Lube-Tech
PUBLISHED BY LUBE: THE EUROPEAN LUBRICANTS INDUSTRY MAGAZINE
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How the NOACK evaporation loss test helps in our understanding of interactions between viscosity, volatility, and oil consumption in engine oils

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Abstract
The NOACK method has been a long-standing approach for quantifying the percentage of volatility loss. Standardised under the ASTM testing method D5800, which measured the rate of evaporation loss of lubricating oils by the Noack Method, lubricants were found to play a critical role in the well-being of vehicles worldwide. Additionally, the evolution of lubricant science has witnessed a substantial reduction in viscosity, encompassing both weight and thickness, over the past several decades. With these, interest in volatility emerged that has been driven by environmental concerns, fuel economy challenges, and overall vehicle enhancement. This article delves into a comprehensive exploration of historical engine oil performance and development, highlighting the evolving significance of tests like the NOACK method in the present day.

Abbreviations
LDV, light duty vehicles; HGV, heavy goods vehicles; RICE, reciprocating internal combustion engines; ICE, internal combustion engines; LVO, low viscosity oil; OEM, original equipment manufacturers; API, American Petroleum Institute.

Introduction
A quarter of the planet's global CO_2 emissions are attributed to fossil fuel combustion, caused by decades of vehicular transfer between people and goods [1]. Planet Earth houses an estimated 1.1 billion Light Duty Vehicles (LDV), defined as transportation weighing less than a designated 3860 kgs, and about 380 million Heavy Goods Vehicles as of 2015 [2]. In 2022, the global production of LDVs was around 60 million, and that of HGVs fell short by 23 million [3]. It would not come as a surprise to find that as economic and industrial development occurs, the growth of light duty vehicles is also rapidly increasing. By 2040, the number of LDVs in production will increase from about 1.31 billion to over 2 billion by 2050 - proportionally bringing in an increase in CO_2 emissions [3,4,5]. Currently, over 99.8% of all land and marine transport vehicles are powered by combustion engines; such engines are referred to as Reciprocating Internal Combustion Engines (RICE) [6].

Internal Combustion Engines (ICE) serve as the primary propulsion systems for ground transport, both in on-road and off-road scenarios [6]. During

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the development of alternative internal combustion engines, there has been a long-term investigation involved in the improvement of engine efficiency, from engine performance to fuel consumption [7]. Under typical conditions, heavy-duty vehicles demonstrate an energy conversion efficiency of 15-20% from fuel potential to wheel power - indicating significant mechanical loss. [8]. Figure 1 demonstrates this energy conversion efficiency. Further, Figure 1 highlights a significant potential for internal engine friction to reach as high as 50% of the mechanical losses in ICEs [9]. Hence, prioritising this area becomes crucial to benefit fuel economy and overall fuel efficiency. This paper examines a method to reduce ICE mechanical losses, focusing on the use of Low Viscosity Oils, which is a promising approach.

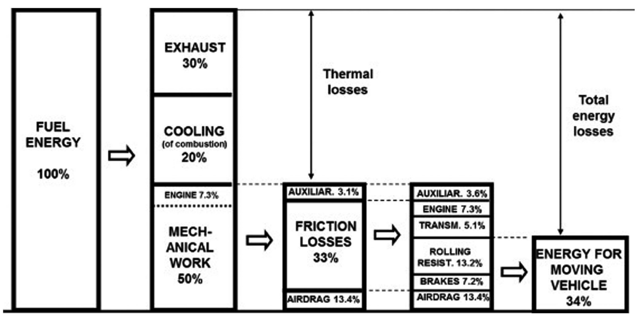

Figure 1: *Diagram of typical energy distribution in an average heavy-duty vehicle. Sourced from [8], under open access*

Tribology of low viscosity oils

3.1 The scale of necessity

Over the past century, the oil industry has remained expensive and difficult to replicate. Transportation is heavily linked to petroleum usage, with around 95% of transport energy being reliant on petroleum-based liquid fuels, and 60% of crude oil is used to make transport fuels [10]. Table 1 shows the demand for energy across the global transport sector in 2018.

However, it is important to note that this chart is only relative to marine, aircraft, and land transport, which account for only half of the total global transport energy demand [10]. Regardless, this portion of the demand is no small feat - Table 2 examines the average daily demand for transport fuels for the third quarter of 2018 [5].

Passenger Sector Energy Demand	
Light Duty Vehicles	44%
Rail, Buses, and 2-3 Wheelers	7%
Aircraft	10%

Freight Transport Energy Demand	
Heavy Duty Road	26%
Marine	8%
Rail and Pipeline	5%

Table 1: *The percentage share of global transport energy demand in 2018 across different transport sectors [10]*

Total	Million Barrels of Oil Equivalent (BOE)	Energy (Exajoules)	Fuel Volume (billion Liters)	Carbon Dioxide Emissions (million kg CO_2)
Gasoline	26.4	0.162	4.985	11,249.0
Diesel/Gasoil	28.1	0.172	4.788	11,973.4
Jet/Kerosene	8.0	0.049	1.361	3,408.8
Residual Fuel Oil (RFO)	7.0	0.043	1.075	2,982.7
Other	30.0	0.184	4.872	12,783.0
Total	99.5	0.610	17.081	42,397.0

Table 2: *Average global daily demand for transport fuels, third quarter 2018 [5,11]*

According to this data, an exajoule is equivalent to 163.4 million Barrel of Oil Equivalent. The second column, energy, is found by dividing the BOE value by the value of 1 exajoule in terms of BOE. The energy value is then converted into fuel volume by multiplying the corresponding volumetric energy density by the energy. For example, 32.5 MJ/l is used for gasoline, 36 MJ/l is used for diesel and jet fuel, and 40 MJ/l is used for residual fuel oil. Therefore, the planet burns through over 11 billion liters of gasoline, diesel, and jet fuel daily [5]. This daily amount of fuel burnt is alarming because it is releasing an equivalent of 42.4 billion grams of carbon dioxide emissions, given 426.10 kg CO_2 released per 42-gallon BOE, which adds significant harm to the environment via increased risk of global warming-induced climate change and with reduced quality of the air that we breathe leading to health problems [11].

Such figures have prompted legislators to promote climate change legislation in hopes of reducing emissions. Also, citizens have protested over seemingly light regulations, further pushing lawmakers for stricter solutions. The growth experienced by the U.S. energy industry as renewable energy sources used in transportation will only be strengthened by the impact of increased environmental regulations [12]. Greenhouse gases (GHGs) are the repercussions brought by the combustion process in ICEs, which significantly contribute to global warming [13]. Accordingly, legislators will have no choice but to place strict financial burdens on oil and gas for their carbon emissions, creating a pressing need for cheaper and cleaner alternative fuels [14]. The environmental, economic, and political variables surrounding the fuel economy necessitate a need to improve ICE efficiency [13].

3.2 Viscosity

In response to these challenges, Original Equipment Manufacturers (OEMs) have spent decades examining and improving upon techniques to reduce fuel consumption. Automobile and lubricant manufacturers developed a standard procedure to measure the energy conservation properties of ICEs–classified by the American Petroleum Institute (API). In the early beginnings, the tribology of oil was mainly focused on improving engine efficiency based on oil conditions. These conditions were assessed via technology that evaluated the oil stress and performance in different driving parameters are considered–such as the distance traveled since the previous oil change, the count of cold starts, the temperature of the oil, and the engine speed [15]. One of the key physical factors that require consideration for assessing the state of engine oil is its viscosity [16], [17].

Viscosity is a lubricant's most major characteristic [18]. Fluids with low viscosity, such as water, provide minimal resistance to motion, whereas fluids with high viscosity present significant resistance [19]. Low Viscosity Oils (LVOs) have been utilised for more than 40 years, used primarily for improving friction losses [20]. This principle operates on the premise that the lower the viscosity of the lubricating oil, the less engine power is needed to attain specific operational conditions [13]. When reducing the viscosity of oil, resistance to motion is lowered, lowering fuel consumption. Test rig studies show a reduction in fuel consumption between 1% and 4%, with factors such as oil temperature, viscosity grades, and various additives observed as contributors [20]. According to the study's results, there has been a consistent trend in the industry in reducing the average viscosity of lubricants.

Further, a grading system was implemented by the Society of Automotive Engineers (SAE) to grade motor oils by viscosity through SAE J300. Since 2015, the viscosity grades range from 8, 12, 16, and increments of 10 starting from 20 and ending at 60 [21]. This system requires testing dynamic and kinematic viscosities at various temperatures to categorise winter and non-winter viscosity grades [22]. Table 3 below shows the minimum and maximum viscosities of oils using the SAE J3000 standard as of January 2015 [22].

Grade	Kinematic Viscosity (cSt) @ 100°C (min)	Kinematic Viscosity (cSt) at 100°C (max)	HTHS Viscosity (cP) @ 150°C (min)
8	4.0	<6.1	1.70
12	5.0	<7.1	2.0
16	6.1	<8.2	2.3
20	5.6	<9.3	2.6
30	9.3	<12.5	2.9
40	12.5	<16.3	2.9 or 3.7
50	16.3	<21.9	3.7
60	21.9	<26.1	3.7

Table 3: *SAE J300 non-winter grades as of January 2015 [22]*

3.3 Volatility

From the beginning of engine oil evolution, viscosity over volatility is seen as the determining characteristic during oil selection. This argument refers to how quickly engine oil vaporises. During the development of early engine oils, volatility did not pose an issue due to their extremely heavy weights. However, the introduction of reduced viscosity altered the relationship between viscosity and volatility quickly. Emission after treatment systems were also absent from early engines. As such, the emissions produced were determined by the lubricants utilised. Engine oils with reduced viscosity generated lower viscous resistance within the engine, leading to improved ICE efficiency and reduced fuel consumption. With the increased reduction of emissions and fuel consumption developing problems for engine oil the engine would eat per mile of operation, volatility had to be reduced to limit engine oil consumption loss from high temperature evaporation and prevent changes occurring in the properties of the oil. Although less viscosity helped to reduce fuel consumption, more vapour was found to be produced by the engine. This indicates an inverse relationship between low viscosity along with higher volatility - raising concerns about increased evaporation loss [23]. Henceforth, a method to determine optimal volatility for engine oil performance, given a lubricant's viscosity, became a necessity.

3.4 Temperature: Viscosity vs. Volatility

Due to this rapid and massive reduction in engine oil weights, base oil viscosities, and an increase in oil volatility, new methods were developed to discern oil volatility that departed from the traditional practice. One such method known as the NOACK volatility test, was adopted by the American Petroleum Institute's engine oil category requirements for Original Equipment Manufacturers.

The NOACK test involves trials of heating engine oils in an evaporating crucible. As such, the crucible is closed by a corresponding screw cover. A small hole atop the crucible allows samples to volatilise freely. The crucible is then heated to 250 °C for an hour, and the final percent volatility loss is recorded using the weight of the empty crucible, crucible with sample, and crucible post-trial. Evaporation loss is obtained from the difference in weight of these variables: ((B - A) - (C - A)) x 100%; where A = empty crucible weight, B = crucible plus sample weight, and C = crucible plus sample after one hour of heating.

It is worth noting that the results obtained from the NOACK are only a modeling estimate of the evaporation component of oil consumption. It is only a reference which can be indicative of how the engine could act in given conditions but not necessarily as actual correlatable performance in an engine. In normal engine operation, high temperatures will typically drive off the lighter ends of a lubricant while in service - resulting in the increased viscosity and thickness of lubricants, leading to reduced fuel economy. A lower NOACK number means less oil consumption due to evaporation when the engine oil gets hot [24].

The industrial standard limit for percent volatility loss by the NOACK method is about 15%, as seen in Figure 2. However, this value has been lowered in recent decades to 13% and lower as various companies used differing procedures and instruments for this method, each of which has different specifications and challenges. Each synthetic oil passes the NOACK standard limit for percent evaporation loss (below 15%) with varying degrees of volatility conservation. As observed in Figure 3, multiple leading brands have differing limits when compared with each other, where the lower the limit is better as it grants the most wear protection [25]. In Figure 3, 0 - 15% represents the industrial standard range, with the green bar representing the ideal (the lowest) limit regarding the dataset. 16 - 20% gives a range of experimental error, and 21% onwards is too high and indicative of poor performance. The lower observed limit indicates reduced oil consumption and minimal emissions, and it keeps engine valves free from debris and accelerated wear. The NOACK method allows for specific volatility measurement in modern low-viscosity oil developments.

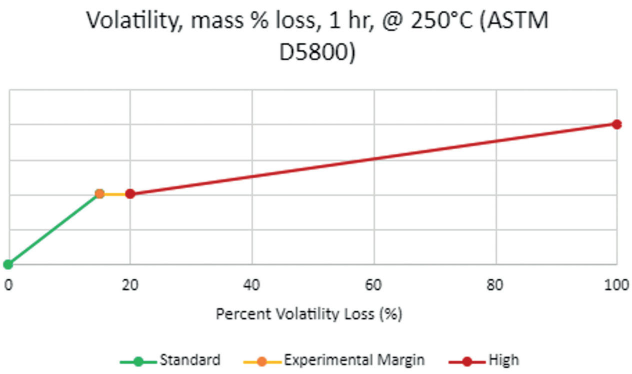

Figure 2: *Volatility, mass % loss, 1 hour, @ 250 °C (ASTM D5800), adapted from [24]*

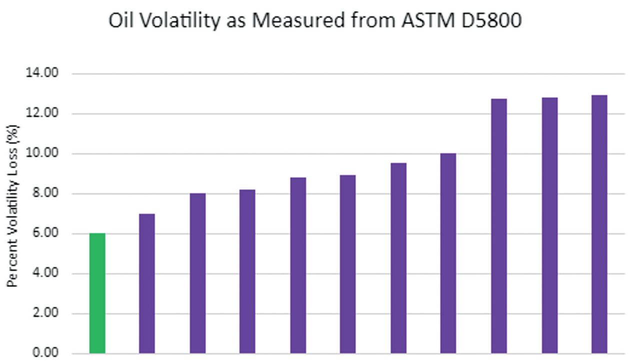

Figure 3: *Oil Volatility Measurements of Leading Synthetic Oil Brands, adapted from [25]*

Nonetheless, the lower percent volatility loss, as indicated by the NOACK limit, is more favorable and indicative of resistance to oil volatility and thermal breakdown, helping improve the efficiency of ICE vehicles. Furthermore, the versatility of NOACK measurements for modern-low viscosity oil developments commercially helps the industry as it allows a variety of developers to create their own NOACK device standardised with ASTM D5800.

3.5 NOACK (D5800) Instrumentation

In order to perform the NOACK test more efficiently, the Koehler Instrument Company has introduced a variant of the NOACK apparatus that conforms to ASTM D5800. Figure 4 below shows a schematic diagram of the device directly from the standardised testing method.

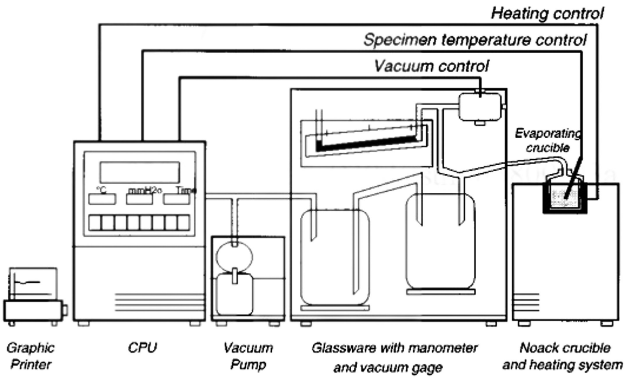

Figure 4: *Schematic of Automatic Non-Woods Metal Noack Evaporation Apparatus [26]*

Koehler Instrument company's Automatic Non-Woods Metal NOACK Evaporation apparatus can be used to determine engine oil volatility. This is necessary for high-temperature environments, which contribute to increased consumption and property modifications of engine oil. The standard test method is consistent – oil samples are placed in an evaporation crucible, which can then be heated to 245.2 °C for an hour. This allows for percent evaporation loss determination. The Noack apparatus is highly digitised and equipped with an electronic regulator that allows for automatic temperature and differential pressure control. With meticulous design and functionality, this state-of-the-art apparatus offers a comprehensive solution to the matter of volatility, allowing for the examination of various substances used in vehicles, particularly lubricating oils.

Conclusion

Understanding the development of oil viscosity and volatility is crucial for various aspects of the oil industry. The historical trajectory of oil affects different global domains, spanning from environmental implications to financial ramifications of the fuel economy to pushes in oil development and science. This paper explored the need for fuel efficiency, characterised by developing and adopting engine oils with low viscosity and minimal volatility. The NOACK volatility test, which has been standardised under ASTM D5800, has emerged as a pivotal focal point in the ongoing evolution of methodologies aimed at quantifying the percentage of volatility loss. This test has gained prominence, particularly in recent initiatives focused on mitigating volatility and enhancing overall product stability - allowing for improved ICE efficiency and reduced harmful emissions into the environment.

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