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EFFECT OF BIOFUEL ON LIGHT-DUTY VEHICLES ENGINE PERFORMANCE AND LUBE OIL DEGRADATION

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ABSTRACT

Biofuel is a renewable, biodegradable and non-toxic fuel that is an alternative to fossil fuel. However, the long-term effect of biodiesel on internal combustion engine operation is not extensively studied. Thus, this study examined the effect of B5 biofuel (blend of 5% refined, bleached and deodourised palm olein oil (RBDPOo) and 95% automotive diesel oil (ADO) on engine performance and lube oil degradation of light-duty vehicles, i.e. *Mercedes Benz (M), Mitsubishi Storm (MS) and Toyota Hilux (TH), up to 80 000 km mileage. ADO was also used for each vehicle brand for comparison. The engine power and torque were examined using chassis dynamometer. Analysis on wear metal content of lube oil was conducted to indicate engine deterioration level. Results showed insignificant deterioration on engine performance of M and MS vehicles using ADO and B5 but B5 vehicles showed lower torque reduction than ADO vehicles. For lube oil analysis, the properties and wear metal contents in B5 vehicles were within acceptable limit as suggested by the International Council on Combustion Engines (CIMAC). Results of this study concluded that the B5 biofuel can be potentially used for selected vehicle brands without engine modifications and normal service intervals can be applied for B5 vehicles.*

Keywords: biofuel, diesel engine, engine performance, lube oil degradation, palm olein oil.

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INTRODUCTION

Driven by the spiraling cost of fossil fuel, energy security and global warming, alternative energy has become a worldwide priority. Some nations have implemented new renewable energy policies, regulatory controls and regulations to replace fossil fuel with renewable fuel (Lapuerta *et al.*, 2011; Mofijur *et al.*, 2015). The increasing demand for energy, particularly diesel fuel in industrial and transportation sectors, plays an important role for the development of a country (Varuvel *et al.*, 2012). However, the combustion of the automotive diesel oil (ADO) emits greenhouse gases (Radhakrishnan *et al.*, 2017), which cause global warming. As a consequence, biofuel is increasingly popular as an alternative fuel to reduce fossil fuel dependency as they are renewable, environmental-friendly, biodegradable and capable of mitigating climate change by expressive carbon dioxide (CO_2) cycle during combustion process (Puppan, 2002). Biofuels are liquid or gaseous fuels that are commercially derived from renewable sources such as vegetable oil and cellulosic biomass (Demirbas, 2007a).

Vegetable oils are a wonderful bio-based resource, can be used as an alternative fuel of conventional compression ignition (CI) engines (Demirbas, 2007b; Huang *et al.*, 2012). Among the vegetable oils olive; palm, soybean, peanut and sunflower oils are mentionable. One challenge that is required to overcome is the higher viscosity of the vegetable oils over the petroleum-based

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diesel. Sometimes transesterification may help to reduce the viscosity of the vegetable oil-based fuels (Shereena and Thangaraj, 2009). Different parameters such as fatty acid content, reaction temperature and methyl esters have direct influence on the performance of the fuel. Study showed on the direct injected vegetable oils and their esters as an efficient fuel for four stroke, single cylinder diesel engine performance and exhaust emissions (Altin *et al.*, 2001). It also revealed that a higher viscosity, thickening in cold condition and drying with time have some negative impact on atomisation, flow and heavy particulate emissions. In a different study, waste cooking oil was used at different percentages (10%, 20% and 30%) in volume to produce biodiesel blends using transesterification process (Abed *et al.*, 2018). Results showed a comparatively lower thermal efficiency of the biodiesel blends was noticed over the diesel fuel. In addition, a higher specific fuel consumption and higher exhaust gas temperature were noticed for the case of biodiesel blends. In addition to vegetable oils, biodiesel, dimethyl ether and Fishcher-Tropsch diesel are also considered as a potential replacement of traditional petroleum-based fuels (Kaur *et al.*, 2017).

Palm oil has huge potential for biofuel application. Malaysia is the world's second largest exporter of palm oil products with more than 87% worldwide export (Masjuki *et al.*, 2013; Parveez *et al.*, 2020). Apart from its environmental benefits and renewability, biofuels from palm oil are economically competitive compared to fossil fuel (Chin *et al.*, 2019). Owing to this, a mandatory biodiesel blend for transportation sector has been implemented in 2011 in Malaysia as carbon reduction commitment for sustainable development (Lim and Lee, 2012). Therefore, since 1 January 2010, every petrol station in Malaysia started selling B5 biodiesel (5% methyl ester blended with 95% ADO) according to the Malaysian governmental regulation (Lim and Teong, 2010).

However, there are some issues pertaining to vehicle engines due to the use of this biofuel. The emission and combustion characteristics of the biofuel caused deterioration in the performance of the engines (Ahmad *et al.*, 2011; Behçet, 2011). For improvement, modifications on engines in various aspects are needed when using biofuel (Gumus *et al.*, 2012; Hossain and Davies, 2012). However, previous studies on biofuel focused mainly on laboratory testing of the engine dynamometer and may not reflect the actual vehicle performance (Franco *et al.*, 2013; Pelkmans and Debal, 2006). Hence, the objective of this study was to examine the performance of unmodified engine of light-duty vehicles using B5 biofuel in up to 80 000 km mileage. A blend of 5% refined, bleached and deodourised palm olein oil (RBDPOo) and 95% ADO, designated as B5 biofuel, was used for the investigation. In addition, the lubricity performance in terms of used lube oil degradation was also tested and compared with fresh lube oil. Results of this study will be useful in understanding biofuel combustion and emission behaviour as well as providing scientific basis for vehicular emission control.

MATERIALS AND METHOD

Materials

The RBDPOo and ADO used for biofuel production were purchased from a commercial local supplier. The ADO was used as control for comparison study with B5. Both ADO and B5 biofuel were stored at 0°C before use.

Experimental

RBDPOo and ADO were melted and homogenised at 70°C for 30 min to destroy any crystal. Binary biofuels were prepared using RBDPOo and ADO in volumetric percentage (v/v) at a mixing ratio of 5%, by adding 50 mL RBDPOo into 950 mL of ADO in sample bottles. The sample bottle was then vigorously shaken for about 10 min and kept idle for about 5 min prior to density measurement using portable submersible density meter (Brand: Lemis VDM-250). To prepare 13 000 L biofuel, skid tank was used by pumping RBDPOo and ADO at a mixing ratio of 5% and thoroughly mixed using a circulation pump until homogenised. The preparation of B5 biofuel was considered to be complete when the densities at the top, middle and bottom of the skid tank were constant and did not vary beyond 0.006 specific gravity, similar to that of ADO (control).

A total of 12 units light-duty diesel vehicles were used in this study, comprising of four units of Mitsubishi Storm (MS), four units of Toyota Hilux (TH) and four units of Mercedes Benz (M). For each brand, two vehicles were fueled by B5, while the other two were fueled by ADO as control. The vehicles selection was based on engine technology, such as common rail direct injection and distributor pump. *Table 1* shows the general specifications for the vehicles. The selected route was a two-way journey from Klang Valley up to southern part of Perak, covering almost 800 km per day. Selected routes included 70% highways and 30% urban and suburban roads to simulate normal driving conditions in Malaysia. Each vehicle was driven simultaneously using the same route but different fuel to minimise variables, particularly traffic conditions which may affect the outcome. Field trials were conducted for a total of 80 000 km mileage to make it parallel with the standard engine warranty offered for new vehicles in Malaysia.

TABLE 1. GENERAL SPECIFICATIONS OF DIFFERENT LIGHT-DUTY VEHICLES

Maker	Mitsubishi Storm	Toyota Hilux	Mercedes Benz
Model	Storm IDI Intercooled	Hilux double cab	E270 CDI
Engine capacity (cc)	2 477	2 494	2 685
Fuel injection system (FIE)	Distributor pump	Common rail (Denso)	Common rail (BOSCH)
Maximum power (hp)	113 bhp @ 4 000 rpm	101 bhp @ 3 600 rpm	175 bhp @ 4 200 rpm
Maximum torque (Nm)	240 Nm @ 2 000 rpm	260 Nm @ 2 400 rpm	400 Nm @ 1 800 rpm

Characterisations. Physical and chemical analyses were carried out for RBDPOo, ADO and B5. The vehicle performance in terms of power and torque for each fuel was conducted on Mustang chassis dynamometer MD 600 as baseline prior to field trials. Chassis dynamometer functions as simulator for a wide range of engine application, similar to the actual behaviour when operated on the road (Amir *et al.*, 2013). Vehicles used for the field trials followed the normal service interval of 5000 km, whereby about 250 mL used lube oil was taken and sent for analysis in accordance to the ASTM D1585 standard method (ASTM, 2015). After achieving cumulative mileage of 80 000 km, the performance of the vehicles was re-analysed using chassis dynamometer at 1500-5000 rpm of third and fourth gears. The experiment was conducted in duplicates for each vehicle.

RESULTS AND DISCUSSION

Physical and Chemical Properties of Fuel

Fuel properties play important roles in CI engines, engine performance, fuel consumption, vehicle emissions and engine durability. *Table 2* shows the chemical and physical properties of RBDPOo, ADO and B5 and their comparisons with the Malaysian Diesel Standard (MS123:1993). The properties of fuels provide a basic knowledge of the fuel performance and potential drawback when they are used in diesel engines. The density of RBDPOo, B5 and ADO are 0.9152, 0.8595 and 0.8565 kg L^{-1}, respectively. The values are close to each other, therefore, the impact of fuel performance and combustion were minimum. B5 showed relatively higher density compared to ADO, which caused the fuel injection system to deliver higher fuel volume, thus, increasing the fuel consumption in B5 light-duty vehicles (Valente *et al.*, 2011). The viscosity of B5 biofuel was 5.066 mm^2 s^{-1}, higher than that of ADO, but it still within the requirement according to the Malaysian Diesel Standard MS123:1993 (1.5-5.8 mm^2 s^{-1}). Fuel viscosity plays an important role on engine performance. Biodiesel is more viscous than fossil diesel as it has large triacylglycerol molecules and higher molecular weight (Williamson and Badr, 1998). Fuel with high viscosity will result in high pumping resistance for fuel deliver, causing the pump to fail prematurely. This also results in poor fuel atomisation by injector leading to poor combustion which will directly affect the engine

TABLE 2. PROPERTIES OF RBDPOo, ADO AND B5 IN COMPARISON WITH THE MALAYSIAN DIESEL STANDARD (MS123:1993)

Properties	Test Method	RBDPOo	ADO	B5	MS123:1993	
					Min.	Max.
Density at 15°C (kg L^{-1})	D 4052	0.9152	0.8565	0.8595	-	-
Cetane number	D 6890	53.6	50.6	51.5	45.0	-
Sulphur content (ppm)	D 4294	-	3060	2890	-	5 000
Lubricity (μm)	IP450	119	306	234	-	-
Gross calorific value (GCV) (MJ kg^{-1})	-	39.740	45.258	45.165	-	-
Flash point (°C)	-	284	83	86	60	-
Water content (ppm)	-	124.5	54.1	137.1	-	-
Cloud point (°C)	-	13	13	13	-	18
Pour point (°C)	-	9	3	3	-	15
Viscosity at 40°C (mm^2 s^{-1})	-	34.8	4.5	5.1	1.5	5.8
Cold filter plugging point (°C)	-	-	9	10	-	-
Ash content (mass%)	-	0.001	0.001	0.001	-	0.010
Carbon residue on 10% distillation residue (wt%)	-	4.76	0.02	0.30	-	0.20

Note: RBDPOo - refined, bleached and deodourised palm olein; ADO - automation diesel oil.

performance and exhaust emission (Valente *et al.*, 2011).

Cetane number is a measure of fuel readiness for autoignition in the combustion chamber after injection (Blin *et al.*, 2013; Jeffrey *et al.*, 2015; Lawlor and Olabi, 2015). Fuel with high cetane number has the benefits of easy cold starting, short ignition delay and low engine noise (Jeffrey *et al.*, 2015; Li *et al.*, 2013). On the contrary, fuel with low cetane number results in combustion deterioration and high emission of hydrocarbons and particulate in the exhaust gas (Jayed *et al.*, 2011). B5 has higher cetane number (51.5) than ADO (50.6), exceeding the minimum value stipulated by the Malaysian Diesel Standard (MS123:1993). In addition, pour point, cloud point and cold filter plugging point (CFPP) are associated with fuel flowability in the fuel system. The cloud point, pour point and CFPP for B5 were 13ºC, 3ºC and 10ºC, respectively, which were lower than the year-wide ambient temperature in Malaysia (33ºC-37ºC). The flash point of fuels determines the flammability of the fuels and is an essential criterion for fuel transportation and storage (Masjuki and Kalam, 2013). The flashpoint of B5 was 86ºC, which is slightly higher than ADO (83ºC) and complied with the minimum standard requirement (MS123:1993). Hence, B5 is safe where transportation and storage are concerned.

Other important fuel parameters are carbon residue, ash content and gross calorific value (GCV). Carbon residue indicates the tendency of fuel to deposit on the injector and combustion chamber, which invariably affects the engine performance as well as the emission (Jeffrey *et al.*, 2015). The carbon residue (10% residue) of B5 was higher than standard (MS 123:1993). However, the ash content of B5 and ADO was similar and thus, it was expected that the wear and tear of the engine moving parts would also be similar. In fuel selection, GCV or energy content is a vital criterion as it reflects combustion efficiency and fuel consumption. This study found that B5 biofuel indicated slightly lower GCV value (45.165 MJ kg^{-1}) than ADO (45.258 MJ kg^{-1}), suggesting higher fuel consumption for B5 compared to ADO in vehicles. It can be inferred that the fuel consumption is high for fuel with high density and low energy content (McCarthy *et al.*, 2011; Munack, 2007).

Vehicle Power Performance

The vehicle performance was carried out using a chassis dynamometer at the start (0 km) and at the end of field trials (80 000 km). Comparisons of maximum power output for both fuels on all vehicles at the start and the end of field trials are shown in *Figure 1*. However, some of the vehicle performances for certain mileage are not depicted in the figure due to accident, major breakdown and theft. The vehicle major breakdown was not due to fuel-related problems. At the start of field trials, ADO and B5 fueled TH had an average power output of 69.75 and 59.6 hp, respectively. The vehicles fueled by ADO had higher power output which could be attributed to high GCV and lower viscosity, thereby leading to better engine combustion. Owing to lower GCV, the vehicles fueled by B5, namely TH3 and TH4, showed slight decrease in their performance, 8.54% and 7.56%, respectively, at the start and the end of field trials. Saiful Islam *et al.* (2014) deduced that biodiesel with low energy content caused low engine power output. Other reasons which reduced vehicle power could be wear and tear of vehicle parts and carbon deposited in combustion chamber and injectors.

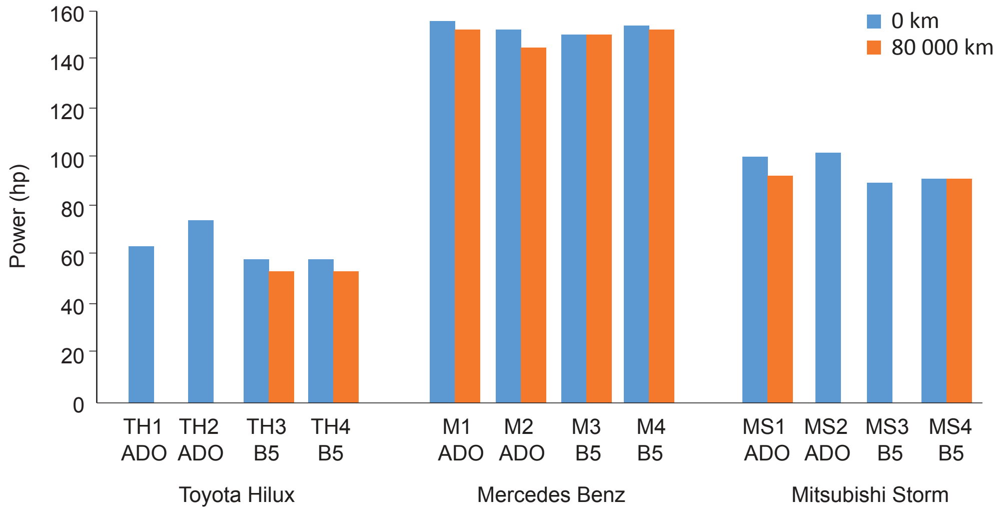

Figure 1. Maximum power output of field trial vehicles measured at 0 km and 80 000 km.

Birgel *et al.* (2008) claimed that the overall system performance may be adversely affected due to the formation of deposits within the holes of the injector nozzle or on the exterior injector tip. Similarly, Husnawan *et al.* (2009) also agreed that the deposits formed in combustion chamber not only affect the engine performance but also its drivability. No comparison can be made on ADO due to a major breakdown of TH1 at 63 000 km, while TH2 was stolen before reaching 80 000 km.

Mercedes Benz (M) which employed common rail fuel injection, showed average maximum power outputs of 116.3 kW (155.9 hp) and 114.7 kW (153.8 hp), for ADO and B5, respectively. B5 has lower power output by 1.3% and this may be related to the GCV of B5 (45.165 MJ kg^{-1}), which was lower by 0.21% compared to ADO. The reductions of power output at the start and end of the trials for B5 were in the range of 0.19%-1.16%, and 1.47%-4.97% for ADO. According to McCarthy *et al.* (2011), low reduction in power output for B5 is probably due to higher oxygen content in biofuel, thus, improving fuel combustion in the engine. A complete combustion can be achieved by diesel engine fueled by biodiesel due to the presence of oxygen in the biodiesel's molecule.

The distributor pump for diesel injection (MS that used old technology) showed an average maximum power of 103.5 and 91.9 hp for ADO and B5, respectively, at the start of the field trials. Decrease in power output (11.16%) on B5 was recorded for vehicles fueled by ADO. After undergoing 80 000 km field trials, the maximum power output of the vehicles fueled by B5 and ADO decreased by 0.54 and 8.44%, respectively. Lower reduction of power output for B5 was recorded compared to ADO. This could be due to high oxygen content in B5 biofuel, thereby resulting in better combustion, as occurred in M vehicles (Lahane and Subramaniam, 2015; Zulqarnaine *et al.*, 2020). Less carbon was deposited in the injectors in the long run, rendering marginal decline in the engine performance. Generally, ADO showed slightly better performance compared to B5 regardless of the engine technologies used. Although common rail diesel injection system is more sensitive and less tolerant to fuel quality, the system employs high injection pressure at low combustion temperature for better engine performance and fuel efficiency while lowering pollutant emission (Jeffrey *et al.*, 2015).

Vehicle Torque Performance

Figure 2 shows the maximum torque produced from vehicles measured at 0 and 80 000 km. Vehicles fueled by B5 showed lower torque compared to vehicles fueled by ADO at 0 km. TH and MS vehicles showed a decrease in performance by 13.6% and 12.33% at maximum torque when fueled by B5, while M vehicles showed only a marginal performance decrease of 0.5% using B5 at 0 km. By comparing the torque at 0 and 80 000 km, TH vehicles showed an average reduction of 1.8% and 3.8% for vehicles fueled by B5. M vehicles showed a reduction of 1.8% and 8.51% for ADO and torque reductions were 1.7% and 2.1% for B5, which were less than ADO. Meanwhile, for ADO of MS vehicles, lower torque reduction (1.15%) was obtained compared to B5 (4.49%). The injection characteristics are greatly affected by the viscosities of the fuel (Sugozu *et al.*, 2011). The reduced torque performance is also due to the lower heating value of the fuel used. In addition, the torque performance is influenced by energy content (GCV), similar to power. Fuel with lower energy content exhibited lower torque performance as reported by McCarthy *et al.* (2011).

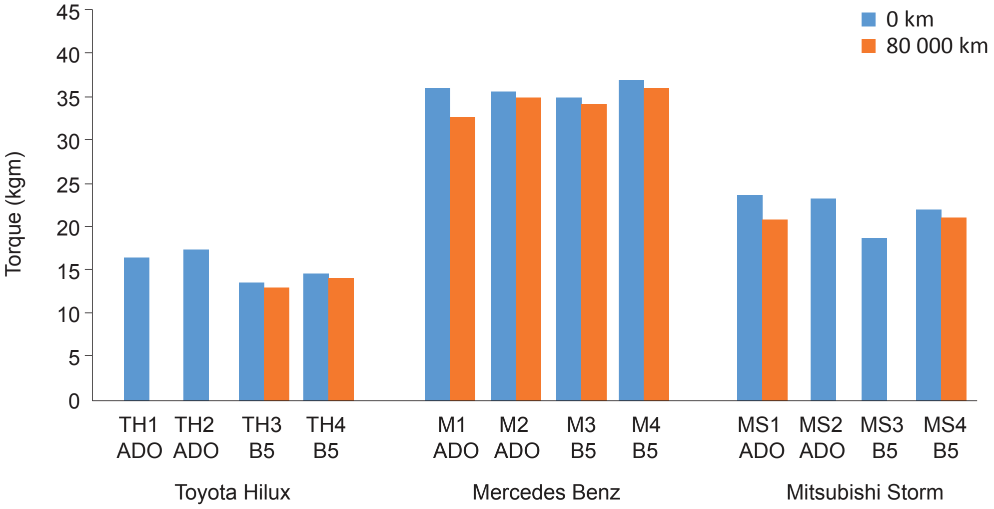

Figure 2. Maximum torque of field trials vehicles measured at start and end of field trials.

Lube Oil Analysis

Lubricant oil for engine serves several purposes including friction and wear reduction, protection of engine parts from corrosion and oxidation and transfer of heat from core engine components (Nagy *et al.*, 2019). It has been reported that biodiesel tends to accumulate in engine crankcase affecting lubricant oil quality compared to diesel owing to its higher viscosity (He *et al.*, 2011; Uy *et al.*, 2011). Thus, by analysing the used lube oil of vehicles fueled by B5 and ADO, the engine conditions could be evaluated. In this study, the analysis of used lube oil was carried out during routine services at 5000 km interval for MS and TH vehicles and 10 000 km interval for M vehicles as recommended by the service center. The effect of fuel used on the performance of lubricant oil in terms of degradation and wear of metal was performed by an accredited external laboratory according to standard method. This can be used to indicate the level of engine deterioration (Vališ *et al.*, 2015). All the analysis of lube oils throughout the routine services up to 80 000 km showed that the properties of used lube oils were still within acceptable limits for all parameters measured. Thus, normal service intervals were appropriate for vehicles fueled by B5. The typical warning limit for metal wear as well as additive deterioration in used lube oil was set by the lube oil laboratory based on their history on engine type, engine technology, type of fuel used, type of lube oil used, service interval, engine operating conditions and top up amount.

In a previous study, the impact of diesel fuel blended with biodiesel from palm oil and jatropha oil were assessed for the evaluation of engine lube oil performance by long duration testing (Gulzar *et al.*, 2016). The blending ratio of biodiesel and diesel fuel was 1:4. A single-cylinder CI engine was chosen for the testing. It was noticed that the acidity and viscosity of used blended fuels were increased and decreased, respectively. On the other hand, a slight increase in wear losses and friction were also noticed. In another study, 20% biodiesel and ultra low sulphur diesel blend were used for the comparative analysis in the assessment of lubricating properties (He *et al.*, 2011). Light duty vehicles and 4000 miles of operation were considered for the testing. Analysis showed a little difference in wear scar, viscosity, total base number, total acid number and soot.

Viscosity. *Figure 3* shows the viscosity of used lube oils of TH vehicle fueled by B5 and ADO. Typical warning limit for used lube oil viscosity is either 45% increase or 25% decrease (viscosity at 40°C) in comparison with fresh lube oil viscosity. Vehicles fueled by ADO were THB0-1 and THB0-2, while THB5-1 and THB5-2 vehicles were fueled by B5. The viscosity of fresh lube oil for THB0-1 was 52.56 $mm^2 s^{-1}$, while the upper and lower limits were 70.96 and 39.43 $mm^2 s^{-1}$, respectively. The viscosity for THB0-1 showed a decreasing trend due to dilution, which gave rise to lowest viscosity (23.22 $mm^2 s^{-1}$) at vehicle mileage of 60 000 km. After inspection, the vehicles were found to have mechanical problems and unable to continue the trials after 63 000 km. For THB0-2, the upper and lower limit viscosities were 170.51 and 94.72 $mm^2 s^{-1}$. For the first 15 000 km, the viscosity of used lube oil was found to be lower (121.8 $mm^2 s^{-1}$) than fresh lube oil (126.3 $mm^2 s^{-1}$). This may be due to contamination that stemmed from fuel dilution which decreased the lubricant viscosity, which in turn, may accelerate wear process as reported by Newell (1999). In addition, Wakiru *et al.* (2017) postulated that viscosity of fuel and the types of engine could increase or reduce the lubricant viscosity. For automotive application, lubricant viscosity tends to decrease due to dilution when the viscosity of fuel used is lower than that of lubricant.

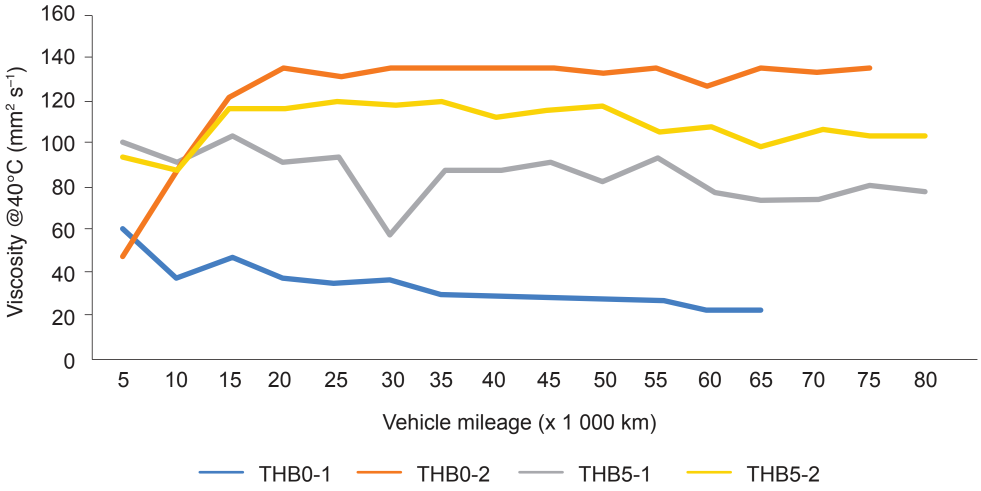

Figure 3. *Viscosity of used lube oil at 40°C for Toyota Hilux fueled by automation diesel oil (ADO) and B5.*

Subsequently, the viscosity of the used lube oil was almost consistent with an average of 134.06 mm² s^{-1}. Used lube oil viscosity of THB5-1 a showed slight decreasing trend with average viscosity of 87.6 mm² s^{-1}, which is still within acceptable limits (76.95 mm² s^{-1} to 138.5 mm² s^{-1}). On the other hand, the upper and lower viscosity limits for THB5-2 were 160.24 and 89.02 mm² s^{-1}, respectively. The average viscosity of used lube oil was 112.12 mm² s^{-1} and it is within acceptable limit.

Total base number. Total base number (TBN) in used lube oil is a measurement of reserved alkalinity in lubricating oil to neutralise acidic materials originated from combustion products condensed in engine parts (CIMAC, 2011). The acidic materials are corrosive to the engine components. Typical minimum level for TBN in used lube oil is 2. Based on *Figure 4*, the TBN for all used lube oils were within limit, indicating that normal service intervals were sufficient to provide required protection to the engine (Marie *et al.*, 2020).

Insoluble pentanes content. Pentanes insoluble is a measure of lube oil degradation due to insoluble contaminants either from fuel combustion and fuel degradation or from oil degradation. Fresh lube oil normally has a value of less than 0.10% by weight and the warning limit for used lube oil is 1.5%. All the TH vehicles tested fueled by ADO or B5 showed pentanes insoluble to be less than 1.5%. The values for THB0-1 ranged from 0.1%-0.24% and for THB0-2 the values were in the range of 0.1%-0.38%. The values for THB5-1 and THB5-2 were in the range of 0.1%-0.75% and 0.1%-1.25%, respectively. This indicated that more insoluble contaminants are present in the used lube oil for the vehicles fueled by B5 (Emma, 2010). The amount of insoluble may increase due to fuel contamination, lube oil degradation and incomplete fuel combustion (CIMAC, 2011).

Wear metal. Wear metal analysis is pivotal for maintenance evaluation. Wear metals measured for used lube oil in this study were chromium (Cr), copper (Cu), aluminum (Al), iron (Fe) and lead (Pb). Iron and lead are two main indicators of potential engine failure mostly analysed for used lube oil (Vališ *et al.*, 2015). *Figures 5* to *7* show the wear metal contents for aluminum, iron and copper in used lube oils at 80 000 km vehicle service. The wear metals of used lube oils of the tested vehicles were within acceptable limit according to CIMAC (2011). The Cr and Pb contents measured in used lube oil throughout the field trials were 1 ppm or less. Their typical warning limits were 40 ppm and 100 ppm, respectively. The origin of Cr was mainly from wear resistant of alloy steel used to fabricate piston ring, roller bearing and crankshaft. The source of lead could be detected from the crankshaft bearing or from the additive used in the lube oil itself (Yunus *et al.*, 2013). The typical warning limit for Al content is 40 ppm and the sources of Al metal were mostly piston, blower and oil pump bushing (Yunus *et al.*, 2013).

All the tested vehicles showed Al content of 5 ppm and below, except for THB0-2. Slightly high Al content was obtained for THB0-2 for the first 20 000 km, which may indicate running condition or mechanical problem. However, after servicing the vehicles at least for four times, the Al content in the used lube oils was below 5 ppm. Cu is the main component for copper bushing, particularly used for valve train bushing, camshaft bushing, bearing overlay and connecting rod bearing (Yunus *et al.*, 2013). The typical warning limit for Cu in used lube oil is 40 ppm and all the vehicles tested had Cu content of less than 10 ppm in used lube oils regardless of the type of fuel used. However, THB0-2 showed a slight increase in Cu content (18 ppm) for 20 000 km service interval. The Fe content in used lube oil mostly originates from piston ring, cylinder liner, valve train

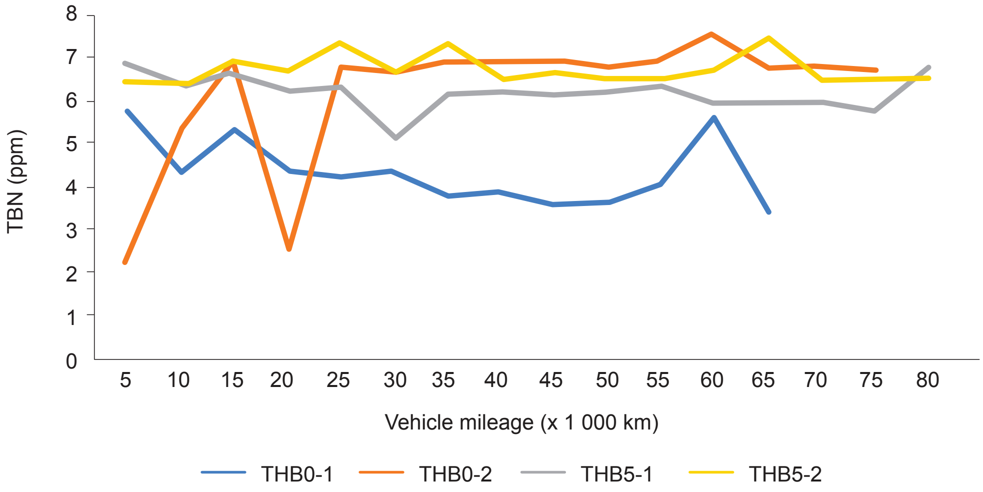

Figure 4. The total base number (TBN) of used lube oil for Toyota Hilux fueled by automation diesel oil (ADO) and B5.

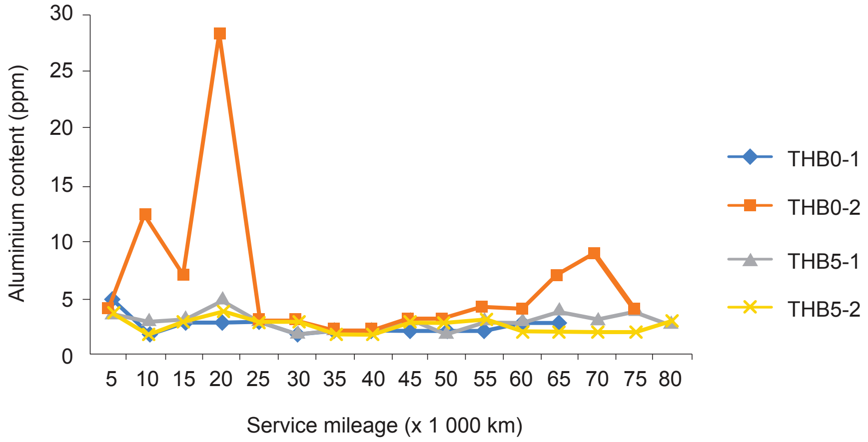

Figure 5. Aluminium (Al) content in used lube oils throughout field trials.

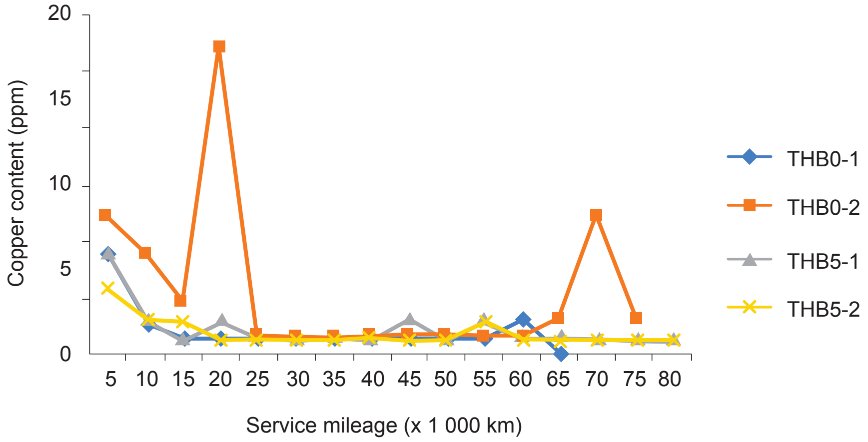

Figure 6. Copper (Cu) content in used lube oils throughout field trials.

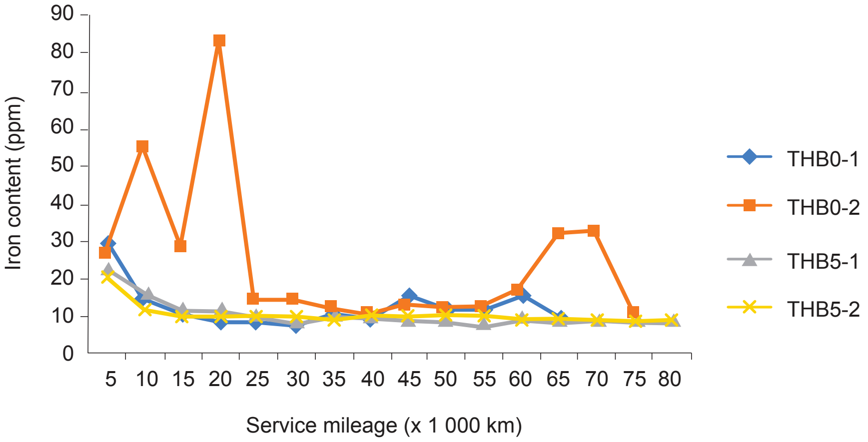

Figure 7. Iron (Fe) content in used lube oils throughout field trials.

and camshaft since Fe is the main engine component (Yunus *et al.*, 2013). The typical warning limit for Fe in used lube oil is 100 ppm. Thus, Fe content in lube oil in all the vehicles tested, regardless of fuel and injection technology used, were less than 30 ppm, except for THB0-2, which exhibited slightly higher Fe content of 30 ppm at second, fourth, 13th and 14th lube oil service intervals. However, the reported values were still lower than 100 ppm.

Silicon content. Silicon is one of the main micro constituents which may expedite the wear and tear of engine parts as well as contaminate the lube oil (Sendilvelan and Anandanatarajan, 2017).

Silicon could enter the engine from air filter, engine breathing systems and seal joint materials (Sendilvelan and Anandanatarajan, 2017). *Figure 8* shows the silicon content in used lube oils of the vehicles tested. It was found that silicon contents of fresh lube oil for THB0-1, THB0-2 and THB5-1 shared the same results, which were at 22 ppm, while THB5-2 recorded 18 ppm. The limit for silicon (Si) content is 20 ppm.

CONCLUSION

In this study, blending of 5% RBDPOo with 95% ADO was performed to produce B5 biofuel, which demonstrated great potential as alternative renewable fuel for diesel vehicles application. Results from field trials on different types of diesel injection systems showed insignificant deterioration on the engine performance as well as on service intervals. The engine power output of B5 was lower than ADO for TH and M vehicles but different scenarios were observed for MS vehicles. All the vehicles fueled by B5 showed lower torque reduction for M and MS vehicles compared to those fueled by ADO. The analysis of used lube oils showed that all the parameters studied including wear metal content of the engine oil were within acceptable limits. Thus, normal service intervals were appropriate for vehicles fueled by B5 (after 80 000 km mileage). There was no fuel-related problem reported on those vehicles tested. Therefore, it can be inferred that B5 biofuel can be used in diesel vehicles, particularly vehicles and machineries in oil palm plantations as part of strategies to reduce and mitigate the use of fossil fuel consumption and global warming, respectively. Sustainability of palm oil in global market could also be enhanced. Nevertheless, it is suggested that this study be extended for exhaust emission, long term fuel storage stability, maximum blending ratio and shelf life to support the results of the use of biofuel blend in compressed ignition engine, either mobile or stationary.

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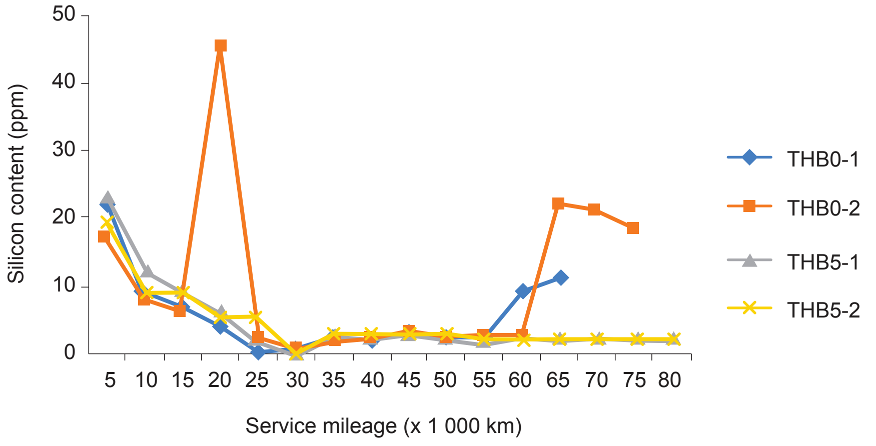

Figure 8. Silicon content in used lube oils throughout field trials.

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