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The evolution of locomotive lubricant specifications

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Trains have been the most efficient mode of transportation on land since the advent of steam engine locomotives. Their contribution to the Industrial Revolution and subsequent societal development cannot be overstated. Though their dominance has diminished in passenger transport, due to the aviation industry taking off in the latter part of the 20th century in most countries, locomotives still move the lion's share of freight and goods. To make the net-zero carbon emission ambitions of the world a reality, railways have a significant role to play due to their efficiency and comparative sustainability. Trains can move a ton of goods approximately 520 miles on a single gallon of fuel. From an emission point of view, locomotive emission requirements have been continuously improved to reduce their carbon monoxide (CO), nitrogen oxides (NOx), and particulate emissions.

Locomotives have the option to rely on either direct electricity or a diesel engine as their primary power source. Electric locomotives use direct current from an electric line to propel the locomotive through the traction motors. On the other hand, diesel locomotives typically use a diesel engine to drive a generator, which generates electricity to power the traction motors. Electric and diesel locomotives have achieved widespread success globally. In the United States alone, they remain crucial in various industrial sectors, responsible for transporting approximately 40% of the country's cargo [1].

As Figure 1 shows, the railway industry is growing in every country, and the energy demand is projected to double in some countries by 2050 [2].

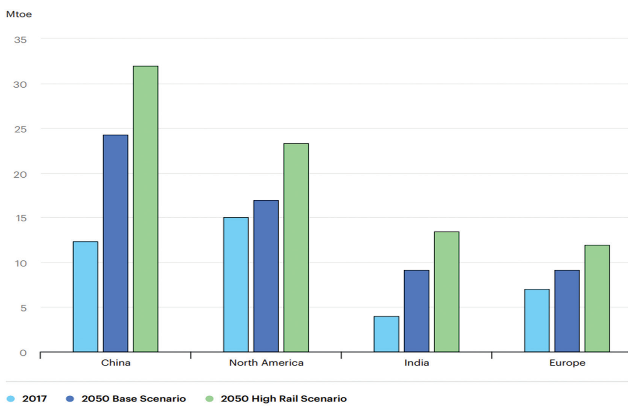

***Figure 1:** Projected rail energy demand growth in selected regions by scenario, 2017-2050 [2].*

Locomotives are environmentally friendly alternatives compared to other existing modes of transportation. A study conducted by the Association of American Railroads showed that replacing the loads carried every day by trucks with trains can contribute to up to 75% less greenhouse gas (GHG) emissions [3]. However, in recent years, the Environmental Protection Agency (EPA) has also placed strict regulations on locomotives to minimise their environmental impact.

Beginning with the initial emissions standards signed by the EPA in December 1997, locomotive engines have been subject to a tiered system of increasingly stringent emissions standards, ranging from Tier 0 to Tier 4. Higher tier numbers are assigned to more recent and stricter emissions standards. Since 2015, the railway industry has been required to meet Tier 4 locomotive engine standards, which impose limits on particulate matter (PM), total hydrocarbon emissions (THC), NOx, and CO, as outlined in Table 1 [4].

Tier	MY	Date	HC	CO	NOx	PM
Tier 0[a]	1973-1992[c]	2010[d]	1.00	5.0	8.0	0.22
Tier 1[a]	1993[c]-2004	2010[d]	0.55	2.2	7.4	0.22
Tier 2[a]	2005-2011	2010[d]	0.30	1.5	5.5	0.10[e]
Tier 3[b]	2012-2014	2012	0.30	1.5	5.5	0.10
Tier 4	2015 or later	2015	0.14[f]	1.5	1.3[f]	0.03

a - Tier 0-2 line-haul locomotives must also meet switch standards of the same tier.
b - Tier 3 line-haul locomotives must also meet Tier 2 switch standards.
c - 1993-2001 locomotive that were not equipped with an intake air coolant system are subject to Tier 0 rather than Tier 1 standards.
d - As early as 2008 if approved engine upgrade kits become available.
e - 0.20 g/bhp-hr until January 1, 2013 (with some exceptions).
f - Manufacturers may elect to meet a combined NOx+HC standard of 1.4 g/bhp-hr.

Table 1: *EPA emissions standards for line-Haul locomotives. HC standard refers to THC for diesel, non-methane hydrocarbons (NMHC) for natural gas, and THC equivalent (THCE) for ethanol engines [4].*

To meet these standards, advancements in technology have been pursued in various areas, including advanced "stop-start" control systems and more efficient locomotive engines, aiming to enhance fuel efficiency and minimise engine idling times [3]. The European Commission is ruling out the strictest emission standards, which is tougher than Tier 4 [Figure 2].

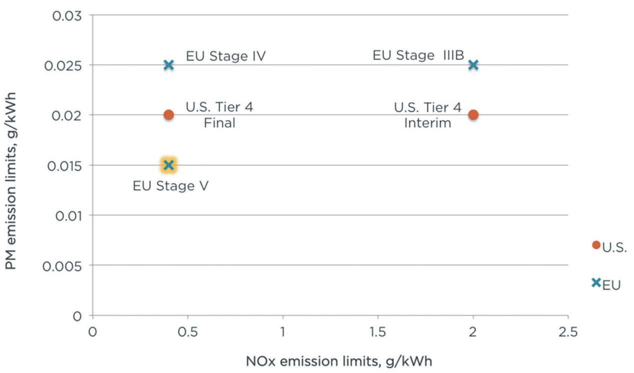

Figure 2: *Comparison of PM and NOx emission limits between the U.S. and EU [4].*

The regulations are slightly different for switch locomotive emissions. According to Tier-4 regulation, switch locomotives are allowed to emit 2.4 g/bhp-hr CO [5].

Diesel engine lubrication

Being the heart of the locomotive, engine lubrication is extremely important for performance and emission control. Locomotive diesel engines typically generate between 1200 to 6000 HP. However, most of the Wabtec (formally known as GE) and Progress Rail (formally known as EMD) locomotive engines are rated at 4500 HP [6]. To keep such engines running smoothly at these horsepower levels, the engine oil must have the necessary qualities to lubricate the piston rings/liners, connecting rods, main bearings, and valve trains. The turbocharger bearings in locomotive engines are also lubricated by the engine oil. The engine oil serves multiple functions, including lubrication, cooling, and maintaining cleanliness by removing combustion byproducts, deposits, and debris. It also helps neutralise acidic combustion byproducts such as sulphuric and nitric acids. Engine oils typically contain an additive system that contains functional components that serve as detergents, dispersants, anti-wear agents, antioxidants, viscosity index improvers, and pour point depressants. These comprehensive additive systems are formulated in the oil to enhance performance and extend oil drain intervals, where applicable.

Typically, the primary anti-wear component found in most motor oils is Zinc Dithio Diphosphate (ZDDP). However, railway engine oils have traditionally been formulated without zinc due to concerns about potential damage to silver wrist-pin bearings used in Progress Rail engines. In contrast, Wabtec engines did not utilise silver bearings and, therefore, did not require zinc-free oils. To ensure operational simplicity and avoid the need to manage different engine oils for a mixed fleet of EMD and Wabtec locomotives, the industry adopted zinc-free oil as the engine oil standard. Although EMD ceased the use of silver bearings in the early 2000s, the practice of utilising zinc-free oil has continued to protect the existing fleet that contains these silver bearings and remains prevalent in the industry today. Prominent additive companies such as Oronite and Infineum continue to cater to the demand for zinc-free engine oils within the industry [7].

In general, additives are added to engine oil formulations to enhance the base fluid and ensure that the finished product meets certain specifications and performance baselines outlined by the manufacturers and environmental regulators. The Locomotive Maintenance Officers Association (LMOA)'s Generation 7 engine oil specification has been established to comply with EPA emissions regulations for Tier 4 (Gallagher, et al., 2016).

The selection of locomotive engine oils depends on a series of factors, one of which includes the sulphur content in the fuel. Given the current global fuel inventory utilised in the rail industry, oils with a Base Number (BN) ranging from 9 to 13 are used to effectively neutralise sulphuric and other acidic by-products produced during the combustion process. In North America, Generation 7 oils with an 11 BN, as determined by ASTM D2896, are considered the standard. Other countries have employed the use of Generation 7, 6, and 5 (or 4LL) oils depending on available fuel and engine type. Compared to Generation 6 oils, Generation 7 oils demonstrate improved base retention and acid control. They are better equipped to handle the added demands posed by the Exhaust Gas Recirculation (EGR) systems and reduced oil consumption in GEVO Tier 4 engines. Furthermore, they maintain compatibility with low (<500 ppm) and ultra-low (<15 ppm) sulphur fuels [8]. As emissions regulations potentially become more stringent and as new formulations offering greater performance gains are developed, the pursuit of such enhancements is expected to continue in future locomotive engine oil formulations.

For the past few years, the use of synthetic engine oils instead of conventional (mineral) oils has become more popular in the automotive industry due to their improved performance and potentially extended oil drain intervals. A similar potential exists within the railway industry. However, the railway industry may find similar levels of application too expensive for older locomotives that may consume more engine oil and newer locomotives since oil contamination will and getting to recommended condemning limits triggers an immediate oil change. Some of these locomotives that are built with older-generation diesel engines have extremely high oil consumption in comparison to a typical car or truck. This makes the use of synthetic oil cost prohibitive. Nonetheless, it may prove useful to utilise synthetic oils in newer locomotives, which could potentially enable longer ODI, increase fuel economy, and improve durability [9].

The automotive industry is witnessing a notable shift towards lower viscosity engine oils. The presence of 15W-40 and 5W-30 grade oils is diminishing, while there is a growing popularity of 0W-20 oils. Japanese original equipment manufacturers (OEMs) have already approved the use of 0W-8 grade oils, and European OEMs are currently conducting tests on 0W-12 oils. For the railway industry, transitioning to lower-viscosity oils presents challenges due to the coexistence of older and newer locomotives within a given fleet. However, the potential for improved fuel economy alone makes it worthwhile to explore the use of lower viscosity oils in newer locomotives. Drawing from the success of lower-viscosity automotive engine oils, achieving a fuel economy improvement of 2 to 3% in locomotive engine oils should be feasible [10]. For railways, such improvements would result in significant cost savings, considering that fuel constitutes a major portion of their overall operating expenses. It must be noted that transitioning from an SAE 40 or 20W-40 grade to a lower viscosity grade such as 5W-30 oils will require the redesign of key engine components. The pursuit of reducing CO_2 emissions may necessitate such changes in the future.

Property	Condemning Limit	Test Method
Pentane Insolubles (maximum)	% (Generation 4LL with ASTM D-975 S500 or less fuel)	ASTM D7317
Kinematic Viscosity, cSt @ 100 ºC (SAE 40)	Maximum 25% increase (above Fresh oil viscosity) Minimum 12.5 cSt	ASTM D445
Total Base Number (minimum)	4.0 (mg.KOH per gm)	ASTM D4739
Water (maximum)	0.2%	ASTM D6304
Soot, oxidation, sulfation, Nitration	Trendline. Instrument and software dependent. Must be correlated with Wabtec lab for reference	ASTM D7889, ASTM E2412
Wear metals & contaminants	Trend line	ASTM D 5185

Table 2: *Condemning Limits for In-service engine lubricating oils [8].*

A full locomotive engine oil change-out event is not done very frequently and is typically done in 3-6 month increments. The oil maintenance frequency relies heavily on numerous factors, including TBN depletion, high soot content, fuel dilution, and oil oxidation. Each of these individual factors, or several of them combined, can lengthen or shorten the service period of the oil. To avoid potential issues, Wabtec recommends frequent testing of engine oils (every 7 to 10 days) and an oil trend analysis program to monitor the outlined limits shown in Tables 2 and 3, to ensure that the engine oils aren't being used beyond their in-service life.

TYPE OF SERVICE	OIL CHANGE PERIOD	MWHr/MONTH					
		7FDL16	7FDL12	7HDL16	GEVO16	GEVO12	P616LD
Severe	3 Months	>400	>300	>600	>600	>400	>300
Medium	3 to 6 Months	300 to 400	225 to 300	450 to 600	400 to 600	300 to 400	225 to 300
Moderate	6 Months	<300	<225	<450	<450	<300	<225

Table 3: *Recommended oil change intervals for Generation 4 "Long Life" oils utilised in Wabtec FDL locomotives alongside general life expectancies according to service load as determined by field experience in Wabtec diesel engines using ASTM D975 specified fuel (No. 2 S500)[N2D] [8].*

Traction motor gear oil

The wheels of the locomotives are driven by electric motors called traction motors. Locomotives are typically equipped with four to six traction motors that drive the wheels. These motors are connected to the drive axle through a gearbox, which incorporates bevel gears along with pinion and bull gears. The traction motors can be powered by either AC or DC drives, although AC drives have gained popularity due to their superior traction control and reduced maintenance requirements [11]. Like any other mechanical component, lubrication is essential to minimise wear, reduce friction, and enhance overall performance. In the case of locomotives, the traction motor gear lubricant serves the additional purpose of lubricating the main bearings. Typically, a synthetic oil based on polyalphaolefins and classified as ISO VG 460 grade, complemented with mild extreme pressure (EP) and anti-wear additives, is used for this application. An example of such a lubricant is the Mobil SHC 634 [12]. Recent specifications outlined by Wabtec for AC traction motor lubricants are depicted in Table 4 [8].

GE Specification D50E32 - AC Traction Motor Gear Case Lubricant

PROPERTIES	D50E32	TEST METHOD
Base Oil	Polyalphaolefin (PAO)	-
ISO VG	460	-
Gravity, API	31.4	ASTM D-1298
Specific Gravity	0.867	ASTM D-1298
Pour Point, °C (°F) maximum	-42 (-44)	ASTM D-97
Flash Point, °C (°F) minimum	250 (482)	ASTM D-1310
Viscosity, cSt at 40°C at 100°C, typical	 414 to 506 45	 ASTM D-445 ASTM D-445
Viscosity Index	159	ASTM D-2270
Rust Protection, ASTM D665A and 665B, Distilled and Synthetic Sea Water	Pass	ASTM D-665
Copper Corrosion, 24 hrs. at 121°C	1B	ASTM D-130
Chemical Activity Analysis, FE8 Test	Pass	FAG FE8
Wear Testing, FZG Scuffing Fail Stage	13+	DIN 51534
RBOT	1500 min	ASTM D-2272
TOST Life, hrs.	10,000+	ASTM D-943
TAN, new product, max. mg KOH/g Oil	<1.0	ASTM D-664
Foaming Characteristics, Seq I, Seq II, and Seq III	0/0/0	ASTM D-892
Hydrolytic Stability, 2-week test cycle, TAN, mg KOH/g Oil	<1.0	ASTM D-2619
Source of Supply: Exxon Mobil™ Oil Company, USA	-	Mobil™ SHC 634
TEST METHODS[1]		
PERFORMANCE		**RESULT**
GE-Wabtec Building 50 Traction Motor Life Test		PASS
Locomotive Field Test		PASS

1. Gear lubricant must pass both tests and/or have engineering approval.

Table 4: *GE (now known as Wabtec) AC traction motor lubricant specifications with required ASTM test methods [8].*

These oils are specifically formulated without the use of active sulphur-phosphorous EP additives due to their potential ability to damage the yellow metals (bronze, brass, etc.) used in many bearing components. Opting for synthetic gear oils provides a substantially extended oil drain interval (ODI) of approximately two years, depending on the specific service conditions and the effectiveness of the gearbox's sealing against dust and contaminants [13]. Although the oil itself can remain in good condition for up to two years, the presence of dirt or other impurities can lead to potential damage to the gears and bearings. Therefore, adhering to the OEMs' recommendation on oil change intervals, like engine oil, is crucial for maintaining the optimal health of the traction motor gears.

Greases

In addition to oils, greases are equally utilised in various locomotive module lubrication systems, particularly in areas where greases are more suitable than oils. Locomotives utilise greases for lubricating bearings in key components such as the main generator, traction motors, U-tube bearings, radiator fans, and wheel bearings. These bearings vary in size, endure different loads, and rotate at different speeds, necessitating greases with optimised compositions specific to each application and environment. Consequently, distinct grease specifications and recommendations are provided for each application type. In general, traction motor greases employ lithium NLGI 3 grade greases formulated with mineral base oils, while U-tube bearings require NLGI 2 synthetic greases such as Mobilith SHCTM 100 and UnirexTM (Table 5).

GE Specification D6A2C17 - UNIREX™ N3 Grease

GE SPECIFICATION D6A2C17 - BALL AND ROLLER BEARING GREASE	D6A2C17	TEST METHOD
Operating temperature range	-20°C to +140°C	
Worked Penetration x 60 strokes, mm/10	220 to 250	ASTM D217 / D1403 (NLGI 3)
Dropping Point, minimum	230°C (446°F)	ASTM D2265
Thickener Type	Lithium Complex	
Base oil	Mineral	
Base Oil Viscosity (cSt at 40°C)	115	ASTM D445
Viscosity Index	95 min	ASTM D2270
Color	Green	
Corrosion protection	Must pass	ASTM D1743
Sources of Supply: Mobil	Unirex™ N3	

Table 5: *GE Specification D6A2C17 for Ball and Roller Bearing Greases [8].*

Both grease types are governed by the GE (now Wabtec) Specification D50E34 and D6A2C17 (Table 5), respectively [8]. Synthetic greases are also commonly used for wheel bearings and generator applications. The choice between synthetic or mineral oil-based greases depends on a number of factors, including service life and ambient operational conditions, and seasonal temperatures [8].

According to a study conducted by the Railway Tie Association, regular rail lubrication can result in a substantial decrease in annual fuel costs. The study found that trains operating on unlubricated rails consumed an average of 5,900 gallons of fuel per million gross tons (MGT). However, the fuel consumption decreased by 31% when proper lubrication was used. Another similar study conducted by the Federal Railway Administration claimed that top-performing rail lubrication systems offered an average fuel savings of 7.7%, with fully loaded trains achieving a 10% reduction in fuel consumption [2]. The rail lubricant must fulfill several key requirements. These requirements include reducing friction to prevent premature wear, providing sufficient adhesion for safe locomotive operation, meeting environmental regulations by being biodegradable and non-toxic, performing well under varying environmental conditions, and minimising noise pollution during braking and on sharp curves [14, 15, 16].

To achieve these goals, two common methods of lubricant application are used, wheel-flange lubrication and wayside lubrication. Wheel-flange lubrication involves a system within the locomotive itself, where the lubricant is dispensed onto the wheel flanges of the first axle in the direction of travel. The lubricant then spreads to the rail surface and other wheel flanges [17].

In contrast, wayside lubrication involves the application of lubricating grease or liquid friction modifiers directly onto the track from wiper bar dispensers positioned on the sides of the rail. These dispensers are electronically controlled to regulate grease flow, manage speed changes, and maintain awareness of train direction [18]. Typically, a combination of wayside and on-board locomotive lubrication systems is employed to minimise wear on both the high and low rails of curved sections [16].

To achieve optimal performance, rail lubricants are typically expected to reduce the coefficient of friction to 0.2 or lower for the gauge face on high rails in curved sections and between 0.3 and 0.4 for the top of the rail [19]. This is usually accomplished by applying greases that contain various soaps (such as calcium, sodium, lithium, and in some cases, boron), along with additives like graphite, lead, Teflon, and molybdenum disulfide, which enable the grease to withstand higher pressures. The choice of grease formulation depends largely on factors such as cost, operating locations, and seasonal temperatures [18,19].

Conclusion

Locomotives have always been one of the most environmentally and economically viable modes of transportation for people, goods, and services. They have been adapted to meet emission standards through technological advancements in diesel engine design, fuels, and high-performance lubricants. Optimised lubricants, tailored for specific operating environments, are essential for the smooth and efficient operation of locomotive components.
The industry is currently following trends from the automotive sector, exploring lower viscosity engine oils and lower ISO VG grade gear oils to enhance fuel economy by reducing friction. Synthetic greases with biodegradability are also gaining traction for bearing module lubrication, offering improved efficiency and longer lifespans. Rail lubrication also plays a vital role in fuel efficiency and maintenance. Ongoing advancements in synthetic grease formulations, additive systems, and environmentally friendly greases will progress simultaneously with lower-viscosity engine oils and gear oils. Achieving efficiency and fuel economy is crucial for the locomotive industry and is driven primarily by cost reduction and environmental concerns. Enhanced lubrication is a key element in ensuring that the rail industry meets these goals.

About the authors

Dr. Raj Shah *is a distinguished professional with a wealth of expertise in the Laternative energy and the Petroleum field.*

Currently serving as the Director at Koehler Instrument Company in New York, he has dedicated the past 28 years to his current company. Dr. Shah's exceptional contributions to the industry have been recognised by his esteemed peers, resulting in his election as a Fellow by prestigious organisations such as IChemE, CMI, STLE, AIC, NLGI, INSTMC, Institute of Physics, The Energy Institute, and The Royal Society of Chemistry.

*In addition to his esteemed reputation, Dr. Shah has been honoured with the ASTM Eagle award. He recently co-edited the highly acclaimed bestseller, "Fuels and Lubricants Handbook," a publication that has garnered widespread acclaim in the industry. Detailed information about this book can be accessed through the following link: ASTM's Long-Awaited Fuels and Lubricants Handbook 2nd Edition Now Available (**https://bit.ly/3u2e6GY**)*

Dr. Shah's academic achievements are equally impressive, having earned his doctorate in Chemical Engineering from The Pennsylvania State University. He holds the distinguished title of Fellow from The Chartered Management Institute, London, and boasts credentials as a Chartered Scientist with the Science Council, a Chartered Petroleum Engineer with the Energy Institute, and a Chartered Engineer with the Engineering Council, UK.

Acknowledging his exceptional accomplishments, Dr. Shah has been bestowed with the honourific *of "Eminent engineer" by Tau Beta Pi, the largest engineering society in the USA. He serves on the Advisory Board of Directors at esteemed institutions such as Farmingdale University (Mechanical Technology), Auburn University (Tribology), School of Engineering design and Innovation at the Pennsylvania State University , State College, PA, SUNY Farmingdale (Engineering Management), and State University of NY, Stony Brook (Chemical Engineering/Material Science and Engineering).*

Furthermore, Dr. Shah holds the position of Adjunct Professor at the State University of New York, Stony Brook, in the Department of Material Science and Chemical Engineering. With an impressive portfolio of approximately 600 publications in the field, he remains actively engaged in the energy industry for over three decades.

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