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EVOLUTION, TRIBOLOGY, AND STANDARDIZATION OF MODERN ENGINE OILS: A COMPREHENSIVE ANALYSIS OF WEAR PROTECTION AND ENVIRONMENTAL COMPATIBILITY

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ABSTRACT

This article investigates the evolution and role of modern engine oils, which have transitioned into an integral structural component of internal combustion engines (ICE). The primary focus is the complex balance between the imperative to drastically reduce carbon emissions and the necessity to increase specific power and thermodynamic efficiency. The report analyzes the industry's shift toward ultra-low High Temperature High Shear (HTHS) viscosity oils to improve fuel economy, which pushes engines into boundary lubrication regimes and necessitates new chemical innovations for wear protection. It explores environmental constraints that limit traditional anti-wear additives like ZDDP due to catalyst poisoning, driving the development of low-ash (Low SAPS) formulations. Furthermore, the study addresses specific tribological challenges in modern GDI/TGDI engines, such as abrasive soot accumulation causing timing chain wear and Low Speed Pre-Ignition (LSPI) triggered by calcium detergents, requiring a shift toward magnesium-based additive packages. Through a comparative analysis of global classification standards (SAE, API, ACEA), the paper concludes that physical viscosity is no longer the sole guarantor of protection and highlights the critical emerging risk of backward incompatibility when using modern, ecologically focused oils in older engine designs.

KEY WORDS*: engine oil, oil grades, tribology, wear protection, environmental compatibility, HTHS vidcosity, low SAPS, LSPI (low speed pre-ignition), oil standardization (API, ACEA, SAE), ZDDP (zinc dialkyl dithiophosphate), CCS, MRV, (TWC) three-way catalysts*

1. INTRODUCTION

In modern automotive engineering science, engine oil has ceased to be merely an after-sales consumable and has transformed into an integral, structural component of the internal combustion engine (ICE). This paradigm shift has been driven by the convergence of two fundamentally opposing forces: the imperative to drastically reduce the carbon footprint and emissions (CO2, NOx, particulate matter) and the necessity to increase the specific power and thermodynamic efficiency of engines. The tribological system, consisting of the piston, cylinder, bearings, and valvetrain, operates under unprecedented load conditions imposed by technologies such as gasoline direct injection (GDI/TGDI), forced induction, and powertrain hybridization.

This scientific report explores in depth the chemical and physical mechanisms through which modern lubricants meet these challenges. The focus is placed on wear protection requirements—traditionally achieved through high viscosity and high levels of additives like zinc dialkyl dithiophosphate (ZDDP)—and environmental constraints that dictate low-viscosity, low-ash (Low SAPS) formulations. The analysis builds upon the classification frameworks of leading global organizations (SAE, API, ACEA, ILSAC), examining how they balance these competing priorities.

2. VISCOSITY CHARACTERISTICS: THE FOUNDATION OF SAE J300

Viscosity remains the most critical physical characteristic of engine oil, determining its ability to form a hydrodynamic film that separates moving metal surfaces. The SAE J300 standard, maintained by the Society of Automotive Engineers, defines the rheological profile of oils; this classification is based not on chemical composition, but on the fluid's behavior under extreme temperature amplitudes.

2.1. Low-Temperature Fluidity and Pumpability

The classification of the so-called "winter" grades (designated with a 'W' - Winter, e.g., 0W, 5W, 10W) is based on two critical simulation tests that ensure engine survival during a cold start:

- Cold Cranking Simulator (CCS, ASTM D5293): This parameter measures the resistance the oil exerts on the rotation of the crankshaft at low temperatures. High shear viscosity in the bearings would prevent the starter from turning the engine to the necessary RPM for ignition. For example, for the SAE 0W grade, the maximum allowable viscosity is 6200 mPa·s at -35°C.
- Mini-Rotary Viscometer (MRV, ASTM D4684): This test is even more critical, as it simulates the oil pump's ability

to draw oil from the sump. If the oil exhibits a "yield stress" and gels, the pump will cavitate, leading to dry operation and catastrophic failures. The limits for MRV are 60,000 mPa·s at temperatures 5 degrees lower than those for CCS (e.g., -40°C for 0W).

2.2. High-Temperature Viscosity and the HTHS Paradox

The "summer" grades (8, 12, 16, 20, 30, 40, etc.) are defined by their kinematic viscosity at 100°C (KV100) and, more importantly for modern tribology, by their High Temperature High Shear (HTHS) viscosity at 150°C.

HTHS viscosity is the most accurate indicator of the oil's behavior in the critical zones of the engine. Polymeric viscosity modifiers (Viscosity Index Improvers) used in multigrade oils can undergo temporary or permanent changes, leading to the thinning of the oil film. Traditionally, the industry relied on HTHS values above 3.5 mPa·s (characteristic of SAE _W-40) to guarantee a full hydrodynamic lubrication regime. However, the drive for fuel economy necessitated the introduction of ultra-low viscosity grades:

- SAE 16 (HTHS ≥ 2.3 mPa·s): Introduced to service hybrid and Japanese engines optimized for low friction.
- SAE 12 (HTHS ≥ 2.0 mPa·s) and SAE 8 (HTHS ≥ 1.7 mPa·s): These grades, defined in the latest revisions of SAE J300, represent the physical limit of liquid lubricants, where the transition from hydrodynamic to mixed or boundary lubrication is almost inevitable, requiring the use of new chemical technologies for surface protection. [1]

Lowering the HTHS from 3.5 to 2.6 mPa·s can lead to a fuel economy improvement of 0.5% to 2.0%, but it exponentially increases the risk of metal-to-metal contact if the engine is not designed with appropriate materials (e.g., Diamond-Like Carbon coatings) and geometry. [2]

3. CHEMICAL ARCHITECTURE AND THE ROLE OF ADDITIVES

To compensate for reduced viscosity, modern oils rely on a complex package of chemical additives that form protective films, neutralize acids, and hold contaminants in suspension.

3.1. ZDDP and the Phosphorus Dilemma

zinc dialkyl dithiophosphate (ZDDP) has remained the "backbone" of wear protection for over 80 years. Its mechanism of action is unique: under conditions of high pressure and temperature (in the friction zone), the ZDDP molecule breaks down and reacts with the metal surface, forming a sacrificial, glassy film of zinc and iron phosphates/sulfides. [3] This film wears away instead of the metal, preventing scuffing.

The problem is that ZDDP contains phosphorus and sulfur. Phosphorus is volatile, and upon oil combustion, it enters the exhaust system where it affects three-way catalysts (TWC) by forming an impermeable layer of cerium phosphate over the noble metals (Pt/Pd/Rh), blocking their catalytic activity. This imposes strict limits on phosphorus (typically < 0.08% or < 800 ppm for API SP and ACEA C-classes), forcing oil manufacturers to seek synergy with new organic friction modifiers or trinuclear molybdenum (MoDTC) to maintain protection with reduced ZDDP content.

3.2. Detergents and the LSPI Problem.

Detergents, traditionally based on calcium and magnesium sulfonates or phenates, are tasked with neutralizing combustion acids (maintaining the alkaline reserve TBN). However, in the era of TGDI engines, calcium detergents proved to be a primary catalyst for the LSPI (Low Speed Pre-Ignition) phenomenon. [4]

The oil-related mechanism of LSPI is explained by the "droplet theory". A microscopic oil droplet rich in calcium detergent enters the combustion chamber and mixes with the fuel. During the compression stroke, the calcium carbonate in the detergent decomposes into calcium oxide (CaO) through an exothermic reaction, generating a localized hot spot that ignites the mixture prematurely. This leads to a "super-detonation" capable of destroying pistons and connecting rods.

The solution, implemented in the new specifications (API SP, ACEA C6/A7), is the replacement of a portion of the calcium with magnesium. Magnesium compounds do not exhibit the same catalytic activity toward auto-ignition, but they are less effective at neutralizing acids at low temperatures, which necessitates a precise balance within the additive package. [4]

4. CLASSIFICATION SYSTEMS: DIFFERENCES AND EVOLUTION

Different global organizations approach oil classification with varying priorities, reflecting the specific automotive fleets in their respective regions.

4.1. API (American Petroleum Institute) – Focus on North America and Asia

The API system evolves along two parallel lines: "S" (Service) for gasoline engines and "C"/"F" (Commercial) for diesel engines.

4.1.1. API SP: The Answer to TGDI Challenges

The API SP standard, introduced in 2020, is a direct response to the problems of downsized engines. [5] It introduces two revolutionary tests that were absent in previous standards [6]:

- Sequence IX (ASTM D8291): A test for LSPI utilizing a Ford 2.0L EcoBoost engine. The requirement is for the average number of pre-ignitions to be under 5 for the entire test.
- Sequence X (ASTM D8279): A test for timing chain wear. In GDI engines, abrasive soot forms, penetrating the chain links and causing elongation. API SP limits the elongation to a maximum of 0.085%.

4.1.2. Heavy-Duty Oils: The Separation of CK-4 and FA-4

In 2016, API took a historic step by dividing the heavy-duty diesel category into two in order to address the incompatibility between fuel economy and the protection of older engines [5]:

- API CK-4: The evolutionary successor to CJ-4. It maintains an HTHS viscosity ≥ 3.5 mPa·s. It is backward compatible and can be used in all older trucks. The focus is on improved oxidation stability and aeration.
- API FA-4: A revolutionary grade with lowered HTHS (2.9–3.2 mPa·s). It is NOT backward compatible. It is designed for post-2017 engines optimized for low viscosity. Its use in an older engine could lead to an oil pressure drop and bearing failures.
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4.2. ACEA (Association des Constructeurs Européens d'Automobiles) – The European Standard.

The European system is significantly more focused on Long Life drain intervals and compatibility with compact diesel and gasoline engines equipped with particulate filters (DPF/GPF). The latest revision for passenger cars is from 2023, and for heavy-duty vehicles – from 2022/2024. [7]

4.2.1. Passenger Car Classes: A/B vs. C

ACEA divides oils into "High SAPS" (A/B) and "Low/Mid SAPS" (C):

- High SAPS (A3/B4): Designed for engines without DPF. They are characterized by a high TBN (≥ 10 mgKOH/g) to neutralize fuel sulfur and a high HTHS (≥ 3.5 mPa·s) for maximum protection under high loads. These are the oils for "old school" durability.
- The new A7/B7 (2021/2023): Upgrades A5/B5 (low HTHS) by adding protection against LSPI and chain wear. This is the equivalent of API SP, but in a High SAPS version, allowing for longer drain intervals.
- Low/Mid SAPS (C-series): This is the "heart" of the European market, mandatory for Euro 5/6 vehicles:
  - C3: The most mainstream class. Mid SAPS (ash ≤ 0.8%), high HTHS (≥ 3.5). It balances DPF protection with engine protection;
  - C5: Focuses on fuel economy (HTHS ≥ 2.6). Requires at least 3% fuel savings compared to a reference oil;
  - C6 (Introduced 2021): Combines the low viscosity of C5 with the new tests for LSPI and chain wear. This is the oil for modern downsized engines with GPF;
  - C7 (Introduced 2023): The new frontier of technology. It defines the SAE 0W-16 class with HTHS ≥ 2.3 mPa·s. Designed for ultra-efficient and hybrid engines where minimizing hydrodynamic losses is priority number one.

4.2.2. Heavy-Duty Classes (E and F series)

ACEA also introduced a division similar to API, but with stricter European tests:

- E8 (Replaces E6): Ultra High-Performance Diesel (UHPD) with Low SAPS. It includes the new Volvo T-13 test for oxidation stability (at very high temperatures) and the COAT test (Caterpillar Oil Aeration Test) for aeration. This is the top-tier class for protection over long intervals.
- F01 (Introduced 2024): The European equivalent of API FA-4. Oils with low HTHS (2.9-3.2) for heavy-duty vehicles, aimed at reducing CO2 according to EU regulations. [8]

5. ASPECTS OF WEAR PROTECTION

Wear protection in the modern engine is a multifaceted problem, requiring management of various failure mechanisms. The primary dilemma is the relationship between HTHS viscosity and oil film thickness.

- Crankshaft Bearings: These operate in a hydrodynamic regime. Reducing HTHS leads to a decrease in the load-bearing capacity of the film. [9] Data from SAE tests indicate that at HTHS < 2.6 mPa·s, bearing wear increases sharply unless polymers with a high Shear Stability Index (SSI) are used to maintain viscosity even under extreme loads. [10]
- Valvetrain (Camshafts/Lifters): Here, lubrication is often mixed or boundary. Because low viscosity (0W-16/20) cannot ensure complete separation, protection depends almost entirely on the tribochemical film formed by the additives (ZDDP/MoDTC). Research indicates that with ultra-low viscosity oils, the role of molybdenum trimers is critical for reducing the friction coefficient and wear in the camshaft zone.

- In diesel engines, soot is a well-known problem leading to oil thickening. In GDI gasoline engines, however, the wear mechanism is different:
- Soot Morphology: Soot in GDI engines has a different nanostructure—it is harder and prone to agglomeration into larger, abrasive clusters comparable to diamond dust. [11]
- Effect on the Timing Chain: These abrasive particles penetrate the clearances between the pins and links of the chain. Upon movement, they act like grinding paste, wearing away the metal. [11] This leads to the physical elongation of the chain, which disrupts valve timing and can cause a piston-to-valve collision.
- Countermeasures: Modern oils (API SP/ACEA C6) require specific dispersants (e.g., succinimides with polyisobutylene chains) to "envelop" the soot and prevent its agglutination into large abrasive formations.

6. ENVIRONMENTAL REQUIREMENTS AND INFLUENCE ON COMPOSITION

Environmental regulations dictate not only physical parameters (viscosity for fuel economy) but also the elemental composition of the oil.

6.1. SAPS Limitations and Aftertreatment Systems.

The acronym SAPS (Sulfated Ash, Phosphorus, Sulfur) defines the chemical elements that are harmful to aftertreatment systems.

- Sulfated Ash: Produced during the combustion of metallic detergents (Ca, Mg, Zn). Because the ash is inorganic, it cannot burn away during the DPF filter regeneration. It accumulates in the filter's pores, reducing its effective volume and increasing backpressure, which degrades fuel economy and power. [12] Therefore, ACEA C4 limits ash to an extremely low 0.5%.
- Phosphorus and Sulfur: Sulfur interferes with the operation of DeNOx catalysts (LNT/SCR), while phosphorus forms a glaze over the platinum/palladium in TWC catalysts.
- Alternative Technologies: The reduction of ZDDP (due to phosphorus) necessitates the use of ashless Organic Friction Modifiers (OFM) based on esters (e.g., glycerol monooleate), which adsorb onto the metal and reduce friction without containing harmful elements. [13]

6.2. Fuel Economy and the Connection to CO2.

Reducing viscosity is the most direct path to reducing CO2 emissions.

- Mechanism: Approximately 10-15% of fuel energy is lost overcoming internal engine friction. A significant portion of this consists of hydrodynamic losses (oil pumping, bearing rotation, piston movement).
- The Effect of 0W-16/0W-20: Transitioning from 5W-30 (HTHS 3.5) to 0W-20 (HTHS 2.6) can reduce consumption by 1.5-2%. [1] The introduction of ACEA C7 (SAE 0W-16) aims for an additional reduction of about 0.3-0.5% compared to 0W-20, which on the scale of millions of vehicles represents thousands of tons of saved CO2 annually. [14, 15]

7. COMPARATIVE ANALYSIS OF CLASS FOCUS

The following table synthesizes how the different classes balance the discussed aspects:

Class / Standard	Application	Focus on Protection (Wear)	Focus on Ecology (SAPS/Economy)	Key Characteristic
ACEA A3/B4	Older / Powerful ICE without DPF	Extreme (High HTHS, High SAPS)	Low (High consumption and emissions)	High alkalinity (TBN), robust film.
ACEA C3	Universal Euro standard	High (High HTHS ≥ 3.5)	High (Mid SAPS, DPF compatible)	Golden standard for diesel with DPF.
ACEA C5 / C6	Modern mainstream vehicles	Balanced (Low HTHS ≥ 2.6)	Very High (Economy + LSPI protection)	C6 adds protection for chains and LSPI.
ACEA C7	Hybrids / Ultra-efficient	Risky for older engines (HTHS ≥ 2.3)	Maximum (0W-16, 0.3% economy)	Technological peak for low friction.
API SP	Global gasoline standard	Focus on chains and LSPI	High (GF-6A/B economy)	Solves TGDI problems.
API CK-4	Heavy-duty (mixed fleet)	High (Backward compatible)	High (EGR/SCR compatible)	Evolutionary, universal for trucks.
API FA-4	Heavy-duty (new)	Specific (Low HTHS)	Maximum for trucks (GHG)	Revolutionary, saves fuel, incompatible with older engines.

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8. CONCLUSION

The analysis of modern engine oil specifications reveals a clear trend: the engineering compromise is shifting decisively in favor of ecological efficiency, but not at the expense of catastrophic failures. The industry has responded to the physical thinning of the oil film (low HTHS) with chemical innovation.

The main conclusions are:

1. Viscosity is no longer a guarantee of protection: Oils with grade 0W-16 (ACEA C7) can offer adequate protection for modern engines, thanks to new additive packages and structural changes in the units themselves, but they are disastrous for older designs.
2. LSPI and soot dictate the chemical composition: The problems of downsizing have forced a fundamental change in the composition of detergents (Ca -> Mg) and dispersants, which is enshrined in the API SP and ACEA C6/A7 standards.
3. Incompatibility is the new risk: With the introduction of classes like ACEA C7 and API FA-4, the risk of incorrect oil selection becomes critical. A "newer" oil is not always "better" for a specific engine if it is not designed to operate in a boundary lubrication regime with low HTHS viscosity.

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