Engine Oil Specifications and Trends

Functional Products Inc.

January 2021

Overview

- Active engine oil specifications as far back as 1998
  - Passenger car, diesel, and heavy duty
- US, Europe, Asia-Pacific specifications
- Changes in engine oil requirements vs. new engine/emission technologies
- Topics will focus on viscometrics and shear stability
  - Functional Products as supplier of viscosity modifiers and VI improver
- *How to formulate will be covered in 'Driveline Formulating'*

Functional Products's Goal

- Training our audience on the basics of modern engine oil specifications, the key organizations, and surrounding history/trends that shaped the market

- Get the fundamentals bench tests right…
  - HTHS
  - NOACK
  - Cold crank simulator (CCS) and mini rotary viscometer (MRV)
  - Shear stability (Sequence IIX and diesel injector)
  - Sulfated Ash, Sulfur and Phosphorus (SAPS)

- … before going after $10,000 - $100,000 Sequence tests

Key Players

- Organizations
  - American Petroleum Institute - API (America)
  - International Standardization and Approval Committee - ILSAC (global)
  - European Automobile Manufacturers' Association - ACEA (Europe)
  - Japanese Automotive Standards Organization - JASO (Japan)

- OEMs w/ their own specifications
  - MAN (Europe)
  - General Motors - GM (America)
  - Detroit Diesel
  - Cummins

- Other
  - Individual passenger car manufacturers (many using ACEA specs)
  - Global DLD

Not an exhaustive list

API and ILSAC Gas Engine

- API is oldest engine oil quality certification program (1930's)
  - Minimum performance specification that other specs are built on
    - Maintains several specs to support existing vehicles

- ILSAC adds new tests and modifies test limits to API minimum spec
  - Maintains one or two active specs, focused on new vehicle trends

API SP
XW-16, XW-20, XW-30

"Donut" logo

ILSAC GF-6A
XW-20, XW-30

"Starburst"

ILSAC GF-6B
0W-16

Specifications

- Developed jointly through various organizations and OEMs

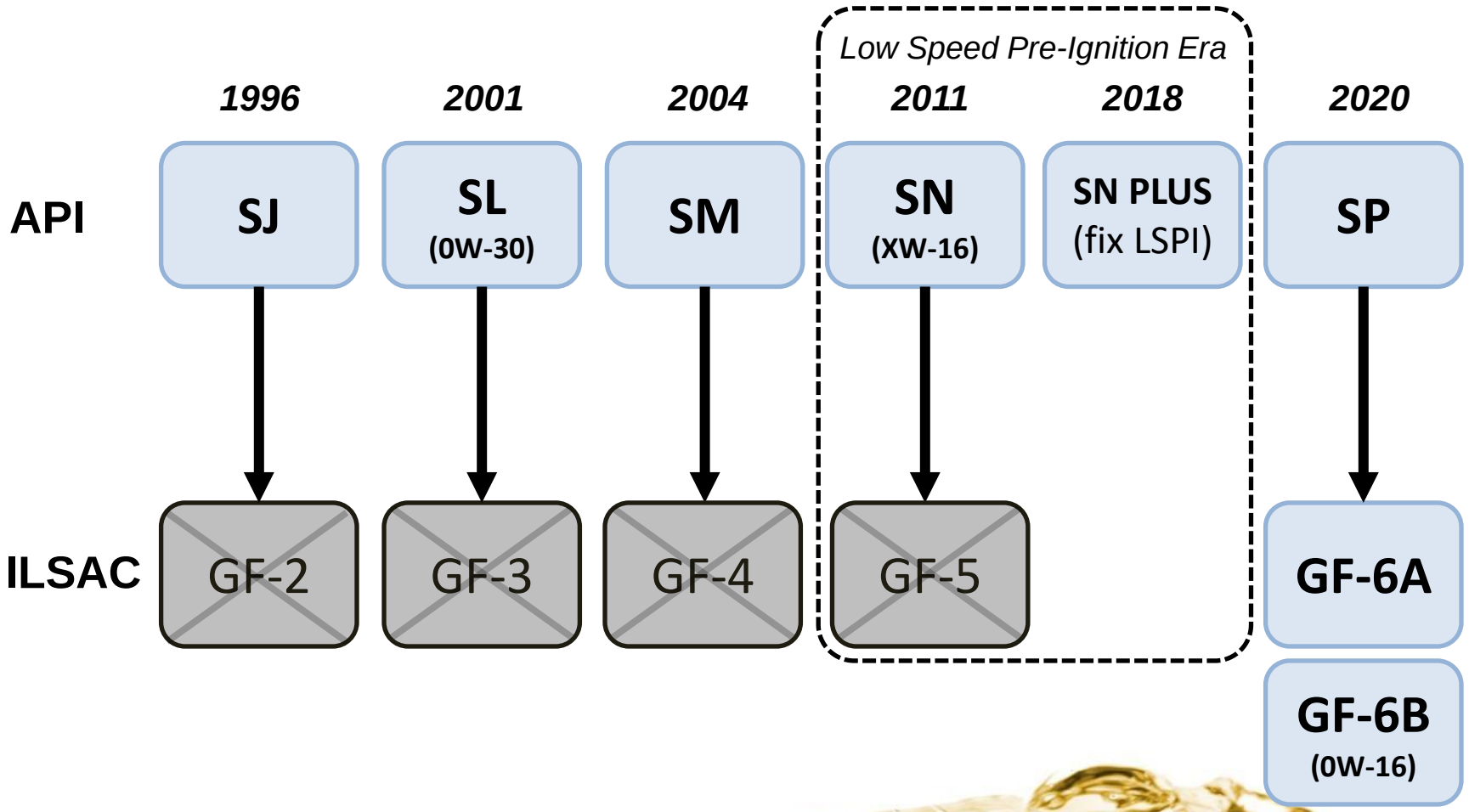
- Updated every 5-10 years to address new technology and policy
  - Fuel efficiency regulations
  - NOx / SOx regulations
  - New fuels (unleaded, biodiesel, ethanol)
  - New hardware (turbochargers, denser engines, direct fuel injection)

- A specification contains a list of agreed upon bench and field tests
  - Bench test - $100 to $1000 each
  - Field or engine rig tests (“Sequence”) - $10,000 to $100,000 each

- Ex: API SN PLUS, ~20 ASTM tests, ~9 Sequences
  - Million dollar effort

API vs. ILSAC Map

- Fairly straightforward



API Engine

	API SJ	API SL	API SM	API SN	API SP
Year	1996	2001	2004	2011	2020
Grades	0W,5W-20 5W,10W-30	0W,5W-20 **0W**,5W,10W-30	0W,5W-20 0W,5W,10W-30	**0W,5W-16** 0W,5W-20 0W,5W,10W-30	0W,5W-16 0W,5W-20 0W,5W,10W-30
HTHS (D4683)	SAE J300	SAE J300	SAE J300	SAE J300	SAE J300
Sequence VIII Shear (D6709)	Stay In Grade	Stay In Grade	Stay In Grade	Stay In Grade	Stay In Grade
K-O Shear (D6278/D7109)					XW-16, >5.8 cSt after 30 cycles
NOACK (D5800)	< 22%	**< 15%**	< 15%	< 15%	< 15%
Sulf. & Phos. (D5185)	< 0.1% P	**< 0.5-0.7% S** 0.06-0.08%P	< 0.5-0.7% S 0.06-0.08% P	< 0.5-0.7% S 0.06-0.08% P	< 0.5-0.6% S 0.06-0.08% P

- May also have a PLUS version of each spec to address issues without rewriting a new specification (low speed pre-ignition and API SN PLUS)

API and ILSAC Differences

- Typically same performance tests and limits
  - ILSAC requires fuel economy testing (Seq. VIE; Seq. VIF for 0W-16)
    - API has equivalent but optional “Resource Conserving” add-on

- API SN vs. GF-5
  - ILSAC specifically requires Seq. VIII shear on XW-20 to remain >5.6 cSt
    - SAE J300 viscosity ranges rewritten later in 2015
  - SN PLUS added Seq. IX LSPI test as stop gap, ILSAC waited for GF-6

- API SP vs. GF-6
    - Co-developed to address LSPI (Seq. IX), timing chain wear (Seq. X)

    - ILSAC separates specs and labeling for XW-20 / XW-30 (GF-6A) vs. XW-16 (GF-6B)

Sequence VIII Shear

- CLR engine test
  - From API SJ and on
  - 0.7L, single piston, gas engine @ 3150 rpm
  - Lubricant at 143°C
  - Copper alloy sleeve in the piston
  - After 10 hrs, lubricant is cleaned and measured

- High heat but low lubricant pressure/speed
  - Milder than 30 cycle D6278 diesel injector
    - D6278 shear in grade should pass Seq. VIII

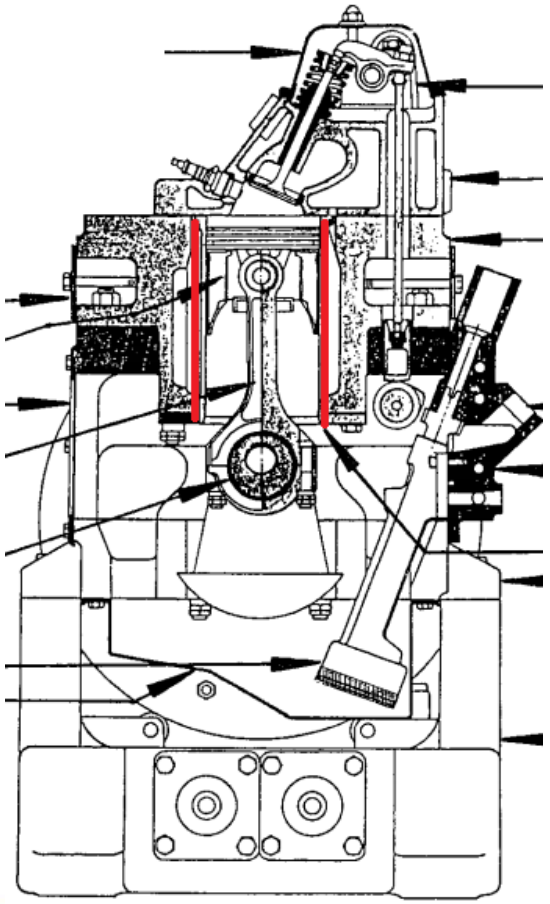


FIG. 1 Sequence VIII Power Section

Engine Tests / Sequences

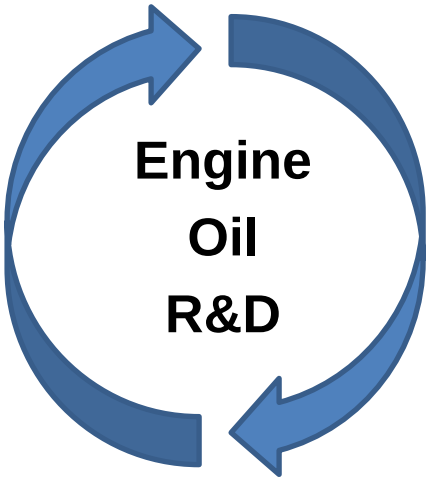
- Tests performed in real, isolated engines to evaluate performance of engine oils in different engines for specific performance

  - Engine taken apart and rated for wear/deposits/corrosion
  - Updated with new parameters, valve trains, engine designs
    - Denoted as IIIA.. IIIF.. IIIGA, IIIGB, etc.

Sequence	Purpose	Started In	
III	Oil thickening, piston deposits, stuck rings	API SH, GF-1	1993
IV	Cam wear on overhead cam engines	API SL, GF-3	2001
V	Engine sludge and varnish	API SL, GF-3	
VI	Fuel efficiency	API SL, GF-3	
VIII	Bearing wear, corrosion, and oil shear stability	API SJ, GF-5	2011
IX	Low speed pre-ignition (LSPI) with turbocharger	API SN+, GF-5	
X	Timing chain wear	API SP, GF-6	2020

Brief History of Engine Oil

Governments
Regulators
Public Policy



Without outside influence, goals are always:

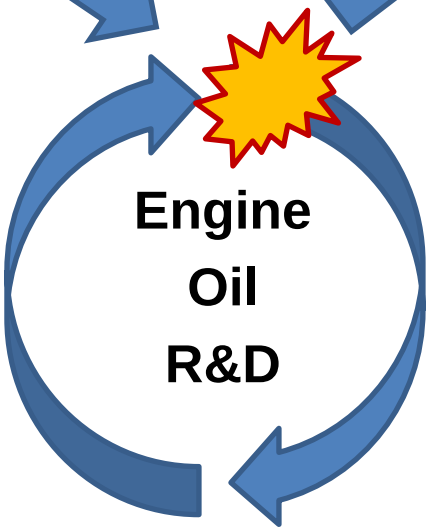
- Less oxidation/sludge/deposits
- Lower corrosion
- Lower wear
- Longer oil change interval

New Engine, Drivetrain, Exhaust Designs

Brief History of Engine Oil

Governments
Regulators
Public Policy

SOx/CO_2/FE Regulations



New environmental specifications

Low HTHS 0W-16

Shear stable VM?

Timing chain wear!

Low SAPS

Low S base oils?

S/P-free antiwear?

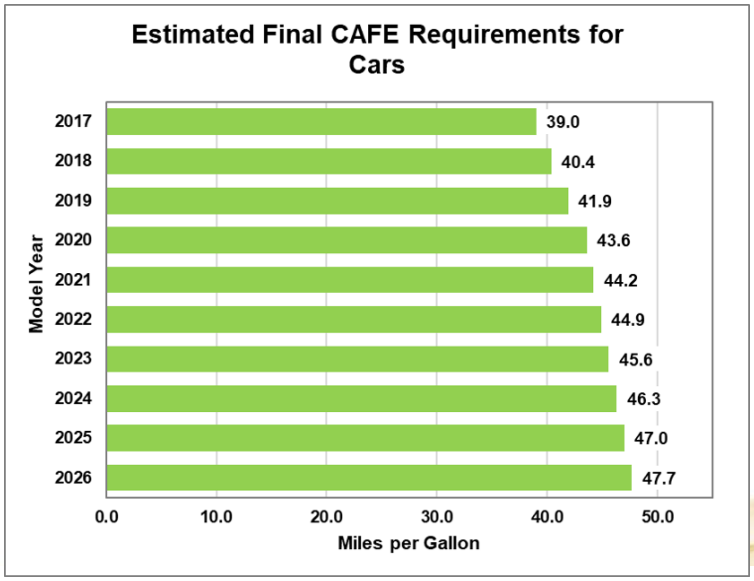
Ashless TBN?

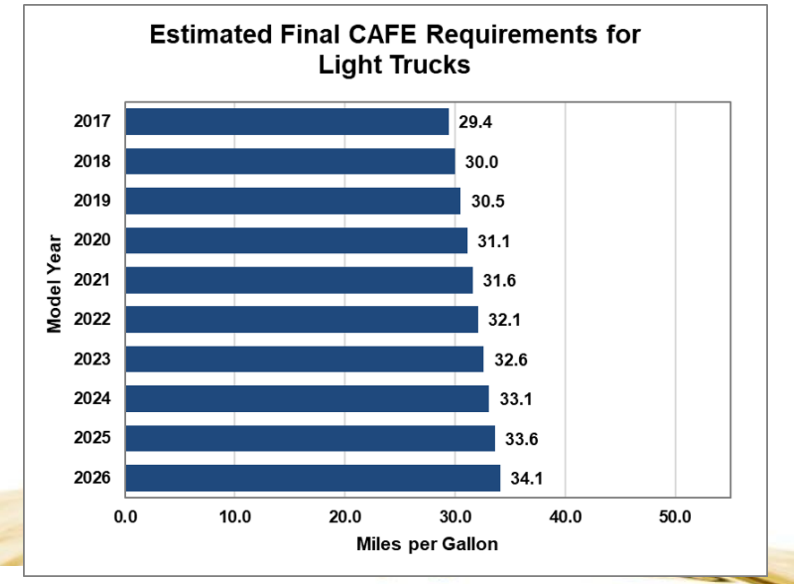
New Engine, Drivetrain, Exhaust Designs

Case 1: CAFE Regulations

- Corporate Average Fuel Economy (CAFE)
  - Mandated average mile per gallon for an auto maker's yearly car output
    - mpg target increases yearly

- Penalty is $5.50 per 0.1 mpg ($55/mpg) over the limit per car
  - 1 million cars x $55/mpg x 2 mpg overage = $110M
    - From 2016-2019 the rate was debated at **$14 per 0.1 mpg** ($280M)





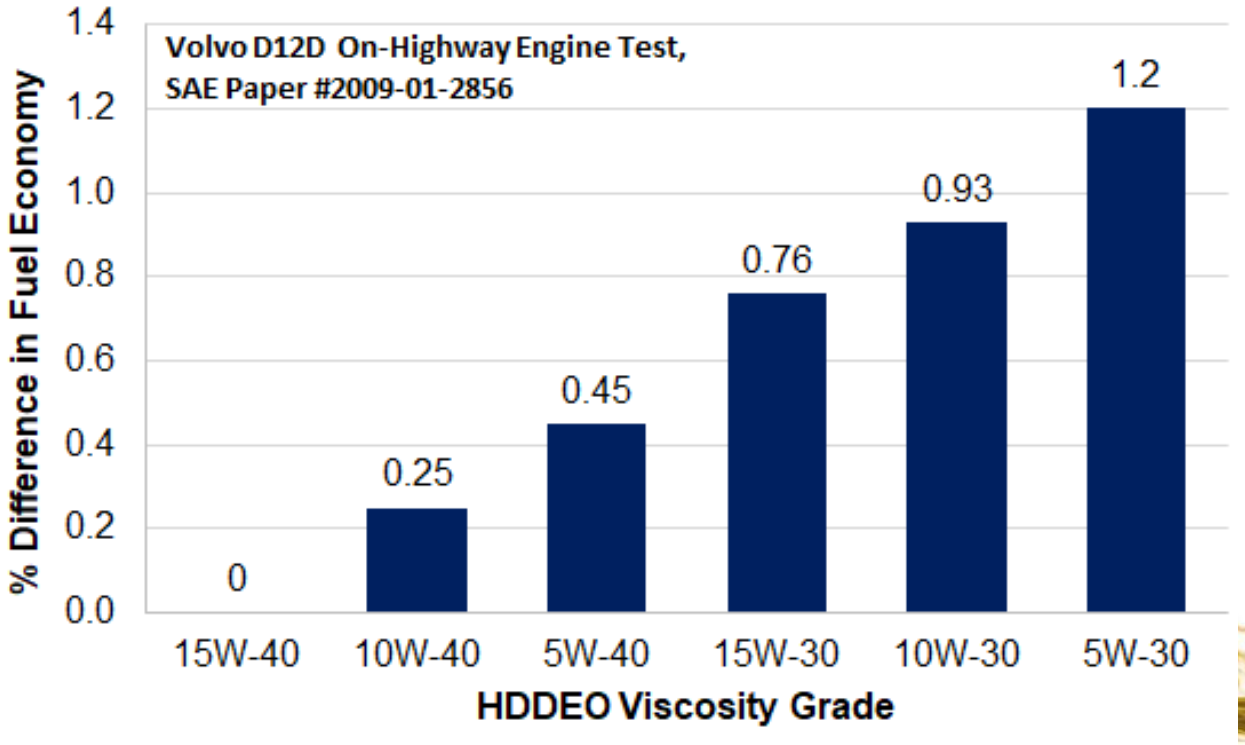
https://www.nhtsa.gov/laws-regulations/corporate-average-fuel-economy
https://eelp.law.harvard.edu/2019/08/corporate-average-fuel-economy-penalties/
US NHTSA, Safer Affordable Fuel-Efficient Vehicles Rule, March 31st 2020

Fuel Economy Strategies

- **Lubricants and fuels**
  - Lower viscosity, low boundary friction
  - Alternative fuel or dual fuel capability (provides ‘credit’ up to ~1 mpg)
- Materials and surface finishing in drivetrain
- Lightweighting
  - Smaller turbocharged and gas direct injection (GDI) engines
  - Aluminum body
- Gadgets
  - Variable valve timing and continuously variable transmissions (CVT)
  - Regenerative breaking
  - Idle Stop-And-Go
- Electric or hybrid electric

Lubricants and FE

- Cost to develop a new vehicle – $800M (update) - $6B (from scratch)
  - $36,000 average cost of car to consumer to implement improvements
- Cost to develop new engine oil – $1M
  - $50 PCMO / $250 HDDEO oil change to implement improvements



https://www.autoblog.com/2010/07/27/why-does-it-cost-so-much-for-automakers-to-develop-new-models/

van Dam, W., Kleijwegt, P., Torreman, M., and Parsons, G., "The Lubricant Contribution to Improved Fuel Economy in Heavy Duty Diesel Engines," SAE Technical Paper 2009-01-2856, 2009

Brief History of Engine Oil 2

Governments
Regulators
Public Policy

SOx/CO_2/FE Regulations

Engine Oil R&D

New environmental specifications

Low HTHS 0W-16

Shear stable VM?

Timing chain wear!

Low SAPS

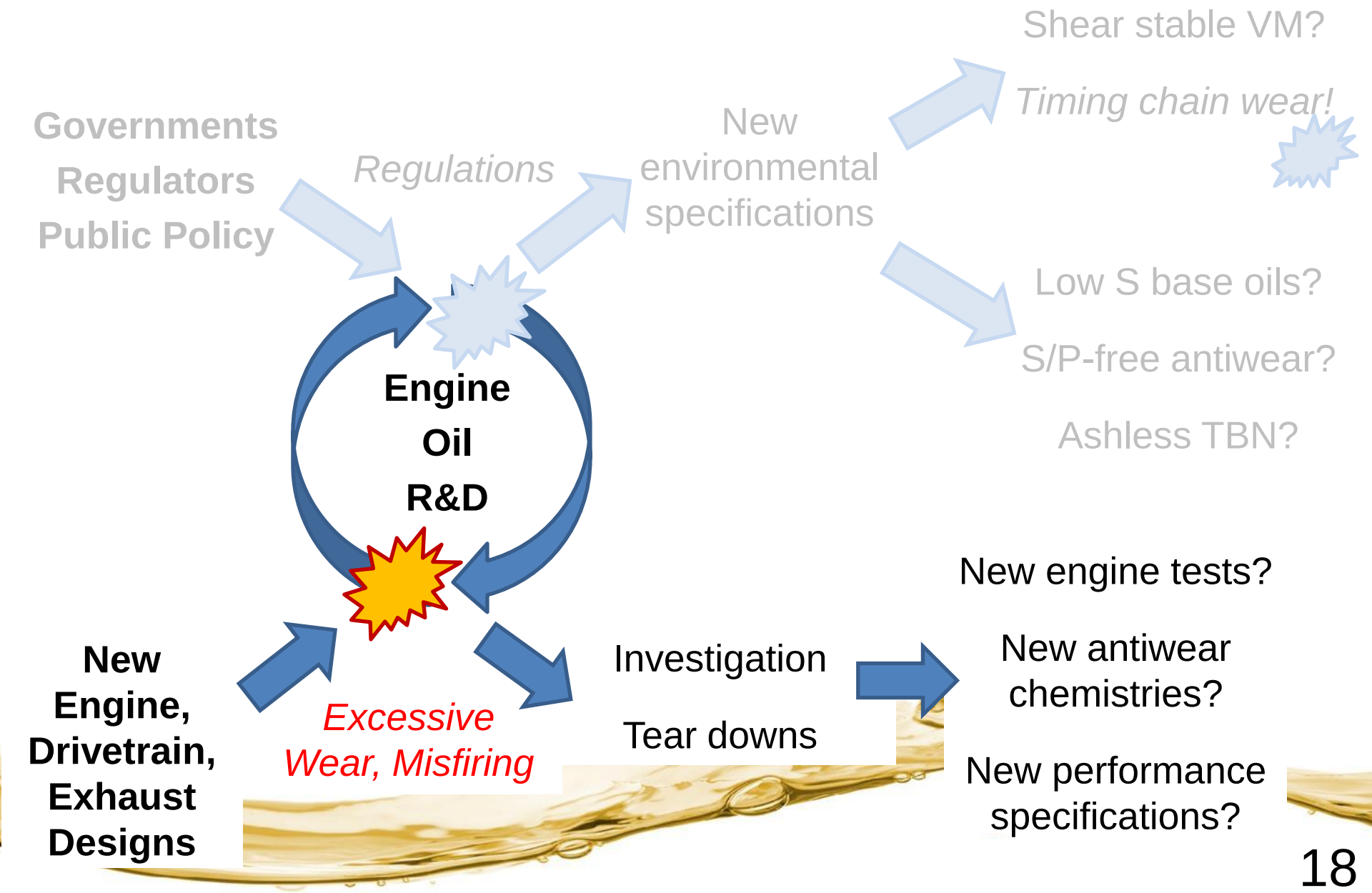
Low S base oils?

S/P-free antiwear?

Ashless TBN?

New Engine, Drivetrain, Exhaust Designs

Brief History of Engine Oil 2

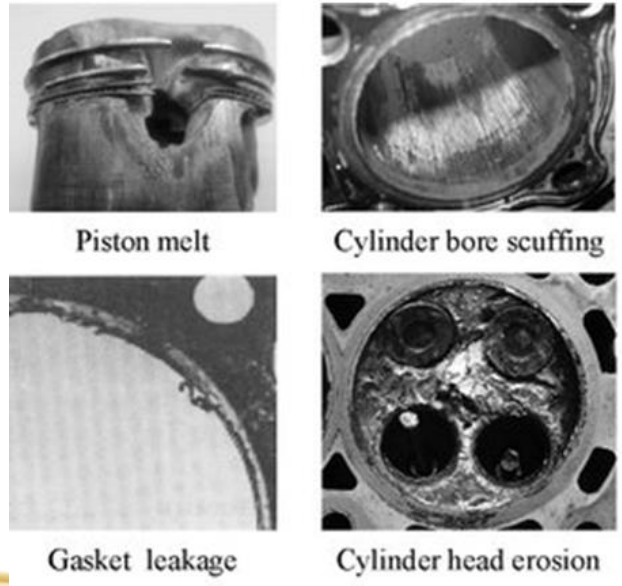


Case 2: Low Speed Pre-Ignition

- Misfiring in direct inject turbocharged engines at low speed, heavy load
  - Random fuel and air ignition before the spark
    - Onboard knock detection unable to correct for LSPI's randomness
      - High pressure causes damage

- 300-700 psi in engine under normal driving conditions
  - 1300-2000 psi during LSPI – racing engine conditions

Normal Engine Knock



LSPI "Super Knock"

Z. Wang, H. Liu, R. Reitz, Knocking combustion in spark-ignition engines
June 2017Progress in Energy and Combustion Science 61:78-112

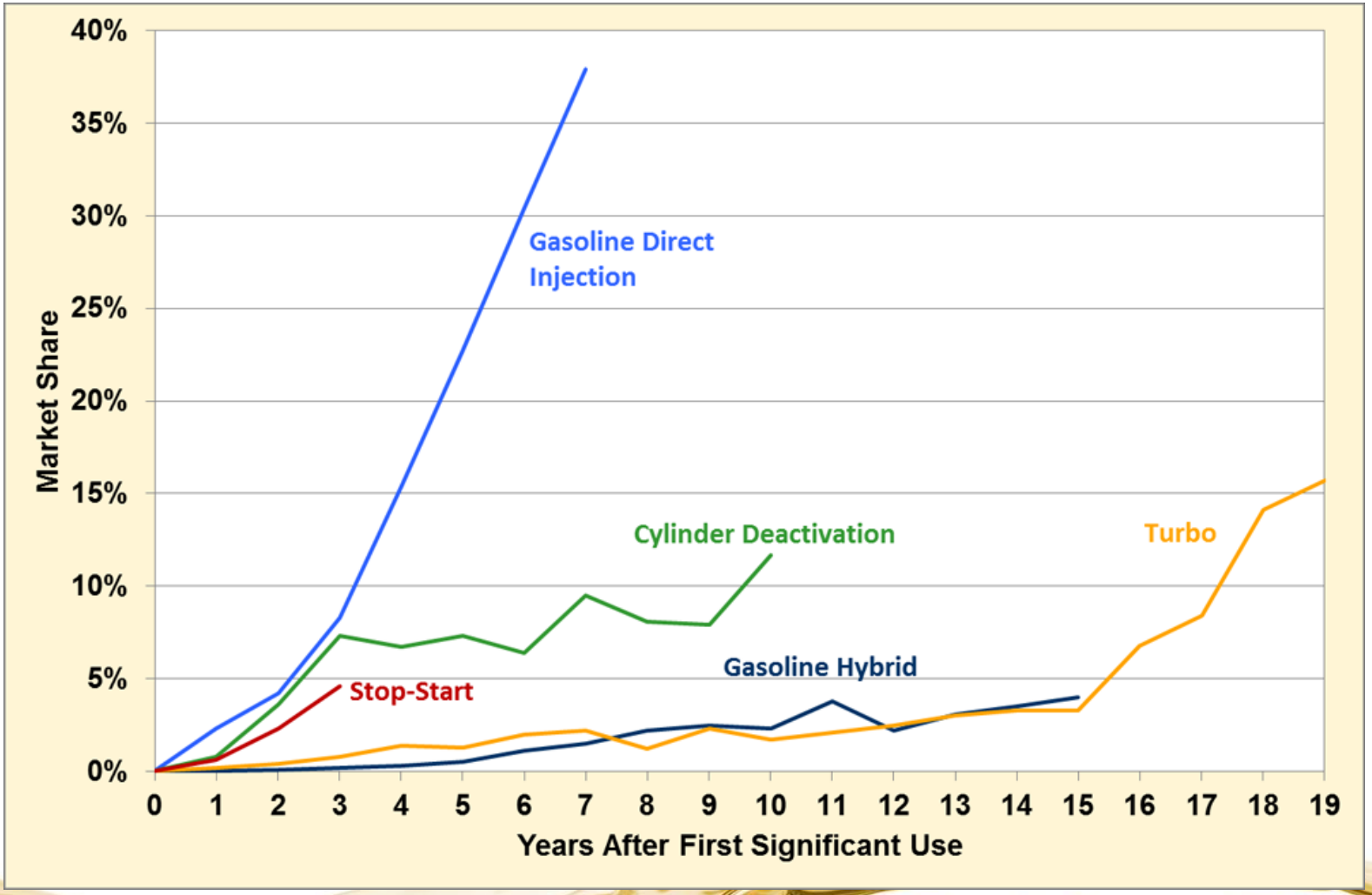
LSPI Investigation

- LSPI thought to be a collision of several different trends:
  - Smaller, hotter engine design
    - Direct injection spray prone to mixing fuel/lube at edge of cylinder
    - Turbocharged engines cruise at speed/load favoring LSPI events
  - Lubricant involvement
    - Fuel/lube droplets from GDI fuel dilution burn and ignite fuel
    - API SL / GF-3 reduced phosphorus (ZDDP) limits leading to more AW
      - Calcium compounds and solid additives correlated with LSPI
- Sequence IX test developed for API SN PLUS and ILSAC GF-6

Elliott, I., Cherpeck, R., Maria, A., and Gunawan, T., "Alternative Engine Oil Formulating Solutions to Reduce Low Speed Pre-Ignition," SAE Technical Paper 2019-01-2153, 2019

Non-Lube Trends for FE

- GDI dominates from 2007 to 2014 (GF-4 in 2004, GF-5 in 2011)



Oak Ridge National Laboratory, *2014 Vehicle Technologies Market Report*, ORNL/TM-2015/85, March 2015.

API Diesel

- Diesel combustion cycle
  - Air compressed first then fuel is injected for combustion
  - Higher fuel economy and energy density per gallon
  - Pressures at 2000-2500 psi (2x gasoline)

- Diesel less refined than gasoline
  - Various levels of sulfur depending on grade and market up to 0.5%
    - Trend for ultralow sulfur diesel (15 ppm) started in 2006 (CJ-4)
  - More soot and particulate, SO_x and NO_x during combustion
    - Abrasive wear and corrosion
      - Sludge and viscosity buildup
  - Higher pressures, more blow-by from cylinder into the oil

API Diesel: CH to CK/FA

- CJ-4 was defining year for modern low emission diesel specifications

	API CH-4	API CI-4	API CJ-4	API CK-4	API FA-4
Year	1998	2002	2006	2017	2017
Grades	10W-30 15W-40		XW-30 XW-40	XW-30 XW-40	XW-30
HTHS (D4683)			>3.5	>3.5	2.9 – 3.2
K-O Shear (D6278/D7109)	In grade, 30 cycle	In grade, 30 cycle	In grade, 90 cycle	In grade, 90 cycle; 5,10W-40: >12.8	In grade, 90 cycle
NOACK (D5800)	<20: XW-30 <18: XW-40	<15	<15 <10: 10W-30	<13	<13
SAPS (D874)			< 1%	< 1%	< 1%
Sulf. & Phos. (D5185)			.12% P .40% S	.12% P .40% S	.12% P .40% S

API Diesel Engine Tests

- Only Sequence IIIF and IIIG carried over from PCMO engine oil testing, dropped as of CK-4

- Diesel engine tests typically based on OEM, examples:
  - Mack
    - T-11 – viscosity increase with soot (CJ-4 and on)
    - T-12 – cylinder wear with turbocharger (CJ-4 and on)
    - T-13 – oxidation, viscosity increase for extended life (**new for CK-4**)
  - Cummins
    - ISM – engine wear and deposits (CJ-4 and on)
    - ISB – valve train wear (CJ-4 and on)
  - Caterpillar
    - 1N – low sulfur fuel version of 1K (CH-4 and on)
    - COAT – oil aeration test (**new for CK-4**)

ACEA

- Most ‘complex’ engine oil specification scheme
  - Categories for different performance and sulfated ash levels
    - Covers a variety of European car makers who will use as baseline

- Naming scheme is more like an ASTM spec – updated every few years
  - ACEA C1-2010 becomes C1-2016 until obsolete
    - vs. ILSAC GF-4 replaced by GF-5, API CH-4 by CI-4, etc.

- ACEA A/B and C for gasoline and light duty diesel
  - Diesel passenger car more common in Europe than Americas

- ACEA E for heavy duty diesel
  - Future F category for low viscosity diesel like API FA-4

ACEA and Emissions

- Main differentiator for subcategories is SAPS level
  - "Sulfated ash, phosphorus and sulfur" (ASTM D874)
  - Less S (and N) for lower SOx and NOx emissions for catalytic converters
  - Less sulfated ash for more efficient gas/diesel particulate filters

  - Includes sulfur from both additives and base oils (Group I → II or III)

Exhaust Aftertreatment Diagram

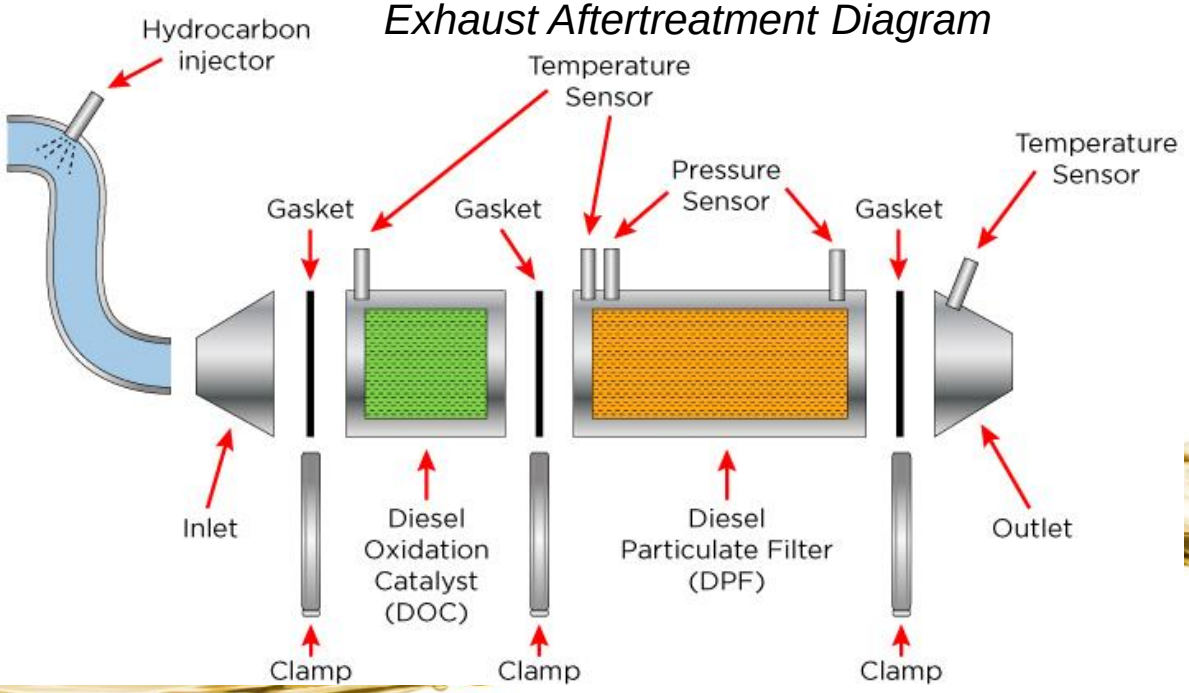


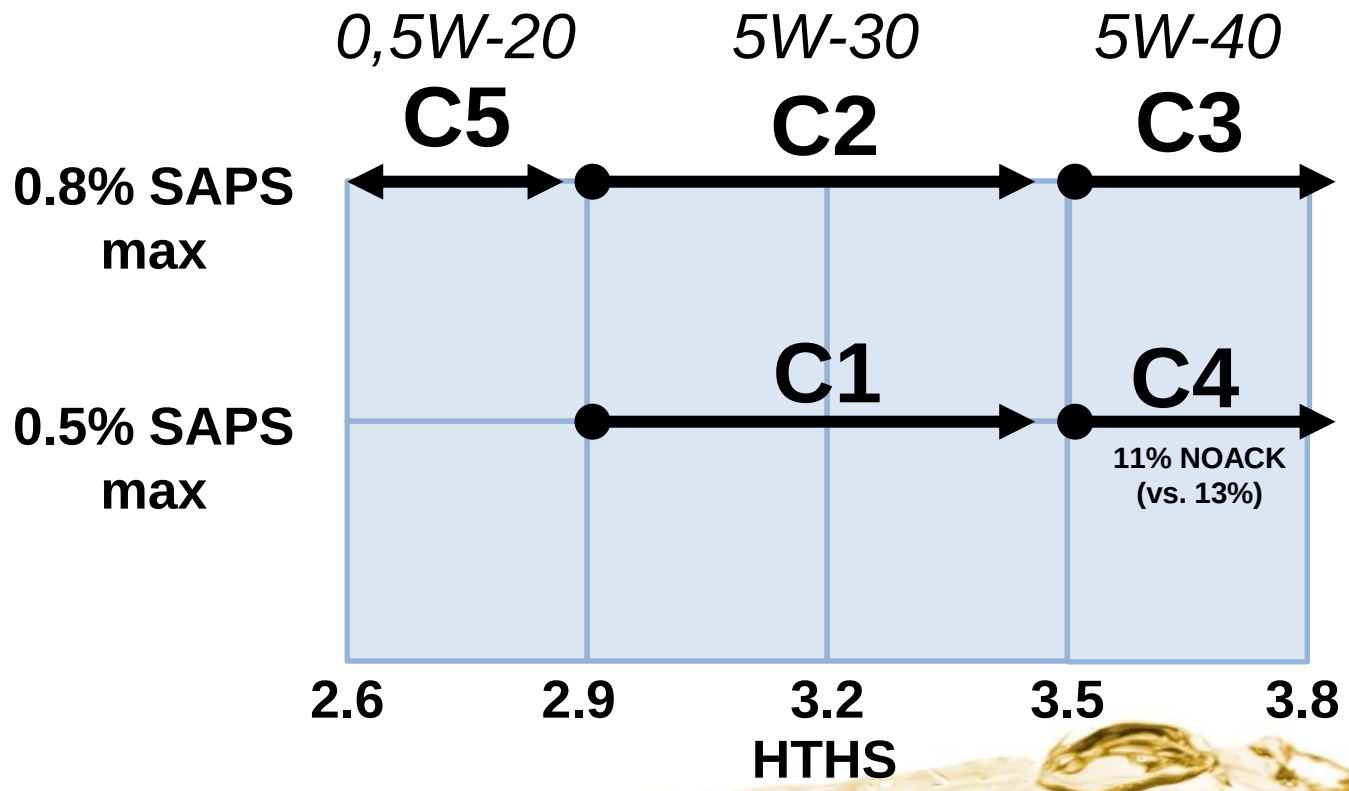
Image from D&W Diesel, 2020

ACEA A/B - 16

- High SAPS
  - A3/B3 – pre- direct fuel injection (HTHS ≥ 3.5)
  - A3/B4 – **plus** extended oil change interval **and** direct fuel injection
    - Tightened CEC L–099-08 diesel engine wear and CEC L-078-99 piston cleanliness / ring sticking; added biodiesel compatibility test
  - A5/B5 – **plus** low viscosity (2.9 to 3.5 HTHS)
    - Added fuel economy test CEC L-054-96
  - ≤ 13% NOACK
- Name comes from combining earlier A and B categories
- A1/B1 eliminated in 2016
- A3/B3 and A5/B5 to be replaced by A3/B4 and A7/B7 (2021?)

ACEA C - 16

- Low SAPS for use with emission reduction technologies (catalyst + filter)
  - Top tier gasoline and light duty diesel
  - A/B are 0.9 - 1.6% SAPS



- Future: Add C6 for LSPI and turbos (2021?)

ACEA E - 16 Diesel

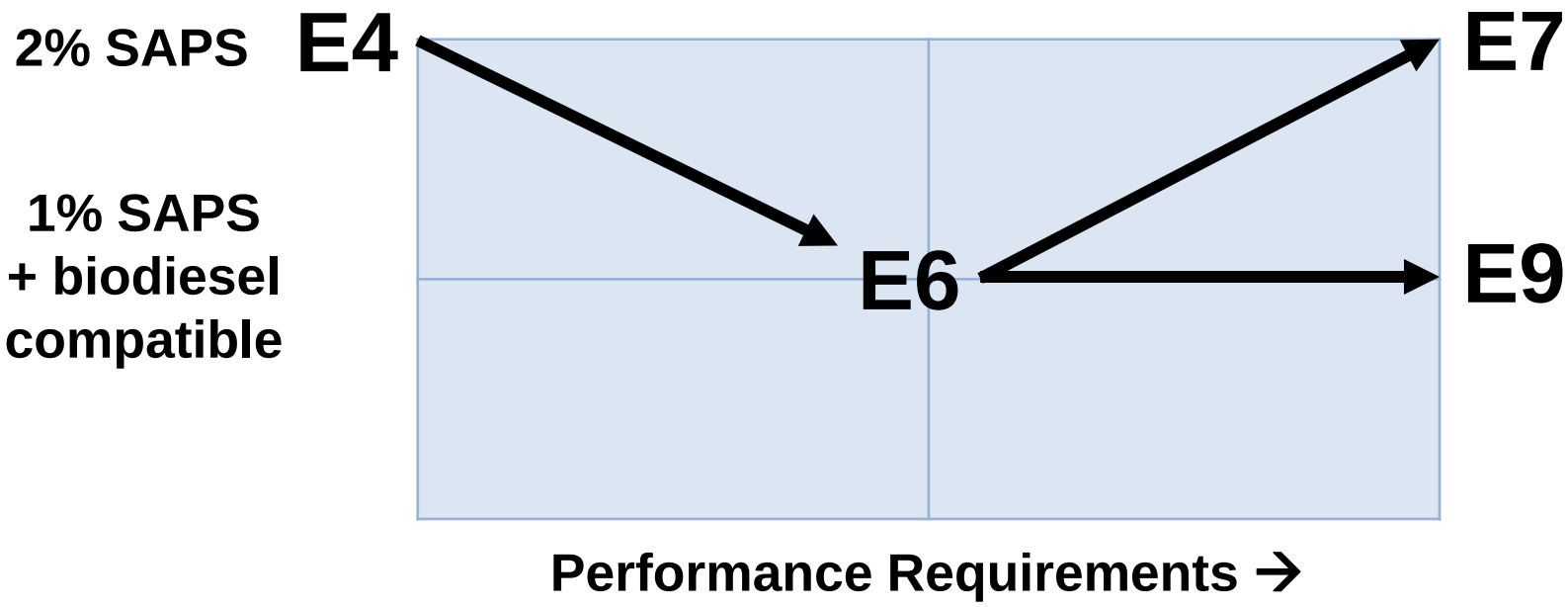
- Heavy duty diesel - all HTHS ≥ 3.5 and ≤ 13% NOACK
  - XW-40's and up

90 cycle
K-O shear

Mack
T12 wear

Cummins ISM
abrasive soot wear

D6594 corrosion limits
(no longer report)



- Future: Replace E6 and E9 with E8 and E11, add low HTHS F8 and F11

ACEA to MAN

- MAN diesel specs branch from ACEA-16, include additional tests
  - Many products have overlapping specs, meet multiple E or MAN reqs.

	ACEA-16		MAN	MAN Visc Grades
Low SAPS <1%	**E9**	→	**3477**	*0W-X, 5W-X, 10W-X*
	E6	→	**3575**	*XW-30, XW-40*
High SAPS <2%	**E7**	→	**3275**	*5W-X, 10W-X, 15W-X*
	E4	→	**3277**	*5W-X, 10W-X*

Global DHD

- Global diesel oil standard for EU / Asia-Pacific exports to foreign countries
  - Heavy duty diesel

- DHD-1: 2001
  - Similar technology level to API CH-4, ACEA E5, and JASO DH-1
  - Extra tests added for high backwards compatibility for various equipment and fuels

- DHD-2: 2005
  - Similar level to API CJ-4 and ACEA E7
  - Never completed

Global DLD

- Light duty diesel engine oil specification, 2002
  - DLD-1 – Basic performance for high sulfur fuel markets, ACEA B2
  - DLD-2 – Fuel efficiency, ACEA B1
  - DLD-3 – High performance, ACEA B3

- Additional tests from European/Asia-Pacific OEMs

	DLD-1	DLD-2	DLD-3
Grades	XW-30, XW-40, XW-50	XW-30 XW-20	XW-30, XW-40, XW-50
HTHS (D4683)	> 3.5	30: >2.9 20: >2.6	>3.5
K-O Shear (D6278/D7109)	50: >15.0; 40: >12.0; 30: > 9.0, 30 cycle	30: >8.6, 20: in grade, 30 cycle	In grade, 30 cycle
NOACK (D5800)	10W: <15; Other, <13	15	13
SAPS (D874)	< 1.8	< 1.3	< 1.6%

JASO Engine Oils

- JASO DL-1 – low SAPS (0.6%) passenger car similar to ACEA C1
- JASO DH-1 – high SAPS HHDEO similar to ACEA E4 / E7
- JASO DH-2 – low SAPS HHDEO similar to ACEA E6 / E9

- **JASO GLV-1 – 0W-12 and 0W-8** (JASO M 364-2019)
  - Ultralow gasoline engine oil
  - Based on GF-5 and API SN performance
    - Adding GF-6B (0W-16) durability tests in future
    - Timing chain wear is a concern

Viscosity	KV100	HTHS	Specifications
0W-20	6.9 – 9.3	≥ 2.6	ACEA C5, ILSAC GF-5
0W-16	6.1 – 8.2	≥ 2.3	ILSAC GF-6B
0W-12	5.0 – 7.1	≥ 2.0	JASO GLV-1
0W-8	4.0 – 6.1	≥ 1.7	JASO GLV-1

JASO MA/MB

- Four-stroke motorcycle oil, 10W-40 most common

- JASO T 903:2016 specification must meet one of:
  - API SG to SN **or** GF-1 to GF-3 **or** ACEA A1/B1 to A5/B5 or C2 to C4
  - **plus** JASO T 904 friction clutch test

  - <20% NOACK volatility, shear in grade by 30 cycle K-O

- Graded on three areas of performance in friction clutch test
  - Dynamic friction, static friction, stop time index
    - **JASO MB** (lowest friction) < **MA1** < **MA** < **MA2** (highest friction)

GM dexos

- GM dexos specifications
  - Full synthetic or synthetic blend
  - Testing on both new and used oils, longer oil change intervals

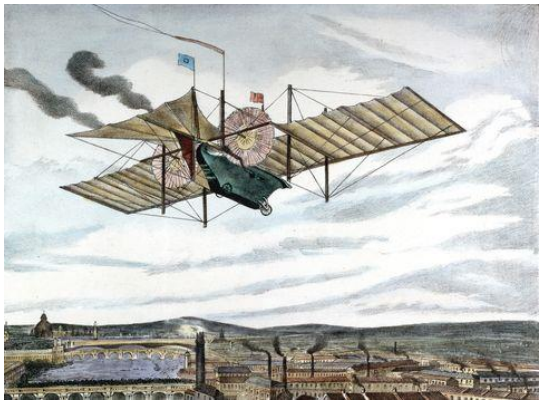
  - dexos1 Gen 2
    - Marketed as higher end version of GF-6

    - vs. Gen 1 – LSPI testing, fuel economy, turbocharge deposits

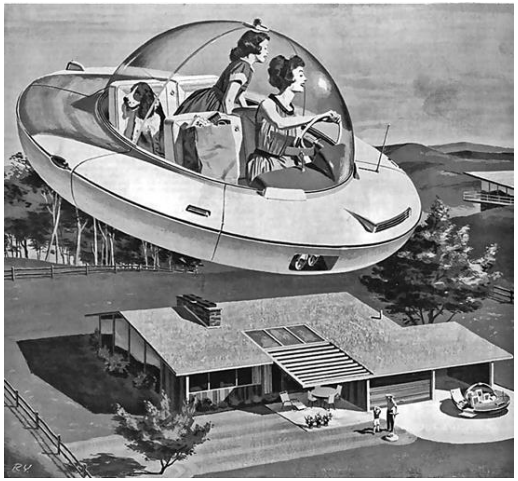
    - Gen 3 planned – extra control on sludge, turbocharger deposits, oxidation, and lower SAPS & NOACK

  - dexos2 – diesel, ACEA C3 diesel with some ILSAC GF-4 tests
    - Originally for gas and diesel until LSPI issue

Where Do We Go From Here?

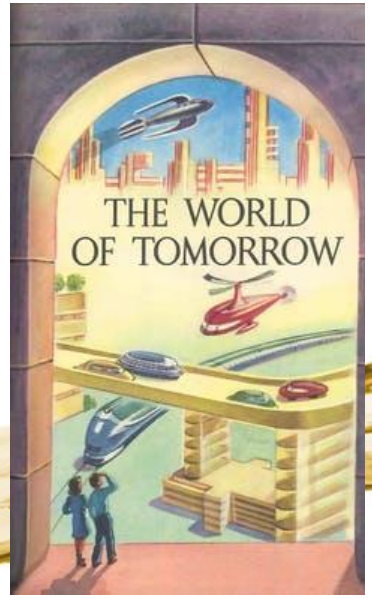


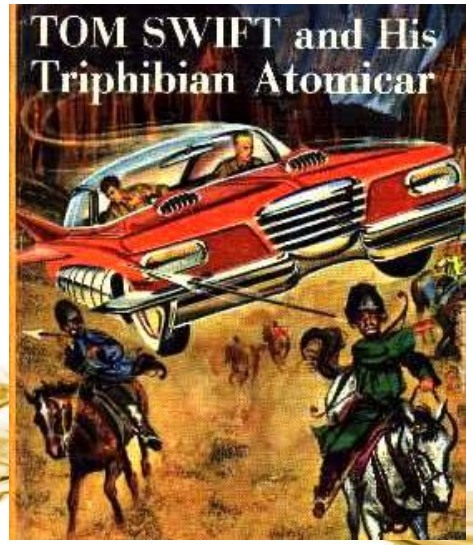
1840's vision



1940's vision

1960's vision





Current Challenges

- Higher power density, higher temperature engines
  - Most industrial applications target 65°C vs. engine oil at 130-150°C
- Lower viscosities – implementation of 8, 12, and 16 grades has only begun
  - 0W-16 in Toyota Camry now
- Longer oil change intervals
  - 3000 miles then is 15000 miles now, ‘fill for life’?
- Increasing shear stability as engine oil continues to do more with less visc
- Fuel dilution from GDI and TGDI tech, a culprit of LSPI
- Emissions and fuel economy regulations pushing for less additives
  - Less zinc, sulfur, phosphorus, and ash

Summary

- Engine oil development is highly dynamic
  - External demands from auto/engine makers, regulators, public
  - Various areas of focus depending on region - US, EU, AP, etc.
    - Fuel economy vs. viscosity, emissions systems vs. S/P/ash antiwear

- Most importantly engine oil starts with fundamental properties like viscosity grade, HTHS, shear stability, and cold flow properties

  - Functional aims to provide knowledge, technical support, and products to meet these critical properties early into formulating