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PERFORMANCE OF B10/B20 USAGE IN HEAVY-DUTY DIESEL VEHICLES

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ABSTRACT

Palm oil biodiesel has been a sustainable and renewable alternative to petroleum since the 1980s. Palm biodiesel was gradually blended with petroleum diesel to introduce environmentally friendly fuels into the Malaysian market. Consumers sought additional information to assess the potential risks of higher palm biodiesel blends. Six diesel trucks under actual on-road conditions were involved in using palm B20 and B10. Fuel economy for the B20 vehicles was 2.020 km L^{-1} and for B10 vehicles was 1.910 km L^{-1}. Idling adjusted fuel economy for the B20 vehicles was 2.107 km L^{-1} and for B10 vehicles was 2.055 km L^{-1}. Statistical analysis indicated no significant difference in fuel economy, vehicle payload affecting fuel economy, or maintenance costs between the B20 and B10 groups. Engine oil samples, taken at 5,000 km intervals, were tested to determine the impact of using the B20 blends. All engine oil samples were found to remain within operational service limits. B20 usage positively impacted engine oil quality with higher total basic number and lower iron content than B10. Statistical analysis demonstrated insignificant differences between the two fuel groups in fuel economy, idling adjusted fuel economy, payload, service cost, viscosity, zinc, sodium, soot in oil and magnesium, with a high degree of confidence.

Keywords: engine oil quality, heavy-duty diesel vehicles, on-road fleet testing, palm biodiesel.

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INTRODUCTION

Biodiesel, a sustainable and eco-friendly diesel alternative derived from vegetable oil through transesterification (Mosarof et al., 2015), has been identified as a viable substitute for petroleum since the 1980s. In Malaysia, palm oil serves as the primary raw material for biodiesel production, and as one of the world's largest palm oil producers, Malaysia produced over 19 million tonnes of crude palm oil in 2017 (Kushairi et al., 2018). Palm biodiesel production in the country commenced in 2006, reaching over 720,000 t in 2017 (Kushairi et al., 2018; Nambiappan et al., 2018). Palm oil's superior oxidation stability and year-round availability make it an abundant resource suitable for sustainable and environmentally friendly fuel production. The global shift away from fossil fuels due to finite reserves and rising carbon dioxide (CO_2) emissions has increased the significance of biofuels as a renewable and low-carbon footprint energy source. Biodiesel, as a prominent commercial fuel worldwide, is increasingly adopted by numerous countries as a substitute for fossil diesel in powering diesel vehicles.

Aligned with the National Biofuel Policy (NBP), Malaysia has introduced palm-based biodiesel blends with diesel, including B5, B7, B10 and B20 (in specific states) (Kushairi et al., 2018; Nambiappan et al., 2018). The National Agricommodity Policy 2021-2030 aims to implement increased B20 and B30 targets by 2022 and 2030, respectively. Despite these goals, there is a lack of operational and technical data for palm B20, hindering informed decisions and addressing concerns about its use in

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diesel vehicles. As diesel vehicle manufacturers' acceptance is crucial for the success of palm biodiesel in the commercial market, comprehensive fleet testing, laboratory analyses and chassis dynamometer investigations are essential for evaluating the impact of the palm B20 blend.

Most reported studies are focused on engine testing with biodiesel blends under controlled laboratory conditions, such as the single cylinder engine experimental setup to investigate the combustion efficiency of biodiesel blends (Sharma et al., 2022). There have been limited field studies on actual on-road operation, particularly regarding the impacts on extended engine durability and operating costs. Fleet tests in the U.S. indicated no significant differences in fuel economy, maintenance costs, or engine wear, although instances of fuel filter plugging were noted for B20 in some cases (Barnitt et al., 2008; Fraer et al., 2005; Lammert et al., 2010; Proc et al., 2006; Tang et al., 2016). However, for palm biodiesel, there remains a notable lack of B20 operational and technical in-use data under actual on-road conditions.

Engine lubricating oil (LO) plays a crucial role in diesel engines, performing functions such as reducing friction and wear, cooling, cleaning, sealing and protecting engine parts. However, the quality and performance of LO can degrade over time due to factors like oxidation, contamination, dilution and degradation. The use of biodiesel blends as alternative fuels for diesel engines is one factor that may influence LO quality and performance. *Table 1* illustrates the significance of LO parameters, along with their minimum and maximum limits.

TABLE 1. LIST OF LO QUALITY TESTING PARAMETERS SIGNIFICANCE AND LIMITS

Parameter	Limit
Viscosity	12.6–16.4 $mm^2 s^{-1}$
Total base number	Min 5.0 mg KOH g^{-1}
Wear metals	Iron: Max 100 ppm Others: Max 40 ppm
Oxidation and nitration	Max 2.0 A cm^{-1}
Sulphation	Max 2.0 A cm^{-1}
Water and coolant contamination	Water: Max 0.3% Coolant: Any detectable amount is a concern
Flash point	Min 220°C
Soot	Max 2.0 A cm^{-1}
Particle count	Max 20 ppm
Pour point	-24°C
Ash content	0.9%–1.5% by weight
Phosphorus and zinc	Phosphorus: 600–1,200 ppm Zinc: 800–1,400 ppm
Specific gravity	0.85–0.89 at 15°C

Hypothesis testing is a common practice in real-world vehicle trials to assess the significance of observed differences or relationships. Using a t-test or ANOVA after data collection helps test hypotheses. Inferential statistics, including techniques like confidence intervals and *P*-values, quantify the uncertainty associated with estimates and determine the statistical significance of findings, aiding in data-driven decision-making (Bietresato et al., 2019). These tests are employed to separate and isolate the considerable background disturbances present during actual on-road driving scenarios, which may significantly impact the results. This underscores the significance of statistical analyses in comparable trials.

Idling fuel consumption, a substantial source of energy waste and emissions, can be influenced by biodiesel blends. Biodiesel's characteristics, including oxygen content and a higher cetane number, may potentially reduce fuel consumption during idling. Real-world vehicle trials, using on-board diagnostics (OBD) systems for data retrieval, offer a practical approach to estimating idling fuel consumption, considering the rudimentary method when sophisticated methods are unavailable.

Payload weight's impact on fuel economy is well-established, with heavier payloads leading to increased fuel consumption. Optimising fuel economy with varying payload weights involves strategies like efficient route planning, load optimisation, vehicle maintenance and driver training. Proper maintenance practices are crucial for optimal fuel economy, as neglected maintenance can result in decreased engine efficiency and increased fuel consumption. Biodiesel's lubricity and impact on engine wear are factors to consider, making maintenance practices essential for achieving optimal fuel efficiency.

In summary, this project aims to acquire the necessary dataset for the understanding of extended palm B20 usage in heavy-duty diesel vehicles under actual on-road driving conditions. The 100,000 km road test, coupled with laboratory analyses, will assess on-road fuel economy, reliability, service maintenance and engine oil performance. The study's results aim to inform government decisions on higher biodiesel blends in Malaysia and instil confidence in the logistics sector regarding the applicability of biodiesel blends in their day-to-day operations.

MATERIALS AND METHODS

The study employs fleet testing to gather actual on-road data on the usage of palm B20 and B10 through operational fleet vehicles. While both fleet testing and stationary engine testing offer valuable insights into biodiesel blend performance, fleet testing presents several advantages, particularly in evaluating real-world applicability and performance. These advantages include exposure to diverse operating conditions, variability in ambient conditions, real-world emissions data, considerations for vehicle integration, assessment of durability and long-term impact, and obtaining direct feedback from drivers.

Fleet testing involves vehicles operating under actual driving conditions, encompassing a range of speeds, accelerations, decelerations, idling periods and more. This comprehensive assessment provides a realistic portrayal of biodiesel performance in various scenarios (McCormick & Westbrook, 2010). In contrast to the controlled environments typical of stationary tests, fleet tests subject biodiesel blends to different weather conditions and temperatures, revealing issues related to cold starts, fuel gelling, or volatility (Shrestha et al., 2005). Fleet tests offer a clearer understanding of real-world emissions and environmental benefits, potentially differing significantly from laboratory results (Durbin et al., 2008).

Additionally, fleet testing can unveil challenges related to the integration of biodiesel with vehicle systems, including potential issues with seals, hoses and compatibility with emission control systems (McCormick & Westbrook, 2010). It provides insights into the long-term impact of biodiesel blends on engine durability, maintenance requirements and overall vehicle lifespan, aspects challenging to replicate in stationary setups. Real-world fleet tests enable drivers to provide feedback on vehicle performance, drivability and potential issues, offering a holistic understanding of biodiesel's impact (Abed et al., 2019). Therefore, data obtained from fleet testing can provide more insightful information for logistics companies and government policymakers interested in the real-time implications of new fuel mandates.

The oil palm fleet company contributed six trucks serving as palm oil tankers transporting processed palm oil from refineries. The fleet company also provided the specifications of the diesel vehicles used in the fleet testing, as shown in *Table 2*.

TABLE 2. SPECIFICATIONS OF THE FLEET VEHICLES

Gross vehicle weight (GVW)	26,100 kg
Maximum power	400 hp (294 kW)
Maximum speed	125 km hr^{-1}
Axle configuration	6 × 2
Engine	D134
Emission norms	Euro 3
Engine cylinders	Inline 6/4/cycle
Displacement (cc)	12,800
Max power	400 hp @ 1,600–1,700 rpm
Max torque	2,000 Nm @ 1,000–1,300 rpm
Transmission	Manual with I shift
Gearbox	12 speed
Fuel tank (L)	400

Test Fuel

Both the B20 and B10 fuels were supplied to the depot in a pre-blended state by the petroleum supplier, Petronas Dagangan Berhad. The specifications of the provided fuel are detailed in *Table 3*.

Fleet Testing

For the fleet testing phase, an appropriate diesel fleet was initially identified for a 100,000 km road test spanning 18–24 months. This specific distance and duration were chosen to align with a similar extended-use fleet testing study conducted for the same purpose (Lammert et al., 2010). The targeted vehicles for the study were suitable trucks and tankers, with fleet type, vehicle specifications, service length and route selections determined based on distance travelled and similarity in vehicle models and functions. Driver behaviour was considered a potential factor that could influence vehicle monitoring, as the drivers were responsible for both driving and ensuring the trucks underwent necessary servicing. To mitigate this influence, the routes assigned to the trucks rarely deviated, ensuring consistent driving patterns whenever the truck engines were operational. The 100,000 km road test involved capturing detailed data on vehicle refuelling, workshop servicing, on-road fuel economy, scheduled maintenance and road call records through onboard vehicle fuel monitoring software and workshop written logs. Results were reported as monthly and cumulative averages, with the latter representing the average results from the study's initiation to any given point. The collected data underwent a two-tailed, paired t-test analysis to determine the statistical significance of differences between the B10 and B20 groups.

The selected vehicles for fleet testing were chosen based on their service length, constituting a significant portion of the fleet. *Table 4* shows the key information of the heavy-duty diesel vehicles used in this study. Vehicle specifications were provided by the fleet company and drivers were instructed to conduct operations without deviation from their assigned delivery routes. These vehicles were primarily engaged in transporting cargo, such as palm oil, between palm oil mills and refineries across Malaysia. The routes were dictated by the operations department of the fleet company and their evaluation was based on Global Positioning System (GPS) tracking data collected from on-board vehicle systems. The LO used in all six trucks was the Petronas Urania 3,000 SAE 15w/40.

TABLE 3. SPECIFICATIONS OF B20 AND B10 FUEL USED IN THE STUDY

Test	Method	Diesel specifications		B10	B20	Unit
		Min	Max			
Acid number	ASTM D664-18e1	-	0.25	< 0.05	< 0.05	mg KOH g^{-1}
Ash	ASTM D482-13	-	0.01	< 0.001	< 0.001	mass %
Carbon residue (on 10% bottom)	ASTM D4530-15	-	0.20	< 0.10	< 0.10	mass %
Cloud point	ASTM D2500-17a	-	19.0	10.0	8.0	°C
Copper corrosion (3 hr at 100°C)	ASTM D130-18	-	1	1A	1A	-
Colour (ASTM)	ASTM D1500-12 (2017)	-	2.5	0.5	L 1.5	-
Density at 15°C	ASTM D4052-18a	0.8100	0.8700	0.8461	0.8490	kg L^{-1}
Electrical conductivity	ASTM D2624-15	50	-	208	359	pS m^{-1}
Flash point	ASTM D93-18	60.0	-	67.0	77.0	°C
Sulphur	ASTM D4294-16e1	-	500	249	804	mg kg^{-1}
Physical distillation at 95% recovered volume	ASTM D86-18	-	370.0	364.3	368.4	°C
Sediment by extraction	ASTM D473-07 (2017)e1	-	0.01	< 0.01	< 0.01	% (m/m)
Water by distillation	ASTM D95-13 (2018)	-	0.05	< 0.05	< 0.05	% (V/V)

TABLE 4. KEY INFORMATION OF THE TRUCKS INVOLVED IN B10/B20 PROJECT

Truck identification	Categories	Year of purchase	Engine	Fuel used
B20-01	Palm oil tanker	2012	Euro3	B20
B20-02				
B20-03				
B10-01	Palm oil tanker	2012	Euro3	B10
B10-02				
B10-03				

The GPS data revealed that, on average, fleet vehicles covered short distances (2.310%), engaged in urban driving (30.515%) and conducted highway driving (67.175%). *Table 5* shows the description of these types of driving. These distinctions were crucial for understanding the driving patterns and conditions encountered during the fleet testing phase, contributing to a comprehensive assessment of biodiesel blend performance in diverse scenarios.

The fleet vehicles utilising B20 fuel were mandated to maintain a sufficient fuel level for deliveries and subsequent returns to the depot for B20 refuelling. Notably, during the fleet testing period, B20 fuel was exclusively available at the fleet company depots and was not commercially accessible at external service stations. Engine oil sampling, a critical aspect of the testing process, was conducted by the fleet company at specified intervals, aligning with each scheduled service interval. The planning of these service intervals adhered to the predetermined schedule established by the fleet company. In particular, the engine oil sampling service interval was set at every 5,000 km, allowing for a strategic balance between accumulating an adequate sample stockpile and obtaining sufficient data points to monitor the degradation of the diesel engine LO samples. This systematic approach ensured a comprehensive and meaningful assessment of the impact of B20 fuel usage on engine oil quality throughout the fleet testing period.

Laboratory Investigation

Fuel sampling, both from onboard and station sources, as well as used engine oil sampling, was carried out at 5,000 km intervals throughout the testing period. The collected samples underwent

TABLE 5. THE DISTINCTION BETWEEN SHORT DISTANCE DRIVING, URBAN DRIVING AND HIGHWAY DRIVING

Driving	Description
Short distance	Any instance of movement under 5 min.
Urban	Vehicle constantly varies in speed and/or does not have a sustained speed of above 50 km hr^{-1} for more than 3 min at a time within the instance. Also includes an instance of speeds below 50 km hr^{-1}. This is not indicative of the road type or environment in which the vehicle is travelling.
Highway	The vehicle has sustained speeds of above 50 km hr^{-1}, or smooth acceleration and deceleration throughout the instance. This does not indicate the vehicle is physically driving on a highway.

thorough analysis to assess various physicochemical properties, including biodiesel, diesel and water content, oxidation stability and other relevant characteristics, as outlined in *Table 3*. The primary focus of the analysis lay in comparing key parameters derived from the data collected in the diesel engine LO samples. These parameters encompassed viscosity, total basic number, wear metals and additives. The samples were sent to an external laboratory for comprehensive testing, providing valuable insights into the impact of B20 and B10 fuel usage on these crucial LO properties.

Statistical Analysis

The data collected was analysed using a two-tailed, paired t-test to assess the statistical significance of the difference between the B10 and B20 groups. With similar make and model of the test vehicles, statistical tests can be employed to ascertain the significance of the fuel blends used by isolating the other background factors that may impact the results obtained. More specifically, the two-tailed test examines if the difference between two sample means is statistically significant and considers the possibility of the difference occurring in either direction within the context of this study. The calculation involves determining the probability, known as the *P*-value, that the observed difference could have happened by chance. If the *P*-value is less than the chosen significance level (commonly set at 0.05), it can then be concluded that the difference between the means is statistically significant. The versatility of a two-tailed t-test lies in its ability to evaluate differences in both directions, assessing whether one mean is either greater or less than the other. The significance level helps control the probability of a Type I error (false positive). Even with small sample sizes, the t-test remains applicable, making it suitable for real-world datasets where collecting large amounts of data might be impractical. Given its adaptability, control, and applicability to smaller datasets, the two-tailed t-test proves to be a fitting statistical analysis method for this study, which focuses on evaluating the impact of B20 and B10 usage in diesel fleet vehicles.

RESULTS AND DISCUSSION

The results presented here are derived from the fleet test data collected by both the local logistic company and the Malaysian Palm Oil Board (MPOB). All the vehicle trials successfully completed at least the second cycle of servicing. This comprehensive dataset provides insights into the extensive utilisation of palm B20 in fleet vehicles over the course of the study.

Fuel Economy

At the conclusion of the trial period, the vehicles collectively utilised 392,259 L of fuel, covering a total distance of 777,479 km. Within this same trial period, the B20 vehicles consumed 174,924 L of B20 and travelled 354,702 km. In comparison, the B10 vehicles consumed 217,335 L of B10 and covered 422,776 km. This difference can be attributed to the greater flexibility of B10 vehicles, which could refuel at conventional petrol stations supplying B10 and make multiple stops on their delivery routes. In contrast, the B20 vehicles had to return to the depot after deliveries to refuel with B20, available exclusively at the depot. It's worth mentioning that the B20 group's lower fuel consumption is partially attributed to one B20 vehicle being taken off service for five months due to transmission repair work, unrelated to the fuel and/or engine systems which may be caused by the fuel used. Additionally, there was a temporary B20 fuel stock depletion in August 2020 due to the petroleum company's supply disruption. Prompt communication between the fleet company's procurement manager and the petroleum company's supply executive ensured a swift resolution, allowing the study to resume without any significant interruption.

Fuel economy is pivotal for logistics companies, allowing them to assess potential profits from deliveries, given that fuel costs constitute a significant portion of operational expenditures alongside maintenance. Over the 18 month period, both groups exhibited similar average fuel economy values of around 2.00 km L^{-1} for each vehicle. While the figure suggests a slight decline in fuel economy when using B10 compared to B20, statistical analysis using a two-tailed test shows that the calculated *P*-value is 0.6577, indicating a high degree of confidence that the observed difference in fuel economy between the two groups is statistically insignificant. Therefore, based on the available data, there is no significant evidence to suggest a difference in fuel economy between the B20 and B10 groups.

To obtain a more accurate representation of fuel economy in this study, the impact of idling on fuel consumption is taken into consideration. For logistics companies, idling time during queues at delivery sites or rest stops during long-haul trips can significantly affect fuel economy as vehicles consume fuel without making progress on deliveries. To address this, idling time data for the fleet vehicles was filtered from the GPS movement data. Any period where the vehicle's engine was on without speed input (indicating idling) was accumulated. Idling fuel consumption was first calculated using Equation (1).

$$\text{Idling fuel consumption (l)} = \text{Total idling time (hr)} \times \text{Vehicle base idling rate} \left(\frac{1}{\text{hr}}\right) \qquad (1)$$

The idling fuel consumption was determined and subtracted from the total fuel consumption to get the adjusted fuel consumption using Equation (2).

$$\text{Adjusted total fuel consumption (l)} = \text{Total fuel consumption (l-)} \left[\text{Idling fuel consumption percentage (\%)} \times \text{Total fuel consumption (l)}\right] \qquad (2)$$

Then, the adjusted fuel consumption rate was acquired by dividing total mileage covered by the adjusted total fuel consumption using Equation (3).

$$\text{Adjusted fuel consumption rate} \left(\frac{\text{km}}{\text{l}}\right) = \frac{\text{Total mileage covered (km)}}{\text{Adjusted total fuel consumption (l)}} \qquad (3)$$

After adjusting for idling fuel consumption, the fuel economy of both the B20 and B10 groups improved, with the B20 fuel economy at 2.10 km L^{-1} and B10 at 2.05 km L^{-1} over the 18 month period. The adjustment aimed to provide a more accurate representation of fuel economy by excluding the fuel consumed during idling periods. *Figure 1* illustrates the adjusted fuel economy of both groups. Despite the improvement in fuel economy after adjusting for idling, there is still no discernible difference between the B20 and B10 groups. A two-tailed, paired t-test, conducted on monthly individual datasets adjusted for idling fuel consumption, indicates that the difference in fuel economy between the two groups is statistically insignificant with a high degree of confidence ($P = 0.8958$). This statistical analysis further supports the conclusion that, when accounting for idling fuel consumption, there is no significant difference in fuel economy between the B20 and B10 groups.

While fuel economy remains consistent, the impact on logistics companies' profit margins may be influenced by other factors such as the increased frequency of servicing and maintenance associated with the use of higher blends of biodiesel, as discussed in the following section.

Vehicle Payload and Fuel Economy

The analysis of running fuel economy per running payload for both the B20 and B10 groups shows no discernible difference. A two-tailed, paired t-test on the available dataset suggests that the difference in running fuel economy per running payload is statistically insignificant with a high degree of confidence ($P = 0.2766$). This finding implies that, within the observed dataset and conditions, the choice between B20 and B10 does not significantly impact the running fuel economy per running payload. The payload weight appears to have a consistent effect on fuel economy for both biodiesel blends.

Service and Maintenance

The fleet vehicles using B20 underwent regular service, including the replacement of LO and the change of fuel and water filters. The

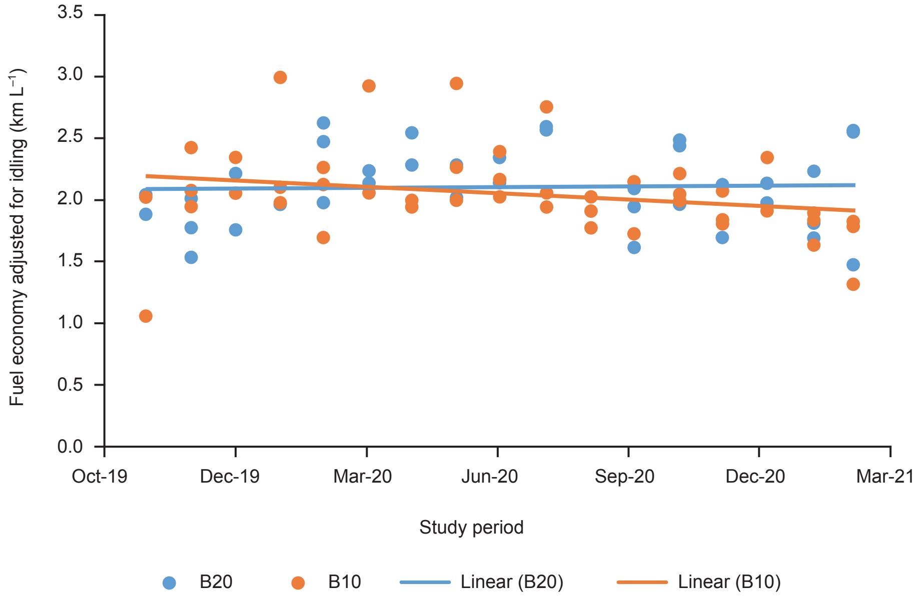

Figure 1. Fuel economy adjusted for idling fuel consumption of B20 and B10 groups of vehicles over 18 months of fleet testing.

service was performed by the in-house transport company technician before switching to B20 diesel. The service at 30,000 km, conducted at the start of the trial period, involved changing filters and engine oil according to the standard service procedure. The sampling intervals for engine oil were planned at 5,000, 10,000, 15,000, 20,000 and 25,000 km. However, real-world challenges such as scheduling conflicts between the maintenance and operations departments, and the nature of fleet operations, where vehicles need to be constantly on the road for deliveries, can make the scheduling of these intervals challenging. Despite these, continuous engine oil samples were collected, and at least one set of samples was obtained for each vehicle. It is important to highlight here that the crucial engine oil sample was collected at the required service interval of 30,000 km. This sample is of significance for data analysis, as it represents the condition of the engine oil after an extended period of usage. In summary, this provides context to the challenges in collecting continuous engine oil samples from fleet vehicles but ensures that key sampling points, especially at the 30,000 km service interval, were closely monitored and carried out.

Service Cost and Fuel Economy

The information provided outlines the breakdown of service costs for vehicles using different biodiesel blends of B10 and B20. The hypothesis under consideration is whether the usage of higher blends of biodiesel would reduce service intervals, consequently increasing operational costs. The service costs for the vehicles at three different service intervals include costs for LO, oil filters, water filters, and fuel filter changes. The total service intervals for each group were 13 times, all conducted at the depot. The basic service cost averaged RM2,194.67 per truck, covering both parts and labour but excluding warranty costs. Notably, there were no reported breakdowns in the engine or fuel system associated with the usage of either B10 or B20 during the vehicle trials. The data suggests that there is no significant difference in the total average service cost per distance travelled between both fuel groups. Similar trials on buses between B20 and diesel also showed no significant increase in maintenance costs across the mileage covered by the test vehicles during the trial period (Proc et al., 2006).

Figure 2 visualises the running average service cost per average mileage covered over each service interval for both groups of vehicles throughout the study. The graph indicates no evident correlation between service cost and mileage covered, suggesting that the type of fuel used did not significantly affect service interval costs. The two-tailed, paired t-test analysis conducted on the dataset further supports this observation, showing that the difference between the groups for running average service cost over running mileage covered is statistically insignificant with a high degree of confidence ($P = 0.1345$).

Engine Lubricating Oil Quality and Biodiesel Blends

To ensure homogeneity, the LO sample was taken after running the engine for at least 15 min. It's worth noting that a certain amount of wear metals, also known as trace metals, in used oil is expected due to normal engine wear. This analysis is crucial for evaluating the impact of biodiesel blends on engine lubrication and wear over the course of the fleet testing period.

Viscosity. The viscosity of LO is a crucial property, and changes in viscosity can indicate the condition of the oil. Viscosity is measured using ASTM D7042-21a or the standard test method for dynamic viscosity and density of liquids by Stabinger viscometer (and the calculation of kinematic viscosity). Higher viscosity may suggest deterioration from oxidation or contamination, while a decrease can indicate oil dilution. *Figure 3* illustrates the scatter plot of viscosity values in the B20 and B10 groups over the course of the fleet testing period, approaching the 30,000 km service interval. The plot displays a decreasing trend in viscosity as the vehicles accumulate mileage, with both groups consistently showing a decrease in viscosity. A two-tailed, paired t-test was performed, indicating that the difference in viscosity between the two groups is statistically insignificant with a high degree of confidence ($P = 0.1110$). The lower viscosity values in the B20 group may be attributed to the presence of inorganic acids, which are more prevalent in higher biodiesel blends. Despite this, the viscosity values for B20 remain within the accepted operational limits for the specific engine oil used in the study. Studies have shown that as engine oil ages, viscosity tends to deteriorate due to oxidation, and dilution of diesel and carbon black can further impact viscosity (Salehi et al., 2017). The results indicate that increased biodiesel content influenced the flowability of the LO, but this effect was not significant during the duration of the fleet test.

Total base number. The total base number (TBN) is a crucial parameter that measures the alkaline reserve or acid-neutralising capacity of diesel engine oil. It gauges the oil's ability to neutralise acids formed during combustion and maintain a

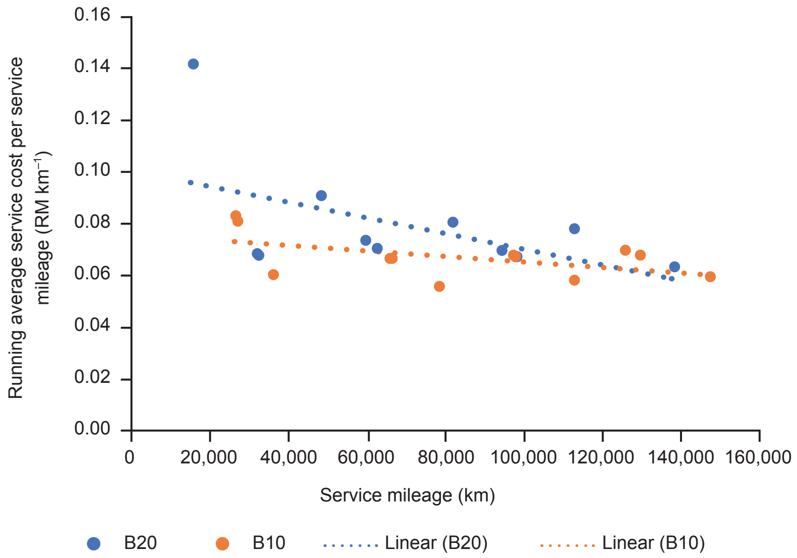

Figure 2. Running average service cost per service mileage at each vehicle service interval mileage.

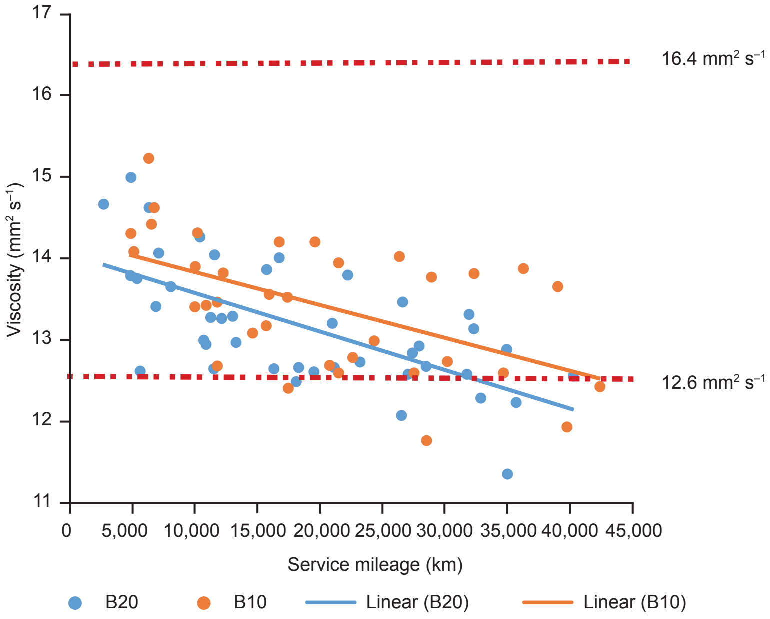

Figure 3. Scatter plot of viscosity at 100°C for B20 and B10 groups of vehicles.

stable pH level. As acidic by-products are generated during combustion, the TBN quantifies the oil's capacity to neutralise these acids, preventing potential damage to engine components. *Figure 4* depicts the scatter plot of TBN values for the B20 and B10 groups, revealing a descending pattern in trendlines for both groups with greater mileage. This could be attributed to incomplete combustion with longer operation, leading to the formation of acidic by-products that lead to TBN depletion. A two-tailed, paired t-test indicates that the difference in TBN values between the two groups is statistically significant with a high degree of confidence (P = 0.0156). The increased biodiesel content in the B20 group contributes to a significant difference in TBN as compared to the B10 group, with marginally lower TBN values. This contrasts with other reported work where elevated formation of acidic by-products from ester hydrolysis in the sump after incomplete combustion was observed in B20 blends, which increased the amount of weak acids in the engine oil (Gulzar et al., 2016). This suggests that monitoring TBN in both high and low blends of biodiesel is essential through timely oil changes to maintain optimal engine protection.

Metals contamination. Metals contamination in engine oil, such as iron, copper and chromium concentrations, provides insights into the wear

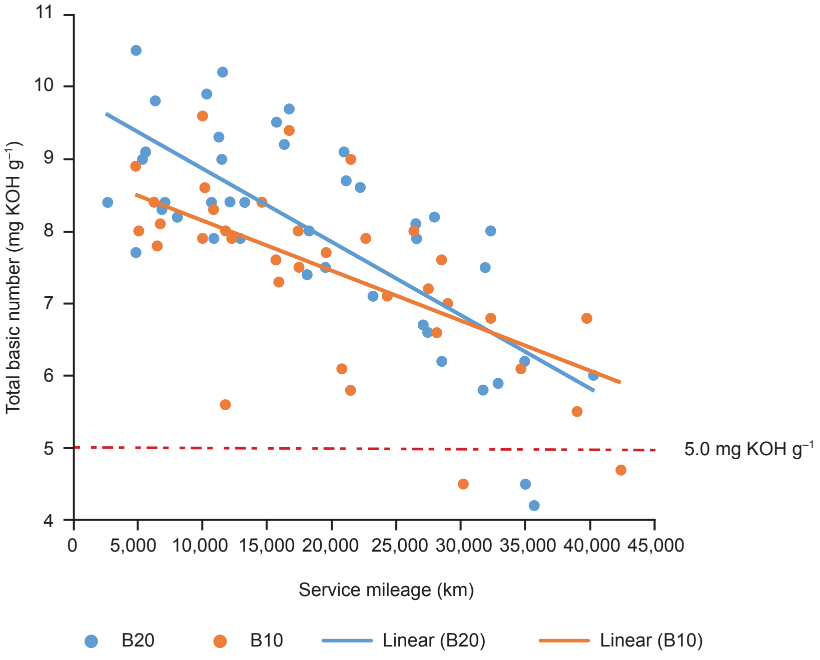

Figure 4. Scatter plot of total basic number for B20 and B10 groups of vehicles.

and tear of the metal engine components. Metals contamination is measured using ASTM D5185-18 or the standard test method for multielement determination of used and unused LO and base oils by inductively coupled plasma atomic emission spectrometry (ICP-AES). Higher concentrations of these metals in used LO after each round of service maintenance can indicate increased degradation due to wear and tear on lubricated engine components. *Figure 5* illustrates the trend of iron particles in both the B20 and B10 groups, showing an increasing pattern over mileage. A two-tailed, paired t-test indicates that the difference in iron content in engine oil between the two groups is statistically significant with a high degree of confidence (P = 0.02346). The average iron concentration in the engine oil increased to 11 ppm for B20 vehicles and 15 ppm for B10 vehicles, with the increased biodiesel content reducing the amount of iron wear in the engine oil due to its higher lubricity property, which is advantageous in high-friction areas of the engine such as the piston heads and sides. This observation aligns with previous studies that found palm oil blends used in engine operation to have lower concentrations of wear metals in the engine oil sump compared to conventional diesel. Additionally, the efficiency of the oil filter also plays a crucial role in removing solid particles, including iron, from the engine oil. A clogged or inefficient filter may allow higher iron levels in the oil, potentially causing increased wear and engine damage. In this study, copper and chromium values for both groups are in trace amounts, suggesting no significant increase in wear and tear. Overall, the results suggest that B20 does not adversely affect engine wear, supporting its viability as a fuel option without compromising engine longevity.

Engine oil evaporation. The metals analysis, particularly focusing on calcium, zinc and phosphorus concentrations in the engine oil, provides insights into the condition and performance of the LO. These metal concentrations can increase as engine oil evaporates during operation, potentially leading to lower oil levels and necessitating an oil change. However, in the case of this study, the metal concentrations showed a stable and consistent trend, indicating that there was no significant reduction that would warrant an oil change before the recommended limit of 30,000 km.

Zinc is a vital additive in diesel engine oil, usually present as zinc dialkyldithiophosphate (ZDDP). These multifunctional additives form a protective film on metal surfaces, reducing wear on critical engine components and acting as an antioxidant to inhibit oil oxidation. The statistical analysis comparing zinc concentrations between the B20 and B10 groups revealed that the difference is statistically insignificant (P = 0.1153), suggesting that the zinc content in the LO remained within acceptable limits for both fuel groups.

Phosphorus, often part of ZDDP additives, also contributes to forming a protective layer on metal surfaces, reducing wear, and preventing oxidation. The statistical analysis indicated that the difference in phosphorus concentrations between the B20 and B10 groups is statistically significant (P = 0.0437), but the recorded phosphorus content

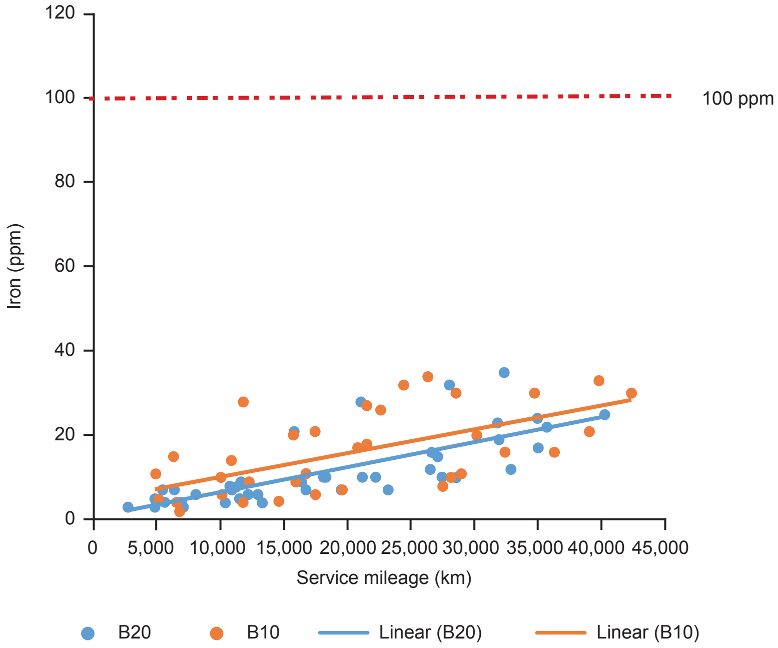

Figure 5. Scatter plot of iron concentration for B20 and B10 groups of vehicles.

from the LO samples did not fall below the minimum limit of 600 ppm. This suggests that the LO used still had remaining usage life for both fuel groups.

Calcium-based additives, such as calcium sulphonate or calcium phenate, serve as detergents and dispersants in diesel engine oil. They prevent the formation of deposits, sludge, and varnish, maintaining engine cleanliness. The statistical analysis showed a significant difference in calcium concentrations between the B20 and B10 groups ($P = 0.0056$), potentially indicating increased sludge build-up in the B10 group due to reduced calcium additives. However, it's important to note that the recorded calcium content from the LO samples did not fall below the minimum 600 ppm limit, indicating that the LO used still had remaining usage life for both fuel groups.

In summary, the metals analysis suggests that the LO used in both B20 and B10 vehicles remained within acceptable limits during the 30,000 km service interval, and there were no indications of excessive wear or degradation that would necessitate early oil changes for the B20 group.

CONCLUSION

This study aimed to assess the impact of utilising palm B20 and B10 on heavy-duty diesel vehicles under actual on-road driving conditions through a combination of fleet testing and laboratory investigations. Comparisons between the B20 and B10 groups focused on fuel economy and service maintenance of the vehicles. Both groups exhibited similar fuel economy, with the B20 group averaging 2.107 km L^{-1} and the B10 group averaging 2.055 km L^{-1}. With engine oil analysis conducted to examine the impact of B20 usage on oil degradation, all engine oil samples were found to remain within the acceptable service quality limits as recommended by the engine oil manufacturer. This indicates that an increased frequency of servicing is not required as commonly thought. The B20 samples displayed degradation trends comparable to those of the B10 samples. The significant statistical difference in TBN and iron content of the B20 group indicates the positive impact on the engine oil condition during on-road trials. Further in-depth investigation, particularly into the benefits of B20 on engine oil lifespan and fuel filter sedimentation, would contribute further valuable insights to the knowledge base of real-world usage of higher biodiesel blends. In conclusion, the study results suggest that the B20 blend is a viable choice for vehicle fleets in logistics companies, as it demonstrates no significant differences in fuel economy and service maintenance intervals as compared to when using the B10 blend.

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