	Current	For high-speed four-stroke cycle diesel engines designed to meet 2010 model year on-highway and Tier 4 non-road exhaust emission standards as well as for previous model year diesel engines. These oils are formulated for use in all applications with diesel fuels ranging in sulfur content up to 500 ppm (0.05% by weight). However, the use of these oils with greater than 15 ppm (0.0015% by weight) sulfur fuel may impact exhaust aftertreatment system durability and/or drain interval. API CJ-4 oils exceed the performance criteria of API CI-4 with CI-4 PLUS, CI-4, CH-4, CG-4 and CF-4 and can effectively lubricate engines calling for those API Service Categories. When using CJ-4 oil with higher than 15 ppm sulfur fuel, consult the engine manufacturer for service interval.
CI-4	Current	Introduced in 2002. For high-speed, four-stroke engines designed to meet 2004 exhaust emission standards implemented in 2002. CI-4 oils are formulated to sustain engine durability where exhaust gas recirculation (EGR) is used and are intended for use with diesel fuels ranging in sulfur content up to 0.5% weight. Can be used in place of CD, CE, CF-4, CG-4, and CH-4 oils. Some CI-4 oils may also qualify for the CI-4 PLUS designation.
CH-4	Current	Introduced in 1998. For high-speed, four-stroke engines designed to meet 1998 exhaust emission standards. CH-4 oils are specifically compounded for use with diesel fuels ranging in sulfur content up to 0.5% weight. Can be used in place of CD, CE, CF-4, and CG-4 oils.

Source: http://www.api.org/~/media/Files/Certification/Engine-Oil-Diesel/Publications/MOTOR_OIL_GUIDE_120116_FINAL_WEB.pdf

API Categories for Diesel Engines continued

DIESEL ENGINES (Follow your vehicle manufacturer's recommendations on oil performance levels)

Category	Status	Service
CF-4	Obsolete	**CAUTION:** Not suitable for use in most diesel-powered automotive engines built after 2009.
CF-2	Obsolete	**CAUTION:** Not suitable for use in most diesel-powered automotive engines built after 2009. Two-stroke cycle engines may have different lubrication requirements than four-stroke engines, so the manufacturer should be contacted for current lubrication recommendations.
CF	Obsolete	**OBSOLETE:** Introduced in 1994. For off-road, indirect-injected and other diesel engines including those using fuel with over 0.5% weight sulfur. Can be used in place of CD oils.
CE	Obsolete	**CAUTION:** Not suitable for use in most diesel-powered automotive engines built after 1994.
CD-II	Obsolete	**CAUTION:** Not suitable for use in most diesel-powered automotive engines built after 1994.
CD	Obsolete	**CAUTION:** Not suitable for use in most diesel-powered automotive engines built after 1994.
CC	Obsolete	**CAUTION:** Not suitable for use in most diesel-powered engines built after 1990.
CB	Obsolete	**CAUTION:** Not suitable for use in most diesel-powered engines built after 1961.
CA	Obsolete	**CAUTION:** Not suitable for use in most diesel-powered engines built after 1959.
FA-4	Current	API Service Category FA-4 describes certain XW-30 oils specifically formulated for use in select high-speed four-stroke cycle diesel engines designed to meet 2017 model year on-highway greenhouse gas (GHG) emission standards. These oils are formulated for use in on-highway applications with diesel fuel sulfur content up to 15 ppm (0.0015% by weight). Refer to individual engine manufacturer recommendations regarding compatibility with API FA-4 oils. These oils are blended to a high temperature high shear (HTHS) viscosity range of 2.9cP–3.2cP to assist in reducing GHG emissions. These oils are especially effective at sustaining emission control system durability where particulate filters and other advanced aftertreatment systems are used. API FA-4 oils are designed to provide enhanced protection against oil oxidation, viscosity loss due to shear, and oil aeration as well as protection against catalyst poisoning, particulate filter blocking, engine wear, piston deposits, degradation of low- and high-temperature properties, and soot-related viscosity increase. API FA-4 oils are not interchangeable or backward compatible with API CK-4, CJ-4, CI-4 with CI-4 PLUS, CI-4, and CH-4 oils. Refer to engine manufacturer recommendations to determine if API FA-4 oils are suitable for use. API FA-4 oils are not recommended for use with fuels having greater than 15 ppm sulfur. For fuels with sulfur content greater than 15 ppm, refer to engine manufacturer recommendations.

Source: http://www.api.org/~/media/Files/Certification/Engine-Oil-Diesel/Publications/MOTOR_OIL_GUIDE_120116_FINAL_WEB.pdf

API Categories for Diesel Engines

- API CF (Obsolete)
- Spec designed for pre-chamber engines operating in high sulfur diesel fuel environments
- The Cat 1M test was being developed using Cat 1K hardware to pass straight grades and high TBN (20-30) oils that the Cat 1K could not tolerate
- Cat 1M was withdrawn in favor of a modified Cat 1G2
- The modified 1G2 was eventually called the Cat 1M-PC

API Categories for Diesel Engines

- API CF-2 (Obsolete)
- Two-stroke diesel specification
- Comprises 6V92TA, L38 and Cat 1M-PC with different limits than CF
- Cat 1M-PC limit is 100 WTD maximum using different deposit weighting scheme compared to API CF
- CF-2 very difficult to achieve in multigrades