TOWARD PC-12: VISCOSITY OPTIMIZATION, WEAR RESISTANCE, AND EMISSION DURABILITY IN NEXT-GENERATION HEAVY-DUTY ENGINE OILS

Heavy-duty engine oil standards are updated periodically to address advances in engine technology and increasing environmental regulations. The PC-12 category, releasing on January 1, 2027, will represent the next generation of heavy-duty diesel engine oil specifications developed through the American Petroleum Institute (API), ASTM International, and original equipment manufacturers (OEMs). Driven both by United States Environmental Protection Agency (EPA) and California Air Resources Board (CARB), there is now a push for a 90% reduction in nitrogen oxide emissions and extended emission-control system life compliance from 400,000 to 650,000 miles. This review examines the key technical advancements associated with PC-12, including the adoption of lower-viscosity grades to improve fuel economy, enhanced oxidation resistance for accommodation of higher engine operating temperatures, and stricter chemical limits on substance accumulation to reduce aftertreatment degradation. Laboratory testing, such as the Mack and Caterpillar tests with the Cummins ISB and Caterpillar C13 platforms, is discussed to address the stricter conditions that PC-12 will have to pass. Despite these advancements, challenges surrounding industry adoption and reformulation costs may become barriers. The conclusion of this paper expresses that the long-term benefits of PC-12 will depend not only on its improvements to modern engines, but also on the ability of lubricant manufacturers, additive suppliers, and OEMs to promptly coordinate the upcoming significant changes.

Introduction

PC-12 is a new category of the heavy-duty engine oil standard that is currently in development through organizations such as the American Petroleum Institute (API), which licenses and classifies engine oils, and ASTM International, which is a standards organization that develops the laboratory tests that assess oil performance [1, 2]. Other main contributors are original equipment manufacturers (OEMs), which are engine and vehicle companies that approve of the oils used for their future engine designs [1, 2]. The main context for this new push is environmental concerns, including stricter limits on NO$_x$, longer required service life for emission-control systems, and pressure to reduce pollution produced from heavy-duty transportation [1, 2]. Specifically, the United States Environmental Protection Agency (EPA) and California Air Resources Board (CARB) are announcing a reduction of 90% in nitrogen oxide and extending life compliance requirements for emission control systems from 400,000 miles to 650,000 miles [3]. Major industry stakeholders cast ballots for the license of the PC-12 to be in effect on January 1, 2027 [4].

Other than the environmental aspect, PC-12 is also necessary for practical and performance aspects. Generally, heavy-duty engine oil categories are updated when modern engine technology changes enough that the previous category cannot keep up [5]. One focus includes lower-viscosity options that lean towards newer, fuel-efficiency-focused engines [4]. However, as viscosity lowers, oils create less wear protection. This refers to the oil's ability to create a lubricating film between surfaces to reduce contact damage. For that reason, the PC-12 must also focus on maintaining wear protection while also being fuel efficient [6]. In addition, there is an emphasis on developing oxidation resistance and thermal stability, as newer engines also generate higher temperature conditions [3]. Another major improvement to be focused on is aftertreatment protection, the protection of parts of the exhaust that allow for reduction in pollution [7].

The implementation of the PC-12 is a major redesign that is built around modern-day focuses on efficiency and conservation. This paper explores research and industrial developments on recent advancements in PC-12 in heavy-duty engine oil technology. The focus is on PC-12's role in catering to modern-day demands, including improvements in fuel efficiency, wear protection while maintaining lower viscosity, oxidation control, limitation of chemicals for durability, and the increase of laboratory checks to ensure PC-12 could be effective in modern engines. The focus is on PC-12's role in meeting modern demands, including improved fuel efficiency, maintained wear protection at lower viscosity, stronger oxidation control, tighter chemical limits for durability, and expanded validation to ensure performance in modern engines.

Past Categories

There will be two new categories of PC-12. The currently used standards are the categories of PC-11, CK-4, and FA-4, which will be replaced by CL-4 and FB-4, respectively. In the current heavy-duty oil generation, CK-4 acted as the generally applicable category used for a wide range of engines, while FA-4 was more specified for newer engines by being lower in viscosity [4]. Even earlier is the CJ-4 category. This structure is a practical solution that caters to varying types of engines used. Companies and manufacturers will not necessarily only provide the newest technology, so providing multiple options creates leeway for consumers.

PC-11 was introduced in 2017, with the primary goals of fuel economy, continued exhaust aftertreatment durability, and incremental engine wear improvements [8]. PC-12's primary goal is slightly similar, but focuses more on enhanced oxidation, wear resistance, and lowering ash accumulation [4]. However, it was not designed for the more extreme conditions of modern engines [4]. There is a push for higher operating temperatures, longer service-life requirements, and lower-viscosity oils to keep up with modern engines. As will be discussed in this review, these issues are what PC-12 is intended to address. Going back to 2007, PC-10 was introduced to improve aftertreatment protection, a way to protect systems in engines that help clean exhaust gases [9]. New categories are organized mainly through the criteria for passing specific tests. For instance, PC-10 had to pass the Mack T-12 test, composing of a 300-hour test that evaluates lubricant performance in the piston ring, liner wear, as well as bearing corrosion [9]. PC-11 goes a step further with tests like the Mack T-13 oxidation test, subjecting engines to 360-hours of high temperature operation [10]. PC-12 will also utilize this test, with the possibility of creating even stricter passing criteria. Adoption of PC-12 is another step towards the future of fuel innovation.

Lower Viscosity and Wear-Protection

One of the most important considerations for heavy-duty oils is the fuel economy. As such, PC-12 strives to provide an even lower-viscosity option that still provides the essential features of fuels. Low viscosity fuels provide a thinner oil that can create better flow in engines [11]. In a 2016 study conducted by Macián *et al.* [11], the research group aimed to test low-viscosity fuels in real-world situations and whether they hinder the vehicle's performance. They provide context stating that only around 15-20% of fuel energy reaches the wheels of vehicles, and up to 50% of the engine's mechanical losses come from engine friction [11]. This data points to the significance of using low-viscosity options, as although efficiency is increased, the increased contact causes increased wear. Their study consisted of a 30,000 km fleet with 39 urban buses [11]. They concluded that there is no significant difference between factors such as engine wear, oil consumption, and viscosity variation when properly formulating low-viscosity oils [11].

The PC-12 will trend towards optimization for these lower viscosity options. More specifically, the 0W-20 and 5W-20 grades. The number before the "W" describes the flow behavior of the oil at low temperatures [12]. This means that 0W-20 is made to be used more for cold starts compared to 5W-20 [12]. The number after the "W" describes the operating temperature viscosity range [12]. From a manufacturer's perspective, Shell Rotella, a supplier of heavy-duty diesel engine oils, identifies these grades as the challenge that PC-12 will need to overcome [13]. These oils are thinner than traditional grades, causing lower wear protection [13].

In a 2021 study by Zhang *et al.* [14], they examined main-bearing lubrication using a six-cylinder, 247-kilowatt diesel engine, comparing 15W-40, higher viscosity, with 0W-20, lower viscosity. The engine and set-up are shown in Figure 1 below. Their results show the diesel engine having mechanical loss from friction reduced by 15.3-23.6% [14]. However, with 0W-20's lower viscosity, the contact percentage increased to more than four times compared to the higher-viscosity options [14]. This increase in contact can be further explained by a 2020 study conducted by Wan *et al*. [15] used computer modeling for a diesel engine bearing at controlled speeds from 1000 to 3000 rotations/min. They wanted to find the exact oil film measurement in which contact occurs [15]. Figure 2 shows the specifics of the model they used. Figure 3 shows the test model they used, called "Sapphire" that consists of mechanical, hydraulic, and auxiliary systems [15]. They found that when the oil layer becomes thinner than 5 micrometers, contact occurs [15]. When this happens, pressure rises from 40 megapascals to 70 megapascals [15]. The results link the reduced film thickness observed in lower-viscosity oils to the higher contact rates reported by Zhang et al. [14] [15].

Infineum, a chemicals company known for developing additive technologies for fuels, reports that the Detroit Diesel DD13 Scuffing Test will improve the wear-protection for PC-12 [16]. Southwest Research Institute, a nonprofit research organization that conducts engine testing, explains the test as a method developed to evaluate an oil's ability to reduce adhesive wear for a diesel engine [17]. Tests run up to 200 hours or until some type of scuffing occurs [17]. PC-12 aims to find the balance between viscosity levels and maintain enough wear protection to provide high-quality oils with a greater fuel economy.

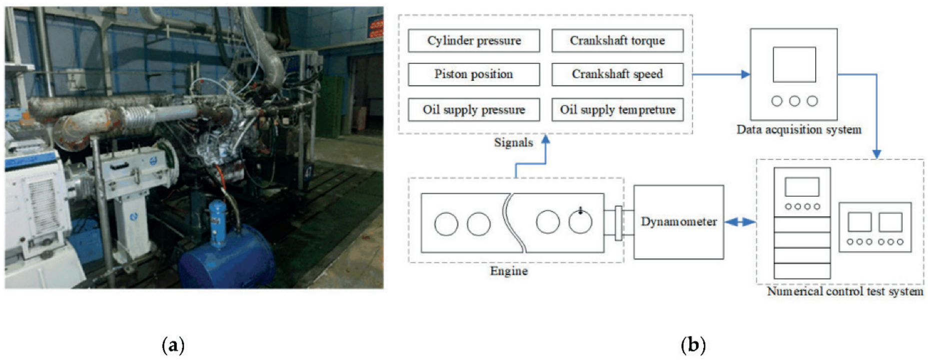

Figure 1: The arrangement of the experimental system: (a) test bench in the lab; (b) diagram of the experimental system. Reproduced from Zhang et al., (2021) [14].

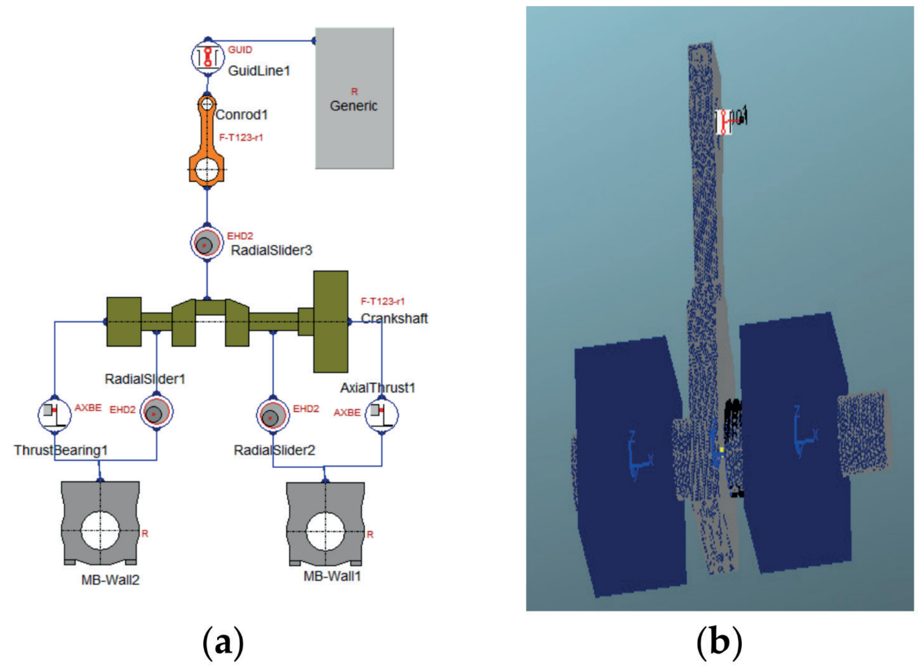

Figure 2: Multibody dynamics model: (a) 2D Excite model; (b) 3D model. Reproduced from Wan et al., (2020) [15]

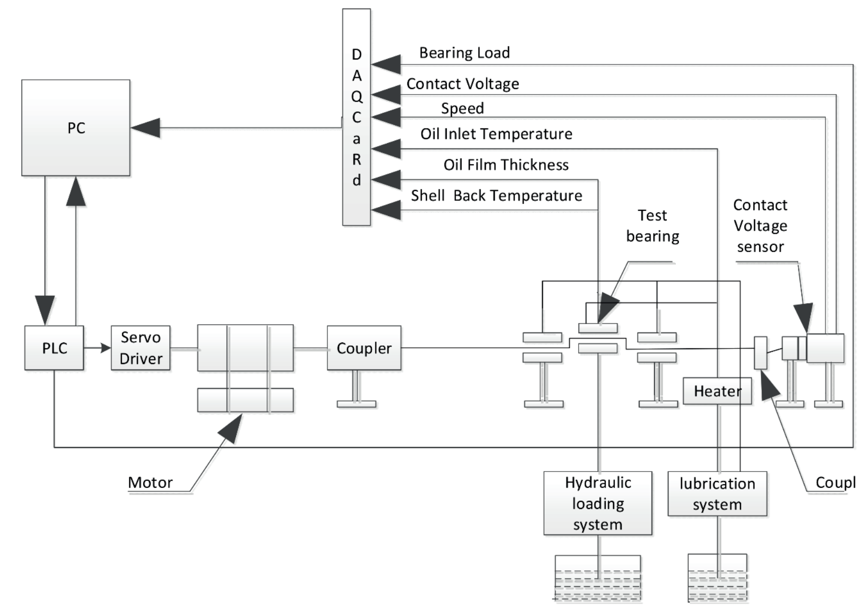

Figure 3: Schematic diagram of the "Sapphire" test bench. Reproduced from Wan et al., (2020) [15]

Oxidation Control

Another improvement PC-12 seeks to achieve is a higher oxidation resistance under higher temperatures. Oil can thicken and lose its ability to protect engine parts when undergoing chemical changes due to extreme temperatures. Improving oxidation protection allows for stronger and more thermally stable oil [4]. This is especially important as modern engines create higher stress on oils through strains such as increased thermal loading and a more demanding emissions strategy that increase system heat and oxygen buildup [4]. A 2023 study conducted by Padgurskas *et al*. [6] supports this point by observing three engine oils in trucks under similar conditions, taking samples after 2500 km and 5000 km of travel [6]. The study revealed that differences in oils are more significant with higher travel times [6]. Acidity rose in all three oils, shown in Figure 4: 1.60 to 2.20 mg KOH/gram for one, 1.66 to 1.96 mg KOH/gram for another, and 1.68 to 1.83 mg KOH/gram even in the most stable oil [6]. Increase in acidity can accelerate the breakdown of engine components that ultimately reduce engine efficiency and lifespan [6]. Further support is given through the 2024 study conducted by Gołębiowski et al. [18]. They studied the oil conditions of a fleet of seven buses using infrared spectroscopy, elemental analysis, and viscosity testing [18]. Figure 5 shows the engines of the buses they used. When the buses traveled more than 30,000 km, it was found that the soot content increased by 36%, iron increased by 22%, oxidation increased by 19%, sulfur increased by 25%, and nitro-oxidation increased by 47% [18]. These changes are reflected in Figure 6, where each sequence of letters and numbers corresponds to a different bus.

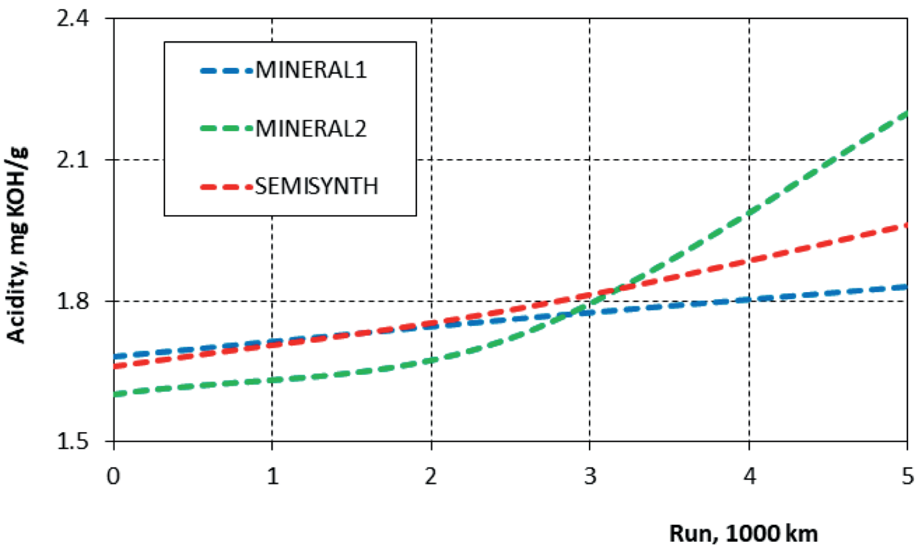

Figure 4: Change in acidity of different engine oils after 5000 km of operation. Reproduced from Juozas Padgurskas et al., (2023) [6].

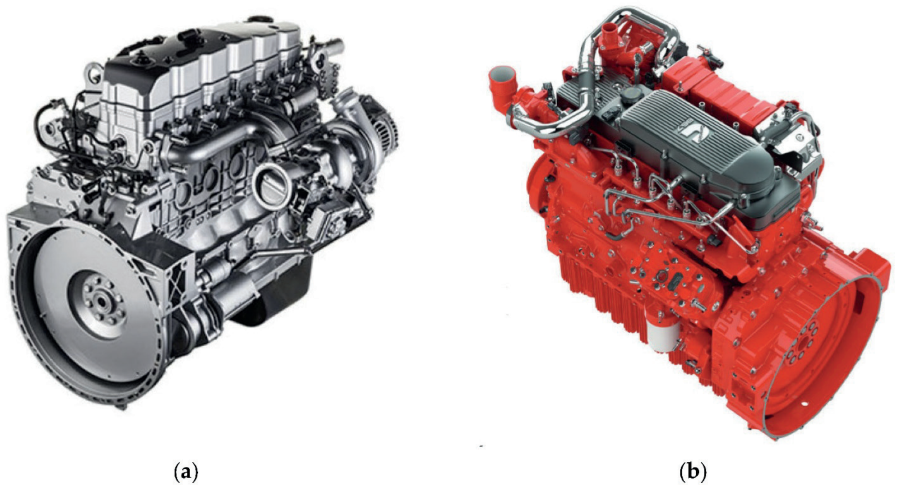

Figure 5: Engine N67 (a) and B6.7 (b). Reproduced from Wojciech Gołębiowski et al., (2024) [18].

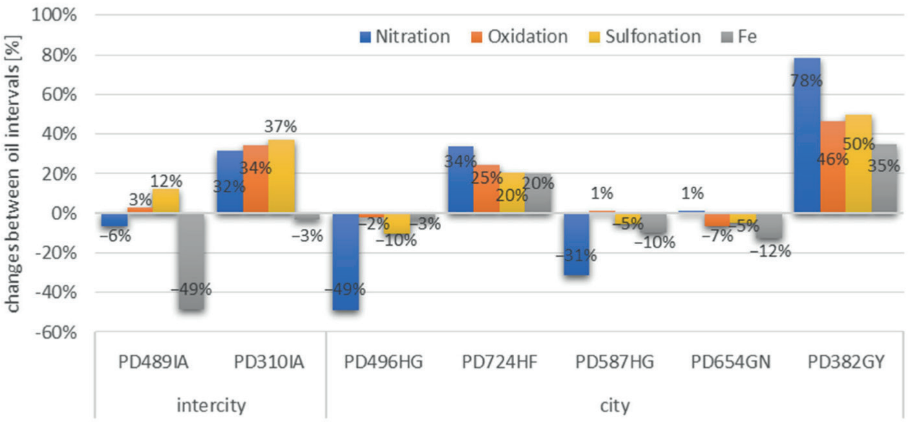

Figure 6: Changes in degradation between oil intervals. Reproduced from Wojciech Gołębiowski et al., (2024) [18].

PC-12 sets stronger requirements to possibly remedy these issues. Infineum also reports that PC-12 will address stronger oxidation control by placing tighter limits in the Volvo T-13 test [16]. Lubrizol, a company that manufactures additives for lubricants, describes the Volvo T-13 test as a 360-hour oxidation test that uses the Volvo D13 diesel engine under high temperatures to see if an oil can resist oxidation [19]. Controlling oxidation allows for cleaner and safer oils.

Aftertreatment Protection

Aftertreatment is essential for controlling pollution levels and engine performance. The 2022 review by Shao *et al*. [20] connects both lubricant issues and engine wear issues to needing aftertreatment protection. Figure 7 shows the various parts, including aftertreatment, that go into emission control. Figure 8 shows the process of measuring emissions. Modern-day diesel emission-control systems utilize parts such as the diesel oxidation catalyst and diesel particulate filter (DPF), which are continuously used over many years [20]. Combustion byproducts from the oil causes build-up of ash, increasing backpressure, as well as increasing chances of poisoning [20]. For extra context, a review by Kamp and Bagi [21] focuses on the tradeoffs between engine protection, lifespan, and maintenance cost. It discusses that accumulated ash raises filter pressure, requiring cleaning at 20-50 grams/liter [21]. Despite this, back pressure rose rapidly, reaching 6 kilopascals after 756 hours [21]. Ash accumulation can also vary heavily, with some areas reaching 500 micrometers while others usually reach 10-25 micrometers [21]. This variability is caused by metallic additives that are the main contributors to ash accumulation in the exhaust [21].

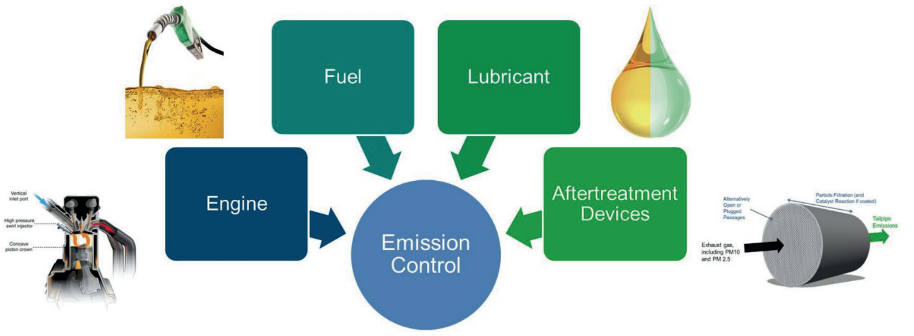

Figure 7. Various components that go into emission control. Reproduced from Shao et al., (2022) [20].

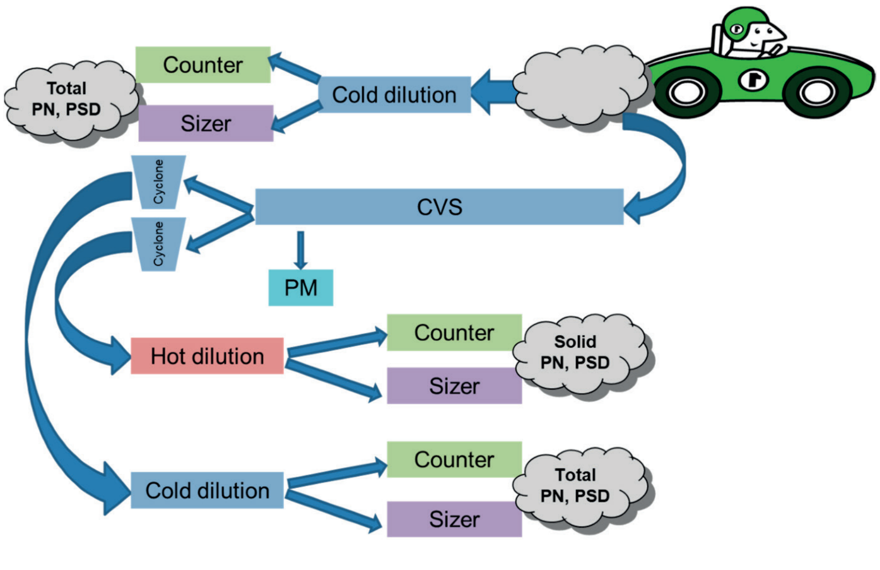

Figure 8. Particulate Emission measurement system. Reproduced from Shao et al., (2022) [20].

PC-12 is addressing this issue by focusing on the chemical and viscometrical limits linked to aftertreatment deterioration. Lubrizol reports that the chemical limits for PC-12 would effectively limit ash amounts to 0.9%, phosphorus to 800 ppm, and sulfur to 0.35% [19]. By constraining the concentration of ash-producing additives and increasing the use of lower-viscosity lubricants, engines will burn more cleanly and accumulate fewer residues [20]. Shell Rotella also states that PC-12 oils are being designed to extend DPF life by reducing ash and buildup using better formulated oil, with additive chemistry being the main cause of this [13]. PC-12 will reduce the flow of harmful compounds into the aftertreatment system, leading to longer DPF service intervals and a higher engine life expectancy.

Looking Ahead

As development on PC-12 continues, one major future benefit includes the optimization of the system for oil validation. This mainly includes the inclusion of modern laboratory tests and the removal of redundant older tests [16]. The new Cummins ISB soot-viscosity test will replace the existing Mack T-11 and Mack T-8 [16]. The Mack tests were used to observe different oils' ability to control accumulation with varying viscosity increases [16]. The new Cummins ISB test is similar but utilizes a more modern engine that more closely replicates the operating conditions of current on-road diesel usage, which improves the correlation between laboratory tests and if the oil were to perform in real-world scenarios [16]. Infineum also notes that this test uses less fuel during testing and can be used with retired engines, adding a resourcefulness factor [16]. In addition, the Caterpillar 1N test is being replaced with the Caterpillar C13 test. The Caterpillar 1N test has been used to evaluate oil consumption and scuffing in a single-cylinder engine, but the Caterpillar C13 allows for a multi-cylinder engine test for improved evaluation. These revamps produce more relevant and reliable tests that allow for increased validation of oil efficiency.

Despite the vast improvements that could be produced, the PC-12 still faces implementation challenges. As the previous category has not changed for a decade, the transition may not be so seamless if operators are already accustomed to CK-4 and FA-4. They have already built an established system for maintenance and infrastructure for the in-use PC-11 oil specifications. Changing the standard will impose logistical and financial friction. There will certainly be an increase in upfront costs to reformulate lubricants to meet PC-12's stricter additive and viscosity requirements, which will be passed on to consumers to face. Conflict with existing engine hardware can also be an issue. While PC-12 is meant for more modern engines, there is still an abundance of older-generation equipment in use. These engines might not hold well against the thinner oil formulations, causing an increase in wear risk rather than the intended result of reducing it. This means the adoption of PC-12 might cause an even larger rift between old and new engines as the newer engines benefit while the older engines fall behind.

These barriers will cause resistance from within the industry that could slow the adoption. Lubricant manufacturers, additive suppliers, and engine OEMs must all agree on the new formulations and testing conditions, and disagreements could delay finalization. There will need to be stricter validations and an agreed consensus to make sure PC-12 can be used commercially.

However, the long-term impact of PC-12 will outweigh the temporary drawbacks. If performed as intended, it will drastically improve environmental and mechanical conditions. Early agreement on cost and compatibility concerns will be instrumental to ensuring that PC-12 will deliver to its full potential. As such, the PC-12 serves as a bridge to a new modern world.

Conclusion

The upcoming PC-12 category is an evolution that reflects the changing world of heavy-duty engine technology. It addresses the many modern constraints that are limited by the current category. By lowering the viscosity, fuel economy can increase as the thinner oil reduces friction created from mechanical systems. This increases overall energy efficiency, also contributing to environmental factors through a lower need for oil. Oxidation is common but detrimental to engine systems. Through intensive procedures, PC-12 oils can be tested to reduce oxidation occurrences. Another detrimental effect is the accumulation of materials without proper aftertreatment. Limitation of chemicals for PC-12 can reduce the elements present in oils. PC-12 is still developing and evolving as the release date draws nearer.

Ultimately, PC-12's greatest challenge is the adoption process. The success or failure of PC-12 all depends on whether the industry can align quickly to bring new oils to the mark without effecting the current equipment in place. If addressed resolutely, PC-12 will represent a new era in both engine longevity and environmental responsibility that will no doubt path the next generation.

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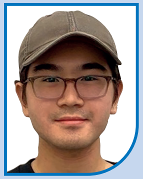

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