Benefits and Impacts of Latest Generation Lubricants in Older Diesel Vehicles under a Circular Economy Perspective: A Case Study in Brazil

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ABSTRACT

With the introduction of PROCONVE P-8 legislation in Brazil, equivalent to EURO VI, which establishes stricter emission limits for diesel vehicles, last-generation lubricants with a minimum performance of API CK-4 have become essential. This paper aims to demonstrate the impacts and benefits of using these lubricants in EURO V, III, or older vehicles from the perspective of circular economy, highlighting possible environmental and economic gains. The case study, conducted in a passenger road transport company in Brazil that uses diesel with 10% biodiesel as fuel, showed a 50% extension in the lifespan of the lubricant oil, enabling other benefits such as fewer maintenance stops. The use of last-generation lubricant oils also results in less used and contaminated lubricant oil (UCLO), meeting one of the basic principles of circular economy. It is concluded that last-generation lubricants, in addition to being necessary to meet the new euro VI vehicle requirements, can also play an important role in the circular economy of lubricants when used in older vehicles. This study provides valuable information for lubricant professionals and contributes to the promotion of sustainable use of natural resources.

RESUMO

Com a introdução da legislação PROCONVE P-8 no Brasil, equivalente ao EURO VI, que estabelece limites mais restritos de emissões para veículos a diesel, os lubrificantes de última geração com desempenho mínimo API CK-4 se tornaram imprescindíveis. Este trabalho objetiva demonstrar os impactos e benefícios do uso desses lubrificantes em veículos EURO V, III ou anteriores, sob a perspectiva da economia circular, destacando possíveis ganhos ambientais e econômicos. O estudo de caso, conduzido em uma empresa de transporte rodoviário de passageiros no Brasil que utiliza diesel com 10% de biodiesel como combustível, mostrou uma extensão em 50% da vida útil do óleo lubrificante, possibilitando outros benefícios como menor número de paradas para manutenção, maior durabilidade do motor e dos sistemas de pós-tratamento. O uso de óleos lubrificantes de última geração também resulta em menos OLUC (óleo lubrificante usado e contaminado) gerado, atendendo a um dos fundamentos básicos da economia circular, e aumenta o rendimento do rerrefino. Conclui-se que os lubrificantes de última geração além de serem necessários para atender as novas exigências dos veículos EURO VI também podem representar um papel importante na economia circular do lubrificante quando utilizados em veículos antigos. Este estudo fornece informações valiosas para os profissionais da área de óleo lubrificante e contribui para a promoção do uso sustentável dos recursos naturais.

INTRODUCTION

Air pollution, greenhouse gases, climate change, circularity, and ESG (Environmental, Social, and Governance) have been recurring topics in global discussions. Among the United Nations' 17 Sustainable Development Goals (SDGs), Goal 13 aims to take urgent action to combat climate change and its impacts. It is estimated that air pollution, particularly fine particulate matter ($PM_{2.5}$), is responsible for over 3.3 million premature deaths annually worldwide [1]. Currently, approximately 90% of the global population lives in regions where the air exceeds acceptable limits for air quality [2].

Given these scenarios and the growing understanding of the negative effects of atmospheric pollutants, continuous regulatory actions are increasing to establish stringent emission limits, especially in the transportation sector. In Brazil, trucks and buses represent a significant portion of pollutant emissions that impact air quality. It is estimated that in 2015, they accounted for 88% of $PM_{2.5}$ emissions and 89% of NO_x emissions from road transport [3].

Brazil has been controlling vehicle emissions through PROCONVE, the Vehicle Emission Control Program, which was established in 1986 through Conama Resolution

No. 18, dated May 6, 1986, with the primary objective of reducing pollutant emission levels from motor vehicles and promoting technological advancements in the country's automotive engineering. Since its implementation, PROCONVE has gone through different phases that gradually reduced emission limits for vehicles manufactured and sold in Brazil. The current phases in effect for each category are MAR-1 for agricultural and road machinery, L-7 for light-duty vehicles, and P-8 for heavy-duty vehicles [4].

PROCONVE P-8 (starting from January 1, 2023) stipulates that, all new heavy-duty diesel cycle vehicles commercialized in Brazil must comply with the new pollutant and noise emission limits. Phase P-8 corresponds to the European standard Euro VI, which came into effect in Europe for all new vehicles sold on December 31, 2013 [2]. There are numerous benefits to the implementation of Phase P-8.

One of the main changes with the implementation of Euro VI in Brazil is the introduction of more advanced technologies in vehicles, particularly in terms of after-treatment systems and the requirement of more advanced onboard computer systems [2].

As a result, the implementation of Euro VI in Brazil through PROCONVE P-8 has also had impacts on the lubricants industry. Lubricants used in diesel engines needed to be reformulated to meet stricter engine efficiency and protection requirements, as well as ensure compatibility with emission control systems. Lubricants have been developed with advanced technologies such as low-viscosity oils, state-of-the-art additives, and special formulations to maximize engine protection, reduce fuel consumption, and prolong the lifespan of after-treatment systems.

LAST GENERATION LUBRICANT OILS

Lubricating oils are essential substances for reducing friction between two moving surfaces by forming a protective film that prevents metal-to-metal contact, which can generate heat and wear. Automotive lubricants have the primary function of minimizing wear between the moving parts of the engine, such as pistons, rings, crankshaft, and camshaft, optimizing performance and extending the engine's lifespan. Their usage accounts for 60% of the national consumption of lubricating oils [5].

In addition to lubrication, lubricating oils perform other important functions. They contribute to engine cooling, corrosion prevention, and oxidation prevention. They also play a role in cleaning by removing residues and impurities that can accumulate in the engine over time [6].

Lubricating oils are obtained through the combination of base oils and additives. Base oils can be derived from petroleum refining or synthesized from chemical reactions [7]. They are classified based on their physical and chemical properties according to the American Petroleum Institute (API) which classifies base oils into five distinct groups. Group I consist of less refined base oils with lower performance in terms of thermal stability and volatility. Group II undergoes additional refining processes, resulting in oils with improved thermal stability and oxidation resistance. Group III, through further advanced refining, offers highly purified oils with excellent thermal stability and resistance to degradation. On the other hand, Group IV comprises synthetic base oils known as Polyalphaolefins (PAOs), while Group V includes all base oils that do not fit into the previous classifications, encompassing, for example, base oils of vegetable origin or esters. The main differences between the base oils in these groups can be summarized in Figure 1 below [8, 9].

API BASE OIL CATEGORIES

Base Oil Category	Sulfur (%)		Saturates (%)	Viscosity Index
Group I (solvent refined)	>0.03	and/or	<90	80 to 120
Group II (hydrotreated)	<0.03	and	>90	80 to 120
Group III (hydrocracked)	<0.03	and	>90	>120
Group IV	PAO Synthetic Lubricants			
Group V	All other base oils not included in Groups I, II, III or IV			

Figure 1. API classification for base oils [9].

Additive substances are added to reinforce or enhance the properties of base oils. Among the additive technologies used are detergents, dispersants, antioxidants, antifoaming agents, viscosity improvers, anti-wear agents, anti-corrosion agents, pour point depressants, and others [6].

There is a wide range of lubricants available in the automotive market, each designed to meet the diverse requirements of engines and vehicles. This diversity of options results from different performance classifications, compositions, and viscosities of lubricants. There are various specifications and classifications for automotive lubricants, especially those used in diesel engines. These specifications are established by international organizations such as API and the European Automobile Manufacturers Association (ACEA). They are crucial to ensure proper performance and protection of these engines [10, 11]. In addition to API and ACEA classifications, it is important to note that vehicle manufacturers may also establish their own specifications with additional requirements that consider the engineering characteristics of the engines and after-treatment systems.

The API CK-4 classification is the latest specification developed by the American Petroleum Institute (API) for lubricants used in diesel engines meeting the stringent Euro

VI standards. This classification offers an improved formulation compared to its predecessors, providing greater oxidation resistance, wear protection, and deposit control, for example, through the introduction of the new Volvo T-13 engine test [12]. These lubricants are formulated to handle the demands of modern Euro VI diesel engines, which have advanced emission after-treatment systems such as diesel particulate filters (DPFs) and selective catalytic reduction (SCR) catalysts [10].

Furthermore, one of the advantages of the API CK-4 classification is its compatibility with previous classifications such as API CJ-4, CI-4, and CH-4, which means that it can be used in older engines that require previous classifications. It offers additional benefits in terms of improved engine protection and performance.

Another benefit of using premium lubricants in older engines is the extension of the oil drain interval. These lubricants are developed with a more advanced formulation, allowing them to maintain their properties for a longer period, even under high load and extreme temperature conditions. On this basis, it expresses that the intervals between oil changes can be extended. In summary, lubricating oils play an indispensable role in the efficient operation and lifespan of automotive engines, performing multiple crucial functions. Therefore, it is extremely important to select the appropriate type of oil and follow the manufacturer's recommendations regarding regular oil changes to ensure optimized performance and increased engine durability.

NOTE: Since the engine oil change interval depends on various factors such as the sulfur content (S) of the fuel used, vehicle model, equipment maintenance conditions, the stress the engine is subjected to, total time since the oil was filled, among others, it is important to always follow the manufacturer's recommendations for determining the correct mileage, hour, or date for maintenance service.

ENVIRONMENTAL PERSPECTIVES

In Brazil, the market for base oils heavily relies on imported Group II and Group III base oils, which have a greater emissions impact due to the logistics process [13, 14]. However, there is a long-term market opportunity in Brazil with the growing usage of formulations incorporating these base oils [15].

The circular economy plays a crucial role in promoting sustainability within the lubricant industry [16]. Re-refining (Figure 2), an essential aspect of the circular economy, enables the recovery and reuse of base oils from used lubricants [17]. By incorporating premium lubricants with higher-quality base oils, the re-refining process can achieve improved efficiency, facilitating the reintegration of these products into the lubricant value chain.

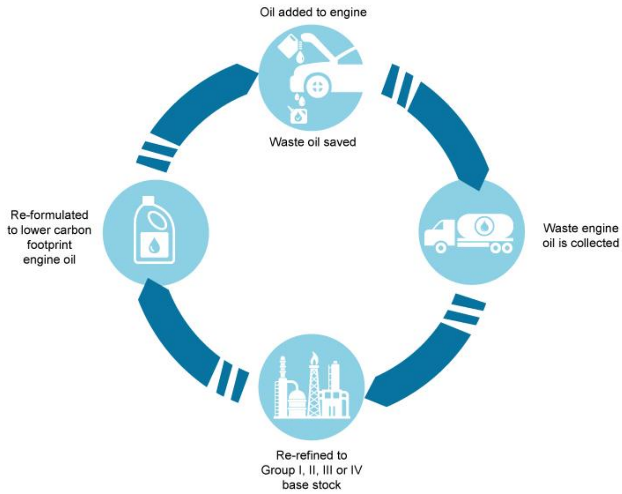

Figure 2. Circular economy in the lubricant value chain [18].

From an environmental perspective, the utilization of the latest generation lubricants, especially those formulated with GII and GIII base oils, offers significant benefits. These lubricants not only provide enhanced performance but also contribute to reduced emissions and improved fuel efficiency in older diesel vehicles. By adopting such lubricants, the environmental impact of these vehicles can be mitigated, contributing to a cleaner and more sustainable transportation sector.

The Brazilian market presents an opportunity for long-term development by exploring the use of GII and GIII formulations. As the market demands better-performing lubricants and strives for sustainability, there is a growing need for locally available high-quality base oils. This shift towards premium lubricants with better base oils enhances the efficiency of the re-refining process, allowing for the successful reincorporation of these products into the lubricant value chain, thereby promoting circularity and reducing the environmental footprint of the industry.

By focusing on re-refining and circularity, as well as the market dynamics of base oils in Brazil, the research highlights the potential for sustainable practices, the benefits of adopting premium lubricants, and the importance of considering the environmental implications of the lubricant industry. Figure 3 demonstrates that the utilization of re-refined base oil can result in a significant reduction of approximately 40% in carbon footprint.

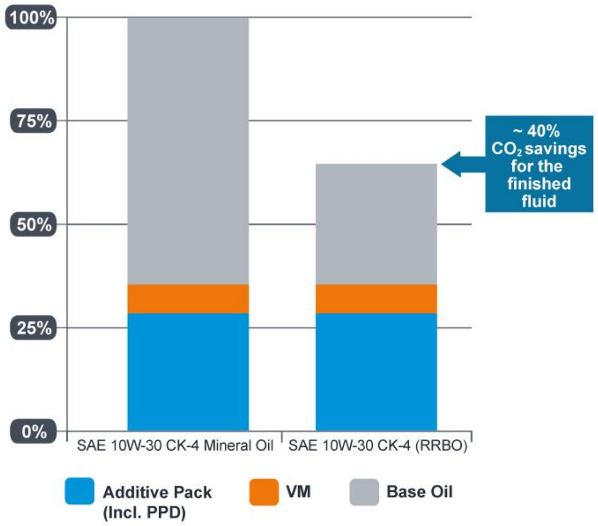

Figure 3. Carbon footprint comparative of refined and re-refined base oil, cradle-to-gate (CF in kg CO_2e/kg) [18].

CASE STUDY

To demonstrate the impacts and benefits of using API CK-4 semi-synthetic premium lubricants in vehicles with technologies prior to Euro VI, a field test was conducted in collaboration with a passenger transport company in Brazil. The test involved selecting 7 Euro V buses to be lubricated with API CK-4 15W-40 semi-synthetic lubricating oil under real driving conditions, with the aim of extending the oil drain interval.

The objective of this field test was to extend the lubricant change interval by 50% by replacing a lower performance API CI-4 standard oil with a premium API CK-4 standard oil. The previous API CI-4 product used in the evaluated fleet was replaced every 60,000 kilometers. Therefore, the aim of the test was to ensure that the tested buses reached 90,000 kilometers in good condition without compromising vehicle performance.

VEHICLE DATA – A total of 7 RSDD model buses manufactured by Mercedes-Benz were monitored, with initial mileage as indicated in the Table 1 below.

Table 1. Vehicle Information.

Selected Vehicle	Initial milage (Km)
ON630	510,285
ON610	509,322
ON510	504,086
ON340	709,700
ON650	500,882
ON290	875,565
ON520	561,633

OIL LUBRICANT DATA – For the test, the latest semi-synthetic lubricating oil was selected, which has been formally recognized and approved by the vehicle manufacturer. The lubricant is classified as SAE 15W40 and meets the minimum performance level of API CK-4.

The tested lubricant was chosen because it is recommended for use in diesel engines of buses equipped with gas after-treatment systems such as SCR or EGR. It also complies with the Euro VI or earlier emission requirements under severe conditions and extended oil drain intervals. In addition to meeting the API CK-4 performance levels, it also meets ACEA E9-2016, MB 228.31, and Volvo VDS-4.5 specifications. The typical physical chemical characteristics of the selected lubricating oil can be found in Table 2.

Table 2. Physical Chemical properties of lubricants.

Typical Analysis	ASTM	Result
Kinematic Viscosity at 100° C	ASTM D445	15.2 mm^2/s
Kinematic Viscosity at 40° C	ASTM D445	116 mm^2/s
Viscosity Index	ASTM D2270	135
Sulfated Ash	ASTM D874	1.0 % massa
Total Base Number	ASTM D2896	10 mg KOH/g

Before the field test, the selected vehicles were lubricated with a mineral lubricant SAE 15W40 with API CI-4 performance level, and the oil drain interval was performed every 60,000 kilometers driven.

FUEL USED – Brazilian fuel is regulated by the National Agency of Petroleum, Natural Gas, and Biofuels (ANP), which establishes the technical specifications for diesel fuel sold in the country. Currently, the maximum sulfur content in diesel sold in the country is 500 parts per million (ppm) for regular diesel and 10 ppm for low-sulfur diesel, known as S-10 diesel. These limits aim to reduce atmospheric pollutant emissions and improve engine efficiency, contributing to environmental preservation and public health [19].

In addition, Brazil also has a mandatory biodiesel blending policy for diesel fuel. Since 2010, when the legislation was implemented, the percentage of biodiesel in diesel has been gradually increasing as indicated in Figure 4. The use of biodiesel helps reduce greenhouse gas emissions and diversify the country's energy matrix. Currently, the applicable blend percentage is 10% biodiesel in diesel fuel [20].

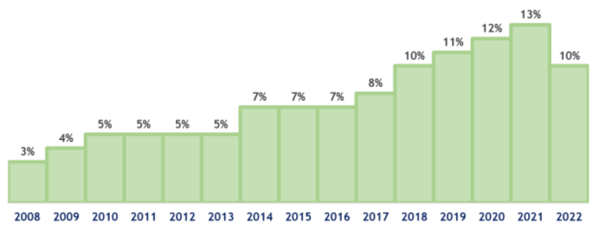

Figure 4. Evolution of the % of Biodiesel in diesel in Brazil [20,21].

In addition to the mentioned positive aspects, biodiesel, by its nature, possesses lubricating properties, which can result in a slight improvement in lubrication and reduction of engine wear. However, it is important to highlight that biodiesel also has characteristics that can influence the degradation of lubricating oils, such as a higher tendency for oxidation and sludge formation. Therefore, to ensure good performance of the lubricating oil in engines using biodiesel, lubricant manufacturers need to develop specific and suitable formulations to handle the characteristics of this biofuel [21].

Taking all the mentioned points into consideration, during the field test period, the fuel used throughout the entire test was diesel S10 with a biodiesel blend of 10%.

FIELD TEST – Procedures were established for the replacement of the lubricant being tested, as well as the periodic sampling of in-use oil to be collected.

For a complete replacement of the lubricating oil, the following procedure was carried out: draining the crankcase, filling with the test lubricant, starting the engine; draining the lubricant, replacing the oil filter, and finally refilling with the lubricant of test.

During the test, lubricating oil was replenished. If the oil level fell below the minimum required, a top-up with new oil was performed. The monitoring of the lubricating oil level was conducted by maintenance personnel to ensure the integrity and proper functioning of the engine. This approach ensured that the tests were conducted under real operating conditions.

The frequency of collecting in-use oil samples for analysis and performance monitoring was carried out according to the schedule indicated in Table 3. The samples were collected and sent for analysis to a specialized laboratory in in-use oil analysis.

Table 3. Frequency of sample.

1st sample	2nd sample	3rd sample	4th sample
Fresh oil	60,000 Km	75,000 Km	90,000 Km

SAMPLE ANALYSIS – According to the sampling frequency indicated in Table 3, samples were collected for physical chemical analysis in a specialized laboratory. The volume of lubricating oil collected for analysis was determined as the minimum required to perform the main laboratory tests, as indicated in table 4, ensuring that there was no significant interference with the total volume of oil in the crankcase. This approach was adopted to obtain precise and reliable results, allowing for a comprehensive evaluation of the lubricant's performance and condition without compromising the functionality of the lubrication system.

Table 4. Sample analysis.

Tests	**ASTM**
Base Number Determination	ASTM D4739
Kinematic viscosity (100°C)	ASTM D7279
Metals	ASTM D5185
Soot and Oxidation	Inside Method

RESULTS

The results obtained from the analysis of used oil samples were satisfactory and within the expected performance limits. All evaluated vehicles reached the target mileage, with test completion ranging from 82,680 kilometers to 99,373 kilometers.

OIL ANALYSIS – The lubricant analysis results were evaluated based on specifications and condemnation limits available in the Vibra Energia S.A. database. During the analysis, any statistically outliers were excluded.

The Total Base Number (TBN) characterizes the alkaline reserve in lubricants, particularly in engine oils where acidic combustion products deplete the alkaline reserve. Figure 5 presents the variation of TBN during the test in vehicles ON510 and ON520. The reduction in TBN indicates the consumption of the lubricant's alkaline reserve [6], but the observed reduction in all vehicles falls within the expected range.

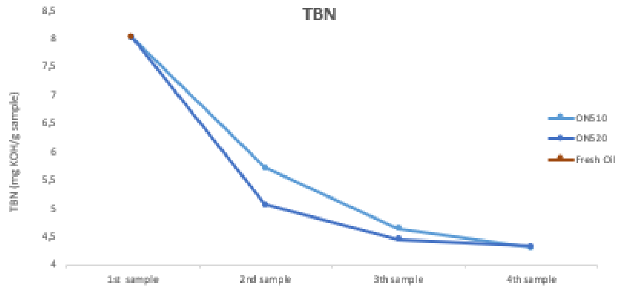

Figure 5. TBN results.

Figure 6 shows the variation of kinematic viscosity at 100°C during the test. The viscosity stability of the lubricating oil is a crucial characteristic for its application, ensuring that the viscosity remains within the allowed range for the SAE grade, thereby guaranteeing the formation of a protective oil film between the lubricated metal parts. A determining factor in this stability is the quality of the viscosity-modifying polymer additive present in the oil formulation. This additive plays a crucial role in maintaining the proper viscosity over time, even under conditions of shear and high temperatures encountered during diesel engine operation [6].

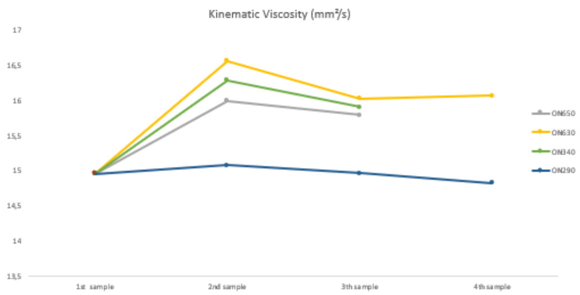

Figure 6. Kinematic viscosity at 100°C.

It is possible to observe that the kinematic viscosity initially increased and then showed a slight decrease during the test. This initial increase is attributed to the expected oxidation behavior, which thickens the oil. After a certain period, the shearing of the viscosity-modifying additive can be observed, resulting in a viscosity reduction. It is important to note that none of the analyzed samples showed results outside the range determined by SAE J300 for a 15W40 grade lubricant, with a specified range of 12.5 mm²/s to 16.3 mm²/s [22].

The wear content of lubricated parts during oil usage can be evaluated by analyzing the metal content in the samples. The metals present in the analysis are directly related to the metallurgy of the lubricated components, and higher levels of these elements indicate greater component wear [23, 24].

Figures 7 and 8, respectively, show the variation in copper and iron content found in the analyzed samples. The increase in copper content is often associated with the wear of components such as bushes, bearings, and sealing rings, where copper is commonly used as a manufacturing material. In addition to copper content, the iron content can also be attributed to the wear of components such as pistons, piston rings, cylinders, and other moving parts of the engine. The lower the variation in iron content, the better the protective capacity of the lubricant and the lower the wear on the parts it provides [24].

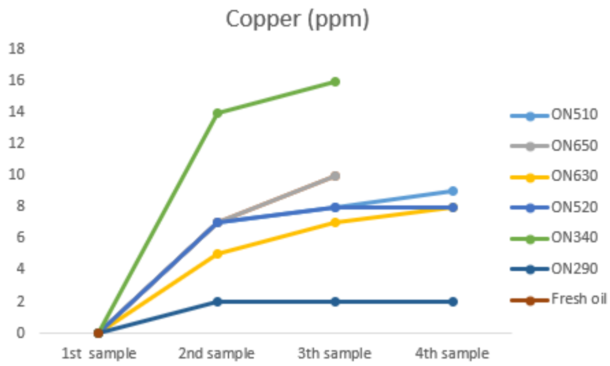

Figure 7. Copper content variation.

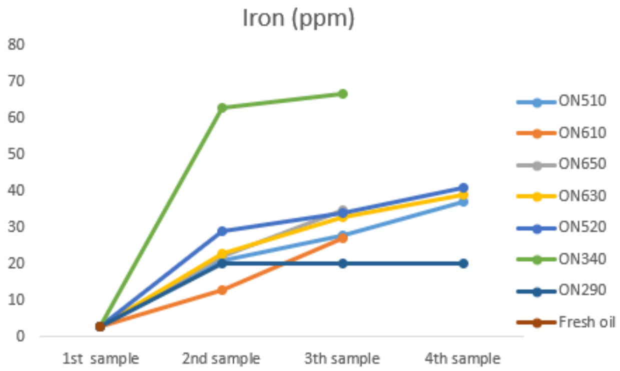

Figure 8. Iron content variation.

The results obtained are within the normal limits for the application, except for the results for the ON340 vehicle, which showed a moderate concentration of iron, indicating a possible onset of engine wear. Therefore, it may not be possible to further extend the oil drain interval for this particular vehicle.

Figures 9 and 10 display the variation in soot and sulfation, measured using the Infrared method, for the analyzed samples, respectively. It can be observed that these levels increase over the course of lubricant usage; however, the obtained results remain within the expected limits for the application. Long-life and reliability are the criteria for the commercial vehicle sector. The HD (Heavy Duty) oils have to match these requirements [6].

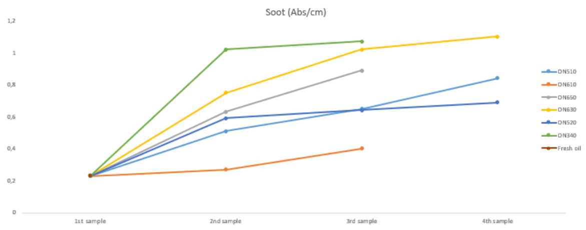

Figure 9. Soot content variation.

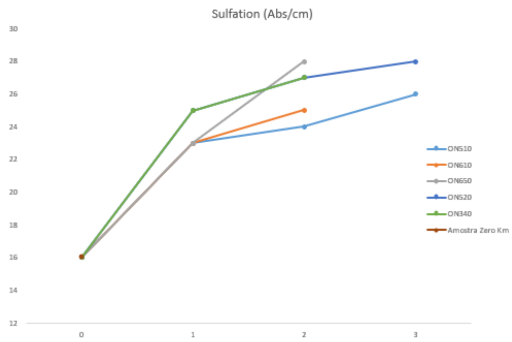

Figure 10. Sulfation content variation.

Soot is a byproduct of incomplete combustion in diesel engines and can accumulate in the lubricant over time. High soot levels can adversely impact engine efficiency, increase component wear, and reduce the lubricant's life. The lubricant plays a crucial role in dispersing and suspending soot particles in the oil, thereby preventing their detrimental effects. Therefore, it is imperative to monitor and control the soot content in diesel lubricants as an integral part of a maintenance program. This ensures that the lubricant effectively performs its detergency and dispersion functions, facilitating the transport of sludge, soot, and abraded particles to the oil filter. This process contributes to the protection and optimal performance of diesel engines [6].

Sulfation occurs due to the presence of sulfur in diesel fuel, which undergoes combustion and converts to sulfur dioxide (SO2). When SO_2 reacts with water, acids are formed, posing a risk of corrosion to metallic engine components. Consequently, effective control of sulfation is crucial in oil monitoring to evaluate the corrosion risk and ensure adequate engine protection.

Based on the analysis of the field test results, it was possible to extend the oil drain interval for EURO V vehicles by utilizing a premium API CK-4 lubricant. This extension was achieved without compromising the vehicles' performance and durability.

ENVIRONMENTAL PERSPECTIVES - The extension of the evaluated lubricant's change interval also led to significant environmental benefits. One of the main advantages was the reduction in the generation of used and contaminated oil (UCLO). With the extended change interval, less UCLO was disposed of, contributing to the reduction of the environmental impact associated with waste management and the disposal of used lubricating oil. This aligns with the principles of the circular economy, where lubricating oil can be recovered, regenerated, and reused, closing the product's life cycle and reducing reliance on natural resources [18].

To quantify the tangible benefits of reducing UCLO generation, an estimated calculation was devised, utilizing certain assumptions and data from the conducted field test, as shown in Table 5.

Table 5 - Considerations for UCLO generation calculation.

Quantity of used lubricating oil per vehicle	28 liters/bus
Total number of fleet vehicles	100 buses
Average kilometers per month	10,000 Km/month
Percentage of lubricating oil lost during engine operation	20%
Drain Interval of API CI-4	60,000 Km
Drain Interval of premium API CK-4	90,000 Km

In this way, it is estimated that within a one-year period, 56,000 liters of lower-performance API CI-4 lubricating oil are required. This results in the generation of 44,800 liters of UCLO per year, considering a 20% loss during the engine operation process. By replacing the oil with a premium API CK-4 lubricant that allows for an extended drain interval, the quantity of oil required for this fleet reduces to 37,334 liters per year, generating 29,867 liters of UCLO per year for treatment. The 50% extension of the lubricating oil drain interval allows for a reduction of approximately 33.3% in UCLO generation.

Furthermore, benefits in the lubricating oil re-refining process can also be expected when using premium lubricants with higher-quality base oils required to meet the quality limits imposed by the latest specifications such as API CK-4. These higher-quality base oils can improve the efficiency of the re-refining process as they generate higher-quality UCLO.

Another relevant point is the positive impact on the conservation of natural resources. As less new lubricant will be required, there will be a reduced demand for raw materials used in lubricant production, such as base oils and additives. This results in a lower consumption of non-renewable natural resources, such as petroleum, and a reduction in the ecological footprint associated with the extraction, processing, and transportation of these resources. In addition to the economic aspect, there is also a reduced dependence on the volatility of raw material prices and a limitation of supply availability risks [16].

Another important aspect is the decrease in energy required for lubricant production and distribution. With longer change intervals, the total amount of lubricant consumed is reduced, leading to lower energy consumption in the manufacturing and logistics related to the production and distribution of these products. This contributes to the reduction of greenhouse gas emissions associated with these activities, promoting an economy with a lower carbon footprint.

NOTE: The obtained results are specific to the case study discussed in this work. For extending the change interval, it is recommended to closely monitor the vehicles and/or equipment by a specialized team and through analysis of used lubricating oil aligned with proper maintenance practices. Adhere to the conditions of use, maintenance, and recommendations of the engine manufacturer's manual.

CONCLUSION

The results obtained from the analysis of used oil samples demonstrated satisfactory performance within the expected limits. The observed reduction in Total Base Number (TBN) is in line with the normal consumption of the lubricant's alkaline reserve. It is important to note that all the analyzed samples remained within the limits established by SAE J300 for a 15W40 grade lubricant, indicating the maintenance of the lubricating film. Additionally, the analysis of metal content in the samples did not reveal significant wear of the metallic components. The variations in the levels of soot and sulfation found throughout the field test were within the expected limits for the application. The results validated the use of a premium API CK-4 lubricant in EURO V vehicles for extending the oil change interval without compromising the performance and durability of the evaluated vehicles.

All evaluated vehicles achieved the expected mileage, concluding the test between 82,680 km and 99,373 km.

The extension of the evaluated lubricant's change interval resulted in significant environmental benefits, including the reduction of UCLO generation. Through estimated calculations, it was found that replacing the lower-performance API CI-4 lubricant with a premium API CK-4 lubricant, with a 50% extended change interval, reduced UCLO generation by approximately 33.3%. Additionally, it can produce higher-quality UCLO, which can improve the re-refining process. This contributes to the circular economy by closing the product's life cycle and reducing dependence on natural resources.

Other benefits were also observed, such as the need for fewer maintenance stops, allowing the vehicle to remain operational for a longer time, increasing its efficiency and productivity. This translates into a significant advantage for commercial vehicle owners and fleet operators, who can make the most of their resources, reduce maintenance costs, and maximize operation time.

In summary, next generation lubricating oils designed initially to meet the demands of new EURO VI engines, when used in older engines, bring numerous environmental benefits, favoring the circular economy. These benefits include the reduction of waste generation (UCLO), conservation of natural resources, and decreased energy consumption and greenhouse gas emissions. This approach contributes to a more sustainable management of lubricants, driving the transition to the use of modern and high-performance lubricating oils. These results not only strengthen sustainability in the lubricant industry but also highlight the importance of adopting responsible and conscious approaches to reduce environmental impact and promote energy efficiency.

FUTURE PERSPECTIVES

In the next stages of the project, monitoring of the generated amount of UCLO will be carried out to develop a more accurate equation and estimations. Additionally, it will be necessary to determine the exact amount of top-up required per vehicle to calculate the precise lubricant loss during combustion. Another important aspect will be conducting vehicle rating analyses to assess other benefits of the lubricant, such as wear prevention and engine cleanliness. Other point is to explore the validation of the theory across different vehicle models and manufacturers.

With these actions, it will be possible to continuously improve the project and maximize its benefits in terms of both environmental sustainability and engine performance.

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