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Analysis of the current lubricant requirements of the latest combustion engines

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The advancement of combustion engines is driven by stricter emission regulations (e.g., Euro/EPA standards), requiring innovations in lubrication. Modern oils must ensure wear protection, emission system compatibility (e.g., DPFs) and fuel efficiency. This paper analyzes updates to ACEA, API, and OEM specifications, focusing on oxidation resistance, low-SAPS formulations, and fuel economy. The trend toward low-viscosity oils (0W-20, 0W-16) reduces friction but challenges lubrication under high loads. The study evaluates these changes' impact on engine durability and future oil development amid tightening sustainability and emission norms. This article will analyze lubricant requirements for passenger cars.

Key words: *engine oils, lubricant standards, API, ACEA, OEM*

1. Introduction

Modern emission requirements (Euro 6/VI standards, EPA Tier 3 regulations) have fundamentally dictated the evolution of internal combustion engine designs, resulting in significant modifications to their operational parameters [14]. Stringent limits on harmful emissions have necessitated combustion process optimization, consequently leading to increased thermomechanical stresses in contemporary powertrain units. This technological transformation has directly influenced the tightening of quality criteria for engine lubricants. In response to these challenges, standardized classification systems (OEM, ACEA, API, SAE) have implemented precise specifications defining:

– Physicochemical parameters of lubricants
– Application ranges for different powertrain types
– Operational boundary conditions (including temperature operating ranges).

The article aims to summarize the current requirements for engine oils set by car manufacturers and industry associations.

2. Engine oil requirements

Engine oil requirements have evolved significantly alongside advancements in powertrain technology and increased machinery accessibility [1]. Initial formulations focused primarily on providing adequate lubrication for naturally aspirated engines with limited service intervals (typically 3000–5000 km) [2]. Industrialization and stringent emission regulations (Euro 6d, EPA Tier 3) have fundamentally transformed lubricant development priorities [3]:

– Increased mechanical/thermal loads (peak cylinder pressures > 200 bar)
– Advanced aftertreatment compatibility (DPF, SCR, GPF systems)
– Extended drain intervals (up to 30,000 km in OEM specifications)
– Restriction of hazardous additives:
  - Zinc dialkyldithiophosphate (ZDDP) reduction to ≤ 0.08% P [3]
  - Sulfated ash limits < 0.8% in Low SAPS formulations [2].

Modern engines increases power density. Table 1 shows comparison between two turbochargered ~2000 cm³ spark ignition engines.

Table 1. Spark ignition engines comparison

Parameter	Lancia Delta HF (1987-1994)	VW EA888 Gen3
Displacement	1995 cm³	1984 cm³
Power Output	158 kW @ 5750 rpm	245 kW @ 6500 rpm
Torque	314 Nm @ 2500 rpm	420 Nm @ 2000 rpm

Power density increase necessitates:

– Piston ring coatings (CrN, MoS_2, DLC) [15]
– Reduced ring pack width (1.2 mm → 0.8 mm)
– Aluminum engine blocks with plasma-sprayed cylinder liners.

One of the next requirements for modern engines is a change in the friction reduction strategy. Modern engines employ low-viscosity oils (SAE 0W-20 replacing 5W-30), variable displacement oil pumps and electronically controlled cooling jets. All organizations describe extended drain oil capability (circa 30,000 km for passenger cars). An extended interval most often causes changes in oil parameters:

– Base number retention (TBN > 50% of initial value)
– Oxidation stability (RPVOT > 150 min) [4]
– Soot handling capacity (< 3% dispersion efficiency loss).

Due to the increase of combustion temperatures and operating temperatures, the oil specification requires:

– CCS viscosity < 6200 mPa·s @ –35°C (SAE 0W)
– HTHS viscosity > 2.6 mPa·s @ 150°C
– Flash point > 230°C.

Emission standards forced some other oil features like: Fuel dilution resistance (< 5% viscosity change at 7% fuel contamination) [15] and aftertreatment compatibility features for example, low SAPS formulation, where the following parameters are limited:

- Phosphorus: 600–800 ppm
- Sulfur: < 0.3%
- Sulfated ash: < 0.5%.

3. Industry standards

3.1. API standards [2]

The American Petroleum Institute (API) has established a standardized engine oil quality classification system, which utilizes a two-letter alphanumeric code to designate performance specifications, where the first letter indicates engine type:

- "S" (Spark Ignition): gasoline/petrol engines (quality progression: SA → SB → SC → SD → SE → SF → SG → SH → SJ → SL → SM → SN → SP → SQ). Note: Each subsequent letter denotes improved performance requirements
- "C" (Compression Ignition): diesel engine (quality progression: CA → CB → CC → CD → CD-II → CE → CF → CF-2 → CF-4 → CG-4 → CH-4 → CI-4 → CJ-4 → CK-4 → FA-4.

Suffix designations: "II" or "2": Applicable to two-stroke diesel engines "4" or no suffix: Applicable to four-stroke diesel engines.

The second letter follows alphabetical progression, with each advancement indicating stricter performance benchmarks (e.g., SN > SM > SL).

FA-4 is a specialized category for fuel-efficient, lower-viscosity diesel oils (HTHS 2.9–3.2 mPa·s).

Obsolete classifications (e.g., SA–SH) remain documented but are no longer certified for modern applications. This system ensures backward compatibility where applicable while mandating compliance with evolving OEM and regulatory requirements.

3.2. Analysis of the evolution of API standards

Table 2 shows API spark ignition oil standards with key advancements.

Table 2. API classification system for gasoline engine oils

API Class	Introduction Year	Key Advancements
SG	1988	Basic oxidation stability, wear protection
SJ	1996	Improved deposit control, phosphorus limits (0.1% max)
SL	2001	Enhanced high-temperature deposit protection
SM	2004	Improved oxidation resistance, extended drain capability
SN	2010	Turbocharger protection, fuel economy improvement
SN PLUS	2018	LSPI (Low-Speed Pre-Ignition) prevention
SP	2020	Advanced LSPI protection, enhanced fuel economy

Critical changes in API Spark ignition oil requirements:

- Phosphorus content reduction (SJ (1996): ≤ 0.1% to SP: ≤ 0.08% due to catalyst protection
- HTHS value decreased from ≥ 2.6 mPa·s to ≥ 2.3 mPa·s (SN) and ≥ 1.7 mPa·s (SP for 0W-16)
- Deposit control (TEOST 33C test limit increased from 30 mg (SM) to 35 mg (SP))
- Fuel economy improvement (sequence VIE test introduced in SP specification and minimum 0.5–1.5% improvement over previous generations.

API standards also introduce requirements resulting from the engine design and limiting its wear and aftertreatment systems wear:

- SN and later standards include specific tests for turbocharger deposit control and high-temperature stability (150°C+ conditions)
- LSPI prevention (SN Plus introduced first test – sequence IX, API SP reduced 50% of LSPI events vs. API SN (due to special additive formulation and Ca/Mo balance
- SP reduced sulfated ash (≤ 1.0%), sulfur content (≤ 0.4%), and phosphorus (≤ 0.08%).

The latest API spark ignition oil requirements have a performance test:

- Sequence IVA: Valve train wear protection
- Sequence VH: Sludge and varnish control
- Sequence VIII: Bearing corrosion
- Sequence IX: LSPI prevention
- Sequence VIE/VID: Fuel economy measurement.

and requires physical parameters:

- Noack volatility: ≤ 15%
- Shear stability: ≤ 10% viscosity loss
- Foaming tendency: < 10 ml/50 ml/10 ml (Seq I/II/III).

The API SQ specification, introduced in 2025, tightened the API SP requirements. Table 3 shows selected differences.

Table 3. API SP/SQ differences

Parameter	API SP	API SQ
LSPI Prevention	50% reduction vs. SN	Enhanced testing protocols
Wear protection	Sequence IVA (valvetrain)	New sequence X (bearing/cylinder tests)
Oxidation stability	ASTM D7528 (TEOST MHT-4)	Stricter deposit limits
Hybrid compatibility	No specific requirements	Fuel dilution resistance
SAPS limits	Phosphorus ≤ 0.08%, sulfur ≤ 0.4%	Further reduced additive restrictions
HTHS viscosity	≥ 2.9 mPa·s (5W-30)	Lower viscosities permitted (0W-12)
Fuel economy	Sequence VIE	Enhanced friction reduction

Technical Improvements in API SQ:

- Enhanced deposit control (30% better high-temperature deposit prevention vs. SP (per ASTM D7097))
- Advanced additive chemistry (optimized calcium/molybdenum ratios for LSPI protection)
- Extended drain capability (improved TBN retention (+15% vs. SP in ASTM D2896).

This analysis includes how API classifications have consistently addressed issues that occur in gasoline technology due to turbocharging, fuel control, and emission configuration control in recent specifications. Moving from SJ to SP means 60% deposit control and 40% attack protection based on standard test protocols and reduced fuel consumption through the HTHS parameter. Near-term development in the context of hybrid vehicles and engine antiwear protection in water-in-oil conditions. New API SQ spec will be the base for some OEM specs for Ford EcoBoost engines and VW EA888 Gen4 engines. Figure 1 shows graphical differences between API standards.

Fig. 1. API spark ignition standards [13]

3.3. ACEA standards

The Association des Constructeurs Européens d'Automobiles (ACEA) [2] establishes rigorous performance standards for engine lubricants, reflecting the evolving demands of modern powertrain technologies and stringent Euro 7 emission regulations. This classification system is structured to address three critical operational domains: durability, emissions compatibility, and energy efficiency.

Modern emission requirements (Euro 6/VI standards, EPA Tier 3 regulations) have fundamentally dictated the evolution of internal combustion engine designs, resulting in significant modifications to their operational parameters. Stringent limits on harmful emissions have necessitated combustion process optimization, consequently leading to increased thermomechanical stresses in contemporary powertrain units. This technological transformation has directly influenced the tightening of quality criteria for engine lubricants. In response to these challenges, standardized classification systems (OEM, ACEA, API, SAE) have implemented precise specifications defining:

- Physicochemical parameters of lubricants
- Application ranges for different powertrain types
- Operational boundary conditions (including temperature operating ranges).

ACEA introduced 4 different oil specification ranges:

- A for gasoline engines
- B for light-duty diesel engines
- C for all engines with aftertreatment systems
- E for heavy-duty diesel engines.

3.4. Analysis of differences of ACEA standards

ACEA describes oil specification by oil parameters, and real engine test [15]:

- viscosity (HTHS measured per CEC L-36-90 (150°C, shear rate 10^6 s^{-1}))
- shear stability measured per (CEC L-14-93, ASTM D6278/D7109) – oils must retain viscosity grade after 30 shear cycles
- volatility (noack evaporation – CEC L-40-93 – maximum mass loss after 1 h at 250°C should be less than 13% depending on spec. (minimum ≤ 11% for C3, C4)
- total base number (TBN) – ASTM D2896/D4739 (minimum ≥ 6.0 mgKOH/g)
- elastomer compatibility (CEC L-112-16 – evaluates seal material degradation after 7-day immersion in fresh oil)
- piston cleanliness & turbo deposits (CEC L-111-16 – EP6CDT – minimum RL259 merit rating for piston deposits)
- Low-temperature sludge & varnish (ASTM D8256 – sequence VH ≥ 7.6 merit for average engine sludge)
- valvetrain wear (ASTM D8350 – sequence IVB ≤ 3.3 mm^3 max intake lifter wear)
- soot handling (CEC L-106-14 – DV6C viscosity increase ≤ 2.5 mm^2/s at 5.5% soot)
- engine wear (CEC L-099-08 – OM646LA camshaft wear ≤ 120 µm)
- piston cleanliness & ring sticking (CEC L-117-20 – VW TDI zero ring sticking, deposits ≥ RL276 – 5 merit)
- low-speed pre-ignition (LSPI – ASTM D829 ≤ 5 pre-ignition events (C6/C7))
- timing chain wear (ASTM D8279 – sequence X ≤ 0.085% elongation.

Tables 4 and 5 show selected results. A and B classes are High SAPS oils, C class is Low/Mid SAPS oil. Tables contain results from the latest ACEA revision.

Figure 2 and 3 show graphical differences between all C and A/B 2023 ACEA specs.

Table 4. ACEA 2023 A/B parameters

Parameter	A3/B4-23	A5/B5-23	A7/B7-23
HTHS	≥ 3.5 mPa·s	2.9–3.5 mPa·s	2.9–3.5 mPa·s
TBN	≥ 10.0 mgKOH/g	≥ 8.0 mgKOH/g	≥ 6.0 mgKOH/g
LSPI Protection	Not required	Not required	Sequence IX ≤ 5 events
Key Application	Conventional turbo	Fuel-efficient ICE	High-performance DI

Table 5. ACEA 2023 C parameters

Parameter	C2-23	C3-23	C5-23
HTHS	≥ 2.9 mPa·s	≥ 3.5 mPa·s	2.6–2.9 mPa·s
Sulfated ash	≤ 0.8%	≤ 0.8%	≤ 0.8%
Phosphorus	0.07–0.09%	0.07–0.09%	0.07–0.09%
Fuel economy	M111 ≥2.5%	Not required	2ZR-FXE ≥0.3%

Fig. 2. 2023 ACEA C standards [13]

Fig. 3. 2023 ACEA C standards [13]

3.5. Analysis of the evolution of ACEA standards

ACEA Oil Sequences, established by the European Automobile Manufacturers' Association, have undergone iterative revisions since their inception in 1996. These updates reflect advancements in [2, 7, 9, 11]:

– Engine technology (e.g., turbocharging, hybridization)
– Emission regulations (Euro norms, aftertreatment compatibility)
– Material compatibility (low-SAPS formulations, elastomer resilience).

Milestones of ACEA revisions:

– 1996 First standardized classification (A/B for gasoline/diesel, C for catalyst-compatible oils), introducing HTHS viscosity as a critical parameter, A3/B3 emphasized shear stability for extended drain intervals
– 2007 split A5/B5 into A5/B5-04 (lower HTHS: 2.9–3.5 mPa·s) for fuel economy, added C4 (ultra-low SAPS: Ash ≤ 0.5%, P ≤ 0.09%)
– 2013 introduced C5 with HTHS ≥ 2.6 mPa·s for reduced friction, mandated Sequence IIIG (ASTM D7320) for oxidation stability
– 2021 A7/B7 debuted with LSPI (low-speed pre-ignition) protection, C6 combined fuel economy with turbocharger deposit control
– 2023 C7 introduced with HTHS ≥ 2.3 mPa·s (ultra-low viscosity for hybrids), stricter LSPI limits (ASTM D8291) for GDI engines.

Table 5 shows the Comparative Analysis of ACEA specs.

Figures 4, 5 and 6 show the evolution of selected ACEA specs.

Table 5. Changes in ACEA specs

Parameter	1996–2004	2007–2016	2021–2023
HTHS viscosity	A3/B3: ≥ 3.5 mPa·s	A5/B5: 2.9–3.5 mPa·s	C7: ≥ 2.3 mPa·s
SAPS limits	Not standardized	C4: Ash ≤ 0.5%	C6: Mid-SAPS
LSPI protection	N/A	A7/B7 introduced	≤ 5 events (ASTM D8291)
Diesel Soot handling	Sequence IIIE	DV4 (CEC L-78-99)	DV6C (CEC L-106-14)

Fig. 4. 2023 ACEA A5/B5 evolution [13]

Fig. 5. 2023 ACEA C2 evolution [13]

Fig. 6. 2023 ACEA A3/B4 evolution [13]

4. OEM oil specifications

OEM (Original Equipment Manufacturer) oil standards constitute a set of technical requirements imposed directly by automotive manufacturers such as BMW, Ford, Mercedes-Benz, and others on lubricants intended for specific engine designs used in their vehicles. Unlike ACEA and API classifications, which provide broad industry-wide benchmarks, OEM specifications are more stringent as they address the precise engineering demands of particular engines or engine families within a manufacturer's lineup.

Overview of selected OEM oil specifications

The BMW Longlife-17 FE+ (LL-17 FE+) specification is a premium engine oil standard based on ACEA C5 developed by BMW Group for modern gasoline and diesel engines. It emphasizes fuel efficiency (FE), extended drain intervals, and enhanced engine protection, particularly for vehicles equipped with particulate filters (GPF/DPF) and turbocharged direct-injection engines.

Key performance requirements [8, 12]:

- Low high-temperature high-shear (HTHS) viscosity (≤ 2.9 mPa·s) to reduce friction and improve efficiency, – Formulated with advanced friction modifiers to meet FE+ (fuel economy plus) requirements
- Compatible with BMW's condition-based service (CBS) system, allowing extended oil change intervals (up to 30,000 km or 2 years, depending on driving conditions)
- Enhanced oxidation stability to prevent oil degradation under high temperatures
- Low SAPS (sulphated ash, phosphorus, sulfur) formulation for compatibility with particular filters
- Improved wear protection (e.g., turbocharger bearings, timing chains)
- Primarily synthetic (group III+/PAO/ester-based) for superior thermal stability
- Advanced additive package with anti-wear agents (e.g., optimized ZDDP levels), detergents & dispersants to prevent deposits, anti-foaming & corrosion inhibitors.

Table 6 shows a comparison between different BMW oil specs. Figure 7 and 8 shows the difference between the different BMW OEM spec and ACEA base of this spec.

Table 6. BMW engine oil comparison

Specification	HTHS Viscosity	SAPS Level	Key applications
LL-17 FE+	≤ 2.9 mPa·s	Mid SAPS	GPF/DPF engines, hybrids
LL-04	≥ 3.5 mPa·s	Low SAPS	Older diesels (DPF-equipped)
LL-01 FE	~3.5 mPa·s	High SAPS	Pre-2020 gasoline engines

Fig. 7. BMW LL 17 FE+ vs. ACEA C5 [13]

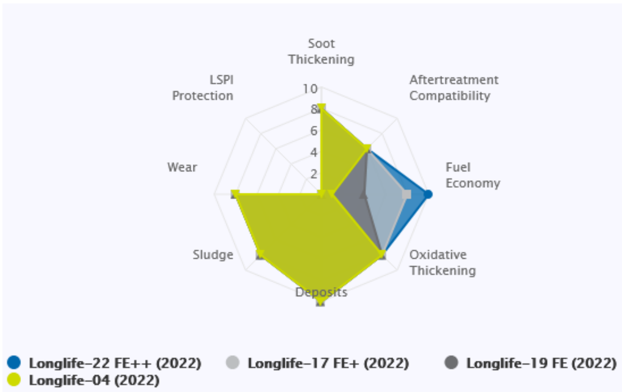

Fig. 8. Comparison of BMW specs [13]

The VW 508.00 (gasoline) and VW 509.00 (diesel) specifications represent Volkswagen Group's latest engine oil standards for vehicles produced since 2019. These specs were developed for WLTP/RDE-compliant engines, particle filter-equipped vehicles (GPF/DPF), and extended drain interval systems.

Key performance requirements:

- SAE 0W-20 grade mandated
- HTHS viscosity 2.6–2.9 mPa·s (lower than previous VW standards)

- Optimized for energy efficiency (FE++ classification)
- Up to 30,000 km/2 years' service intervals
- Compatible with VW's flexible service regime
- Sulphated ash ≤ 0.8%, phosphorus ≤ 0.05%, sulfur ≤ 0.2%
- Enhanced engine protection (special anti-wear additives for: timing chain systems, turbocharger bearings, direct injection components
- Improved oxidation stability for hybrid applications.

Additionally, this specification requires full synthetic (Group III+/PAO) base oils.

Table 9 shows comparison between different VW oil specs. Figure 9 shows comparison of VW specs.

Table 8. BMW engine oil comparison [5]

Specification	HTHS Viscosity	SAPS Level	Key Applications
LL-17 FE+	≤ 2.9 mPa·s	Mid SAPS	GPF/DPF engines, hybrids
LL-04	≥ 3.5 mPa·s	Low SAPS	Older diesels (DPF-equipped)
LL-01 FE	~3.5 mPa·s	High SAPS	Pre-2020 gasoline engines

Table 9. VW engine oil comparison

Specification	Viscosity	SAPS Level	Key Applications
508.00/509.00	0W-20	Ultra-Low	GPF/DPF (2019+)
504.00/507.00	5W-30	Low	Pre-WLTP vehicles
502.00/505.00	5W-40	High	Older generations

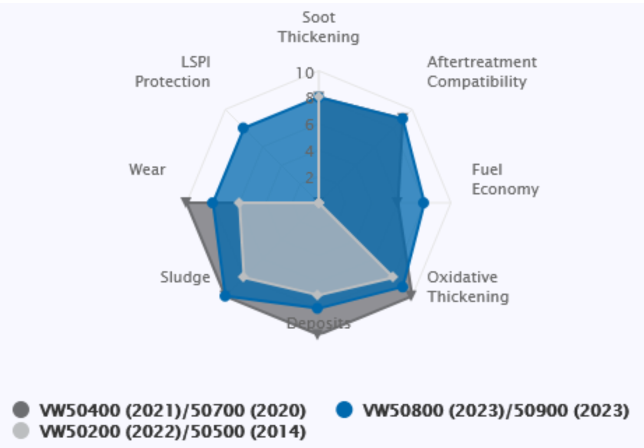

Fig. 9. Comparison of VW specs [13]

5. Specific lubricant requirements for internal combustion engines in hybrid electric vehicles

5.1. Introduction

Conventional internal combustion engines (ICEs) are designed to operate under relatively stable load and temperature conditions. In hybrid electric vehicles (HEVs, PHEVs), the ICE operates in a fundamentally new, dynamic environment that presents a unique set of challenges for engine lubricants. The necessity to cooperate with an electric motor, frequent start-stop cycles, and operation at low-load ranges significantly impact oil degradation and the formation of specific contaminants. This chapter details the key requirements for lubricants intended for use in hybrid engines, focusing on issues related to fuel dilution, oxidation and wear.

5.2. Characterization of ICE operation in a hybrid system and its impact on lubricant

The primary difference in the operation of a hybrid engine is its discontinuous and often brief operation. The engine is started and stopped multiple times during a single drive cycle to cooperate with or recharge the electric motor. This leads to several key phenomena [10]:

- Reduced operating temperature: the ICE in a hybrid system often operates within its optimal but relatively low-load range, resulting in a lower average oil sump temperature compared to conventional engines. Low temperature hinders the evaporation of condensed water and unburned fuel that enters the crankcase (a phenomenon known as fuel dilution).
- Frequent start-stop cycles: each start-up event is associated with momentary, intense boundary wear, as the oil film has not yet fully protected all tribological pairs. The repeated nature of this cycle accelerates the degradation of anti-wear additives and the base oil itself.
- Prolonged engine-off periods: when the vehicle is driven solely by electric power, the ICE cools down completely. During these periods, combustion by-products and water can condense into the oil, leading to the formation of acids and sludge

5.3. Main challenges and requirements for engine lubricants

5.3.1. Fuel dilution

This is one of the most critical challenges in hybrid engines, particularly in those with gasoline direct injection (GDI). During frequent cold starts, fuel injected into the cylinder partially washes down the liner walls and enters the crankcase. The low operating temperature of the engine prevents its effective evaporation. A high degree of fuel dilution (above 5–10%) reduces the oil's viscosity, leading to increased wear and risk of bearing damage. Furthermore, gasoline degrades performance additives and lowers the oil's flash point, posing a potential safety hazard.

Requirement: lubricants for hybrid engines must exhibit high volatility performance (low Noack volatility) and viscosity stability in the presence of diluents to maintain an adequate lubricating film.

5.3.2. Oxidation and acid contamination

Despite a generally lower bulk oil temperature, local temperatures in the combustion chamber and exhaust system remain very high. While a conventional engine operates stably after reaching its operating temperature, a hybrid engine repeatedly undergoes rapid heating and cooling phases. These thermal cycles promote oil oxidation. Additionally, condensed water and combustion blow-by gases (oxides of sulfur and nitrogen) form acids that attack metallic surfaces and lead to corrosion.

Requirement: exceptionally high thermal-oxidative stability and a robust total base number (TBN) are necessary to neutralize acids formed over extended oil drain intervals.

5.3.3. Wear and wear protection

Frequent starts mean repeated periods of operation under boundary lubrication conditions, where the protection from anti-wear additives (e.g., ZDDP) is crucial [10,11]. Concurrently, modern emission standards limit the use of some traditional additive chemistries. Furthermore, a weakened oil film due to fuel dilution further increases the risk of adhesive and abrasive wear.

Requirement: the lubricant must contain an advanced package of anti-wear and friction modifier additives that provide immediate protection at start-up, are resistant to fuel dilution, and meet environmental regulations. Manufacturers' requirements specifically for hybrid vehicles are not observed. Manufacturers typically require API SP/SQ and ACEA C5. In the case of OEM specifications, hybrid vehicles use oils identical to those used in conventional engines.

6. Conclusions

The automotive lubrication industry has undergone a paradigm shift in engine oil specifications, driven by increasingly stringent emissions regulations and rapid technological advancements in powertrain design. Our comprehensive analysis reveals that while API and ACEA specifications continue to provide fundamental performance benchmarks, OEM-specific requirements have emerged as the dominant force shaping lubricant formulations. This evolution reflects the growing complexity of modern engine architectures and aftertreatment systems.

The industry-wide transition to ultra-low viscosity grades (0W-20, 0W-16 and lower) represents a critical response to WLTP and RDE emission protocols [6, 12]. However, this shift has introduced significant technical challenges in maintaining adequate engine protection while achieving fuel economy targets. The reduction of HTHS viscosity to ≤ 2.3 mPa·s necessitates the development of advanced anti-wear additives, including molybdenum dithiocarbamate compounds and precision-formulated ZDDP packages, to prevent boundary lubrication failures. Simultaneously, the prevalence of turbocharged gasoline direct injection (TGDI) engines has made Low-Speed Pre-Ignition (LSPI) mitigation a paramount concern, driving the creation of new test protocols.

The electrification of vehicle powertrains has introduced unprecedented formulation challenges. Modern hybrid systems require lubricants capable of withstanding ≥ 15% fuel dilution. OEMs are responding with proprietary test methods that frequently precede ACEA/API updates by 12-18 months. While ACEA C6 (2022) and API SP provide partial harmonization, they lack the engine-specific validation sequences and aftertreatment compatibility requirements mandated by leading automakers.

Looking ahead, the industry must prioritize several key development areas. Next-generation friction modifiers stable below 100°C are essential for optimizing cold-start fuel economy, while advanced soot-handling dispersants will be critical for extending DPF service intervals. The establishment of OEM-collaborative test benches for hybrid-specific wear modes and high-throughput screening methods for LSPI inhibitor development should be considered urgent infrastructure investments.

The impending transition to synthetic fuels and hydrogen combustion systems will necessitate fundamental reformulation of lubricant chemistries. Key focus areas include enhanced high-temperature stability (>150°C bulk oil temperatures) and novel additive packages compatible with emerging seal and gasket materials. The formation of industry consortia to develop standardized lubricants test methods and bio-based base oil specifications should be prioritized to ensure a cohesive transition to alternative propulsion technologies.

In conclusion, the lubrication industry stands at an inflection point, where the traditional boundaries between mechanical protection, emissions compliance, and energy efficiency are being radically redefined. Success in this new paradigm will require unprecedented collaboration between additive chemists, OEM engineers, and testing organizations to develop solutions that meet the competing demands of tomorrow's powertrain technologies.

Nomenclature

HTHS	high temperature high share
SAPS	sulfated ash phosphorus and sulfur
ACEA	European Automobile Manufacturers' Association
API	American Petroleum Institute
SI	spark ignition
DI	direct injection
LSPI	low-speed pre-ignition

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