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Emissions from In-use Buses and Light Duty Trucks Operating on Palm Methyl Ester and Coconut Methyl Ester in Thailand

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Abstract – *Biodiesel is attracting attention as an alternative fuel which will allow us to reduce fossil fuel use and help to lower greenhouse gas emissions than fossil fuels. Besides this effect, it can also help to reduce air pollutant emissions such as carbon monoxide (CO) and particulate matter (PM). In this paper, exhaust emission characteristics of in-use buses and light duty trucks operating on palm methyl ester (PME) and coconut methyl ester (CME) in Bangkok, Thailand are compared with petroleum diesel by chassis dynamometer emission testing. The test fuels are 100% petroleum diesel, PME20 (20% PME and 80% petroleum diesel) and CME20 (20% CME and 80% petroleum diesel). The overall test results show that nitrogen oxide (NOx) emissions from PME20 are slightly higher compared with those from diesel. CO and PM emissions from PME20 and CME20 are lower than those from diesel, and larger reductions were observed for PM especially in CME20. Carbon dioxide (CO_2) emissions are almost comparable with no significant difference among the different fuel types. This study indicates that utilization of PME and CME might reduce local air pollutant emissions without increasing tailpipe CO_2 emissions, and also indicates that CME has greater reduction potential than PME.*

Keywords – Biodiesel, coconut methyl ester, exhaust emissions, palm methyl ester, Thailand.

1. INTRODUCTION

Global warming has become an undeniable reality. The Intergovernmental Panel on Climate Change (IPCC) released the "Fourth Assessment Report of the IPCC, Climate Change 2007" on February 2007. The report concludes that global warming is "unequivocal" and it strengthens the previous assessment that recent warming in the past 50 years is "very likely" due to human activity related greenhouse gas emissions. Evidence that human activities are the major cause of recent climate change is even stronger than in prior assessments. It is pointed out more clearly now that many natural systems are being affected by climate change, particularly temperature increases [1].

In these circumstances, the reduction of greenhouse gases has become a serious concern for international society. In particular, considering the high share and growth rate of global emissions from the transport sector, reduction measures in the field of transportation has become much more urgent, not only in developed countries but also in developing countries.

Utilization of biofuels such as biodiesel and bioethanol are attracting attention as a promising measure for reducing greenhouse gas emissions in the transport sector. These biomass-derived fuels are considered to emit less greenhouse gases than fossil fuels in their lifecycle [2]-[4], although some studies show the opposite results [5]. Especially, it is reported that if land use change processes of oil cultivation for biofuels are included in the lifecycle analysis, the lifecycle greenhouse gas emissions of biofuels are significantly higher than that of fossil fuels, depending on the previous land use for cultivating oil crops such as rain forests [6]-[8].

Biodiesel, which can be produced through, for instance, transesterification of vegetable oils or animal fats, also has an advantage in its potential to reduce vehicle air pollutants such as PM, CO, hydrocarbons (HC), and sulfur oxides (SOx) [9]-[11]. Demirbas [12] reported in the review paper that the use of biodiesel in a conventional diesel engine dramatically reduces the emissions of unburned hydrocarbons, CO, CO_2, sulfates, polycyclic aromatic hydrocarbons, nitrated polycyclic aromatic hydrocarbons, ozone-forming hydrocarbons, and PM. Many previous studies show that biodiesel use generally reduces PM and CO emissions, and slightly increases or reduces NOx emissions [9]-[19]. In a comprehensive analysis of biodiesel emissions and impacts, the U.S. Environmental Protection Agency reports that soybean-based biodiesel, blends of 20% biodiesel and 80% petroleum diesel (B20), provides a reduction of 10.1% in PM and 11.0% in CO with an increase of 2.0% in NOx compared with 100% petroleum diesel, even though these results were obtained through testing relatively old engines [20]. The

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report also shows that the impact of biodiesel on emissions varies depending on the type of feedstock, for example, soybean, rapeseed or animal fat. McCormick *et al.* [21] tested more recent vehicles and reported that the impact of B20 on NOx, PM, and CO emissions is 0.6% ± 1.8%, −16.4% ± 10%, and −17.1% ± 6.1%, respectively, compared with petroleum diesel. Durbin *et al.* [22] tested ARCO emissions control diesel (EC-D) and three 20% biodiesel blends (one yellow grease and two soy-based). The results show that the EC-D and the yellow grease biodiesel blend both showed significant reductions in total hydrocarbons (THC) and CO emissions over the test vehicle fleet and NOx emissions were comparable for the different fuel types for most of the vehicles tested. The soy-based biodiesel blends showed smaller emissions differences over the test vehicles, including some increases in PM emissions. Labeckas *et al.* [23] analyzed the emission characteristics of four stroke, four-cylinder, direct injection, unmodified diesel engine operating on neat rapeseed methyl ester and its blends with diesel fuel. They found that CO, HC and visible emissions had decreased while an oxide of nitrogen emissions increased for methyl ester compared to diesel. Mazzoleni *et al.* [24] reported increased emissions of PM, cold-start CO and hot-stabilized HC with blending 20% biodiesel into petroleum diesel. These results were obtained through on-road real-world conditions, not in a laboratory, with off-specification B20. Ropkins *et al.* [25] also performed a real-world comparison of vehicle exhaust emissions for diesel and B5. It is reported that, at the total journey measurement level, replacing diesel with a B5 substitute could result in significant increase in NOx emissions (8–13%) and no significant effect was observed for CO, CO_2 and HC.

Turrio-Baldassarri *et al.* [26] compared the chemical and toxicological characteristics of emissions from an urban bus engine fueled with diesel and biodiesel blend. They show that the use of biodiesel blend result in small reductions of emissions of most of the aromatic and polyaromatic compounds, and formaldehyde has a statistically significant increase of 18% with biodiesel blend. Dwivedia *et al.* [27] tested diesel and B20 in terms of metals and benzene soluble organic fraction. Results indicated comparatively lower emission of particulate from B20-fuelled engine than diesel engine exhaust. Metals like Cd, Pb, Na, and Ni in particulate of B20 exhaust were lower than those in the exhaust of mineral diesel, however, emissions of Fe, Cr, Ni Zn, and Mg were higher in B20 exhaust.

Biodiesel is being used mainly in North America and Europe, and production is increasing year by year. In Europe, biodiesel is produced mostly from rapeseed and to a much lesser extent from sunflowers. In North America, biodiesel is mainly produced from soybeans and to a lesser extent from canola. Consequently, much of the research on biodiesel emissions characteristics is focused on these feedstock. However, not as much as these feedstock, researches on emission characteristics for other feedstock have been also undertaken. Narayana Reddy *et al.* [28] studied the performance of jatropha oil fuelled diesel engine. The authors concluded that advancing the injection timing and increasing the injector-opening pressure reduce HC and smoke emissions significantly. Ramadhas *et al.* [29] shows emission evaluation of a diesel engine fueled with rubber seed methyl ester that the exhaust gas emissions are reduced with increase in biodiesel concentration. Puhana *et al.* [17] studied mahua oil methyl ester, and the results show that emissions of CO, HC fuelled with mahua oil methyl ester are significantly lower compared with diesel, and oxides of nitrogen were slightly low for ester compared with diesel. Raheman [30] presented the results of emission tests of karanja methyl ester, and it was found that blends of karanja methyl ester with diesel reduced emissions such as CO, smoke density and NOx on an average of 80%, 50% and 26%, respectively. Lapuerta *et al.* [31] tested two different biodiesel fuels obtained from waste cooking oils with different previous uses. It is reported that a sharp decrease was observed in both smoke and PM emissions as the biodiesel concentration was increased. The mean particle size was also reduced with the biodiesel concentration.

In recent years, other countries have also developed an interest in introducing biodiesel, due mainly to increasing crude oil prices. Especially, developing countries in tropical or subtropical regions have been producing or preparing to produce biodiesel. In the near future, production in developing countries will increase rapidly with the increased demand in the domestic market as well as export to developed countries. The main feedstock for biodiesel in tropical or subtropical regions is likely to be palm oil, coconut oil or jatropha seeds, etc.

As of today, the research on emission characteristics of biodiesel fuels such as PME or CME is limited compared with rapeseed methyl ester or soybean methyl ester. In the EPA's comprehensive analysis based on the data of previous studies, reviewed feedstock are limited to soybeans, rapeseed, canola oil, grease, tallow, and lard [20]. Kalam and Masjuki [32] present the results of emission tests on palm methyl ester biodiesel, reporting that blending 7.5% and 15% of palm methyl ester reduces NOx emissions as well as CO and HC compared with 100% petroleum diesel. They also reported that 20% palm diesel with 1% antioxidant additive shows better results such as less HC, CO and NOx emissions as compared to pure diesel fuel [33].

In these circumstances, this paper summarizes emission characteristics of in-use buses and light duty trucks operating on PME and CME in Bangkok Thailand. Comparison with emissions data from petroleum diesel is also provided.

2. VEHICLE EMISSION TESTS

Test Facilities

In order to analyze pollutant emissions from in-use diesel vehicles, chassis dynamometer emission tests were performed at the Automotive Emission Laboratory, Pollution Control Department (PCD), Ministry of Natural Resources and Environment, Thailand.

Figures 1 and 2 show the schematic diagram of PCD emission analyzer system.

Table 1 lists the details of the major instruments installed in the PCD emission analysis system. Chemiluminescence analyzer was used to measure NOx. THC was analyzed using a flame ionization detector (FID). Nondispersive infrared analyzer (NDIR) was used to measure CO_2 and CO. A secondary dilution tunnel was used for heavy duty truck PM sampling.

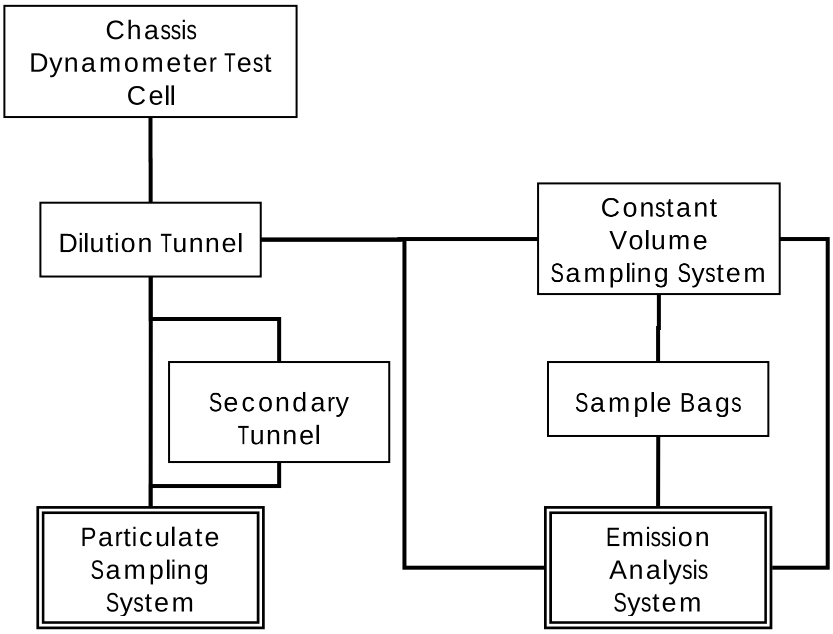

Fig. 1. PCD emission analyzer system for heavy duty diesel.

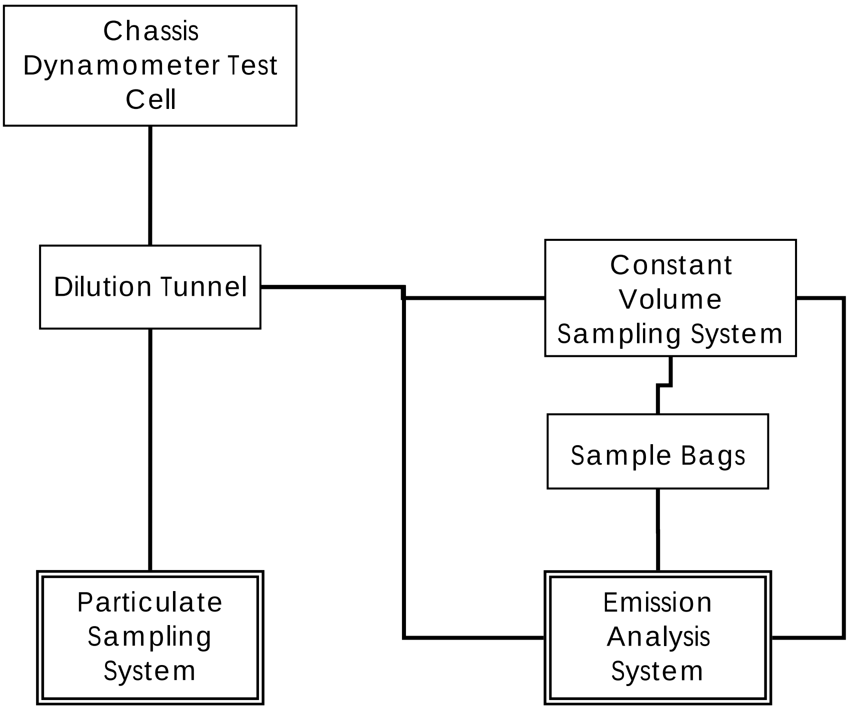

Fig. 2. PCD emission analyzer system for light duty diesel.

Table 1. Details of PCD emission analysis system.

Facilities	Items	Heavy Duty Diesel	Light Duty Diesel
Chassis dynamometer	Manufacturer	Schench Komeg (Germany)	Schench Pegasus (Germany)
	Types	FP500/GS 500	EMDY 48
Emission analysis system	Manufacturer	PIERBURG (Germany)	PIERBURG (Germany)
	Types	AMA2000 TYPE D	AMA2000 TYPE D
	NOx analyzer	CLD PM-2000	CLD PM-2000
	THC analyzer	FID PM-2000	FID PM-2000
	CO/CO_2 analyzer	NDIR PIA-2000	NDIR PIA-2000
	HC analyzer	NDIR PIA-2000	NDIR PIA-2000
Other facilities	CVS*1)	CVS 150 WT	CVS 60 CFV
	PS*2)	PS 2000 D	PS 2000 D

*1) CVS: Constant Volume Sampling System
*2) PS: Particulate Sampling

Table 2. Specifications of tested vehicles.

	Light Duty Truck 1	Light Duty Truck 2	Bus 1	Bus 2
Vehicle manufacturer	Toyota (Tiger)	Toyota (Hilux)	Hino	Daewoo
Gross vehicle weight (kg)	2,580	2,580	15,300	15,300
Engine model year	2002	1990	1994	1997
Engine displacement (L)	2.5	2.5	8.0	8.0
Engine power (hp)	107hp/ 3800 rpm	89 hp / 4200 rpm	250 hp / 2400 rpm	240 hp / 2400 rpm

Test Vehicles

A total of four (4) in-use vehicles were tested. Two (2) of these vehicles were Bangkok Mass Transit Authority (BMTA) buses: a relatively old “hot-bus” with no air conditioning and a relatively new bus with air conditioning. The other two vehicles were light duty trucks: a 2002 Toyota Tiger and a 1990 Toyota Hilux. Table 2 shows the specifications of tested vehicles.

Test Fuels

Each vehicle was tested on a series of the following 3 fuels:

- 100% petroleum diesel
- PME blended biodiesel (PME20), 20% PME and 80% petroleum diesel. PME was produced from palm olein in Thailand by the Thai Royal Navy.
- CME blended biodiesel (CME20), 20% CME and 80% petroleum diesel. CME was produced in the Philippines by a local biodiesel producer.

A summary of the fuel specifications is shown in Table 3. Most of the elements were analyzed at the laboratory of PTT Public Company Limited, Thailand. Density of PME20 and CME20 is greater than that of petroleum diesel, and the cetane number of PME20 and CME20 is lower than that of petroleum diesel. CME20 has the highest oxygen content. The fatty acid profiles of PME and CME are shown in Table 4. The molecular structures of PME and CME are significantly different from each other; the major contents of PME is methyl oleate (C18:1), on the other hand methyl laurate (C12) contains over 50% of CME, and CME is highly saturated while PME contains about 60% of unsaturated methyl ester. PME has longer hydrocarbon chain and more double bonds than CME.

Driving Cycles

Driving cycles adopted in the emission tests are shown in Figures 3 and 4.

For buses, four driving cycles were tested for each vehicle: Bangkok Driving Cycle Phase 2 for Buses (BKK2, Average speed 9.4 km/h), Bangkok Driving Cycle Phase 4 for Buses (BKK4, Average speed 24.0 km/h), urban part of European Transient Cycle (ETC), and revised AC2540. Bangkok driving cycles were developed to reflect actual driving conditions and characteristics of Bangkok [34]. AC2540 was developed in DIESEL project in Thailand.

For light duty trucks, five driving cycles were tested for each vehicle: Bangkok Driving Cycle Phase 2 for Light Duty Trucks (BKK2, Average speed 15.0 km/h), Bangkok Driving Cycle Phase 4 for Light Duty Trucks (BKK4, Average speed 34.9 km/h), European Urban Driving Cycle (ECE15), European Extra Urban Driving Cycle for low-powered vehicles (EUDC), and revised AC2540.

Items Monitored

Major pollutants in exhaust gases were analyzed both by continuous sampling and by bag sampling. For continuous sampling, the pollutants analyzed were NOx, CO, THC, CO_2, and PM. For bag sampling, NOx, CO, THC, and CO_2 were analyzed. PM mass was analyzed by filter sampling. Test conditions such as ambient temperature and humidity of the laboratory were also monitored. Chassis dynamometer tests were carried out carefully, checking the repeatability of emissions and keeping the fuel temperature constant.

Table 3. Specifications of fuels tested in this study.

Characteristics	Petroleum diesel	PME20	CME20
Density (g/L)	0.830	0.840	0.838
Sulfur content (mass%)	0.0236	0.0222	0.0176
Cetane Number	57.8	56.7	54.2
C content (mass%)	86.6	84.6	83.9
H content (mass%)	13.4	13.2	13.2
O content (mass%)	-	2.2	2.9

Table 4. Fatty acid profiles of PME and CME (wt %).

	PME	CME
Methyl caprylate (C8)	-	7.6
Methyl caprate (C10)	-	6.7
Methyl Laurate (C12)	0.4	53.1
Methyl Myristate (C14)	0.9	19.6
Methyl Palmitate (C16)	38.5	7.6
Methyl Stearate (C18:0)	0.1	1.3
Methyl Oleate (C18:1)	58.1	3.2
Methyl Linoleate (C18:2)	1.8	0.6
Methyl Linolenate (C18:3)	0.1	-
Others	0.1	0.3
C content	76.4	73.3
H content	12.4	12.3
O content	11.2	14.4

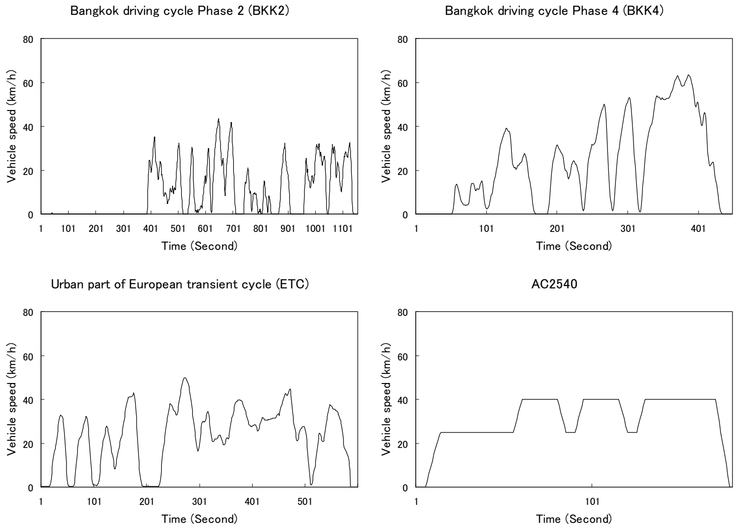

Fig. 3. Driving cycles for buses.

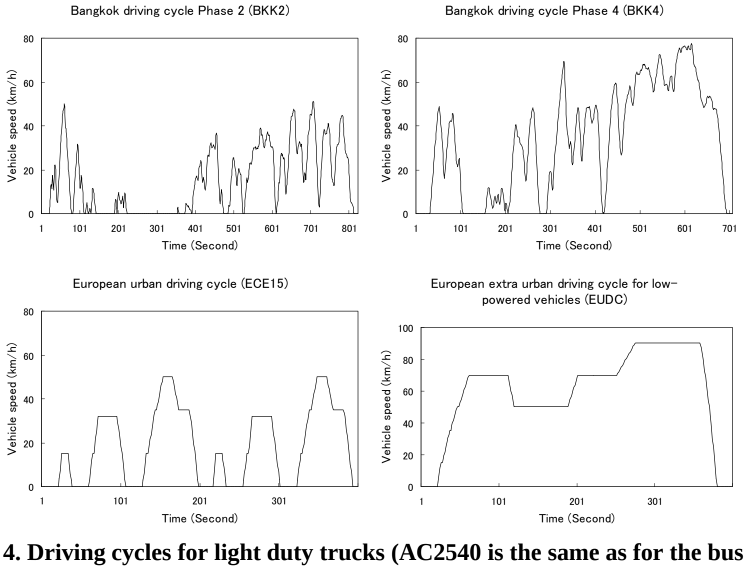

Fig. 4. Driving cycles for light duty trucks (AC2540 is the same as for the buses).

3. RESULTS AND DISCUSSION

Nitrogen Oxides (NOx)

Figures 5 and 6 show the NOx emissions from each vehicle and the ratio of NOx emissions between different fuel types.

BDF20/Diesel ratios in Figure 6 are calculated by Equations 1 and 2.

The ratio for each vehicle;

$$(BDF20/diesel\,ratio)_{Tested\ vehicle} = \frac{\sum_{i=Driving\ cycle} \frac{(emission\,of\ BDF20)_i}{(emission\,of\ diesel)_i}}{Nunmer\,of\ driving\,cycles\,tested} \qquad (1)$$

The ratio for average on buses or light duty trucks;

$$(BDF20/diesel\,ratio)_{Average\ on\ buses/light\ duty\ trucks} = \frac{(BDF20/diesel\,ratio)_{Bus1/LD1} + (BDF20/diesel\,ratio)_{Bus2/LD2}}{2} \qquad (2)$$

The results for each vehicle show that NOx emissions for the BKK2 driving cycle are the highest among all cycles tested in this experiment. As noted above, the BKK2 driving cycle was developed based on real-world Bangkok driving data. It has a high fraction of idle mode reflecting Bangkok's traffic conditions. NOx emissions were almost comparable for the different fuel types. However, PME20 emissions are slightly higher compared to diesel. The difference is highest in the Bus 2 – AC2540 cycle at 8.5%. Compared with diesel, the overall test results show that NOx emissions from PME20 are 3.4% and 2.2% higher on average for buses and light duty trucks, respectively. The impact of PME20 on NOx emissions obtained in this study is almost comparable with the EPA study showing a increase rate of 2.0% for B20 [20]. Many previous studies have also shown that biodiesel increases NOx emissions [9]-[19]. On the other hand, in this study, CME20 emissions show no significant difference when compared with diesel. Compared with PME20, the overall test results show that CME20 emissions are 2.6% and 1.8% lower on average for buses and light duty trucks, respectively.

A possible reason why PME20 use increases NOx emissions in vehicles is because it has higher oxygen content than petroleum diesel. NOx emissions are highly dependent on combustion temperature along with oxygen. The double bonds in biodiesel may also participate in some combustion or precombustion chemistry to increase NOx. For fuels containing a mixture of molecules the iodine number is a measure of the degree of unsaturation or number of double bonds, and there is a highly linear relationship between iodine number and NOx [35]. Another possibility is differences in the speed of sound and isentropic bulk modulus of biodiesel relative to petroleum diesel. Tat *et al.* [36], [37] suggested that higher value of the speed of sound and isentropic bulk modulus of methyl soyester can advance the effective injection timing and cause NOx to increase.

Taking into account the results of Graboski *et al.* [35], showing highly linear relationship between increasing NOx emissions and increasing number of double bonds, the reason of the difference in NOx emissions between PME20 and CME20 may be possibly attributed to the differences in molecular structures of the methyl esters; PME consists mainly of methyl oleate (C18:1) has more double bonds than CME which consists mainly of methyl laurate (C12).

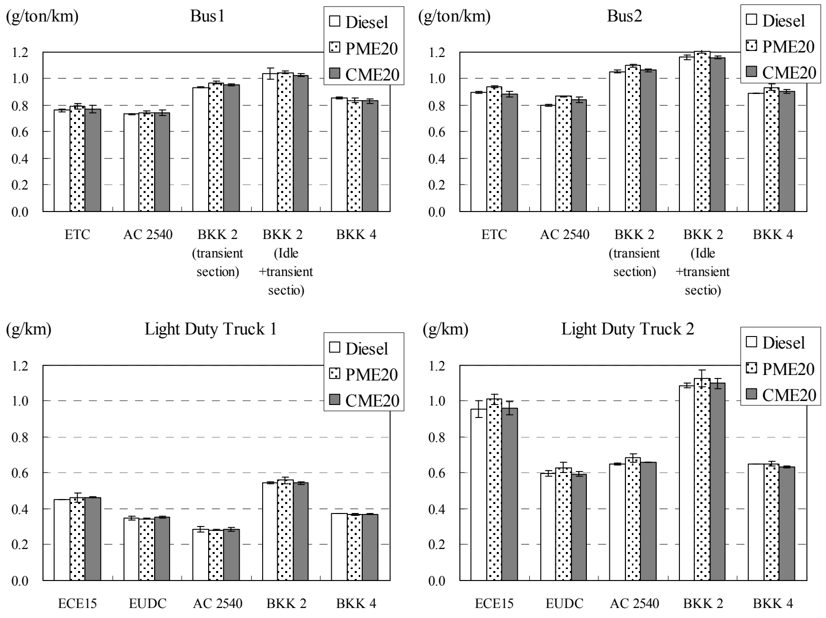

Fig. 5. NOx emissions by type of vehicle and driving cycle.

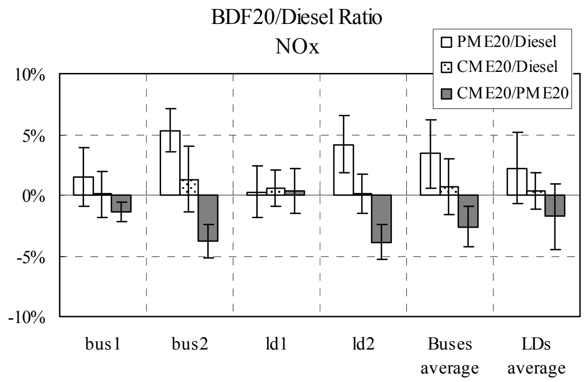

Fig. 6. Ratio between NOx emissions by different fuel types.

Carbon Monoxide (CO)

Figures 7 and 8 show the CO emissions for each vehicle and the ratio of CO emissions between different fuel types.

The results show that CO emissions are higher for BKK driving cycles, especially for buses. For most tests, CO emissions from vehicles fueled with biodiesel were reduced. For PME20 and CME20, the reduction rate was highest for the Light Duty Truck 1 – AC2540 cycle at 19.1% and 32.2%, respectively. Compared with diesel, the overall test results show that CO emissions from PME20 are 2.7% and 4.0% lower on average for buses and light duty trucks, respectively. For CME20, the reduction rate is much higher than that for PME20, at 9.3% and 12.1% lower on average for buses and light duty trucks, respectively. The impact of PME20 on CO emissions obtained in this study is smaller than the EPA study showing a reduction rate of 11.0% for B20 [20]; however, it is almost equal to the reduction rate of CME20.

Biodiesel use reduces CO emissions from vehicles mainly because it has higher oxygen content than petroleum diesel. For example, neat CME used in this study contains 14.4% oxygen by weight whereas petroleum diesel contains almost no oxygen. The presence of fuel oxygen allows more complete combustion of fuel, and therefore CO emissions from CME20 and PME20 are lower compared to petroleum diesel. The difference in CO emissions between PME20 and CME20 may be explained by the differences in number of carbon in a molecular and oxygen content.

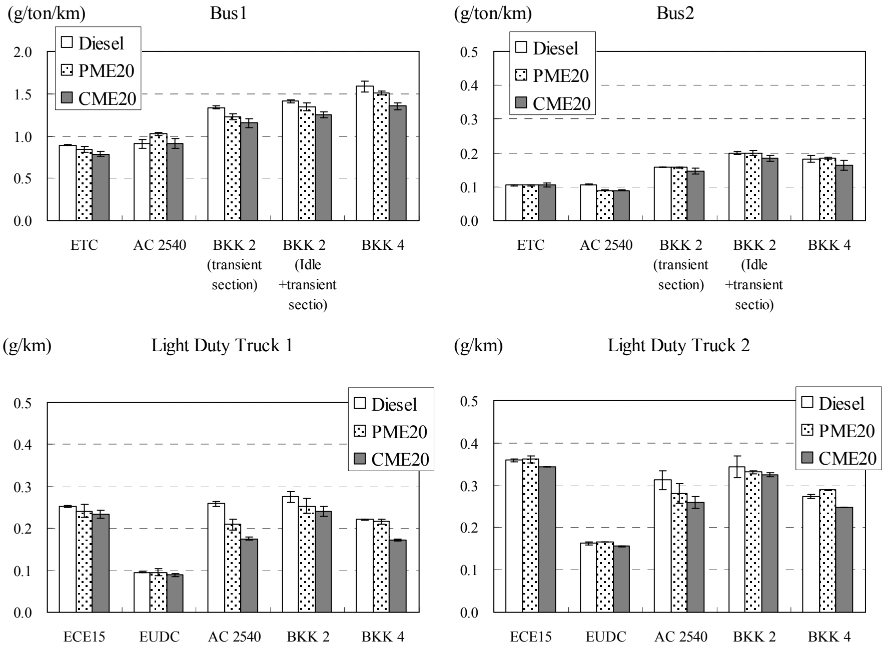

Fig. 7. CO emissions by type of vehicle and driving cycle.

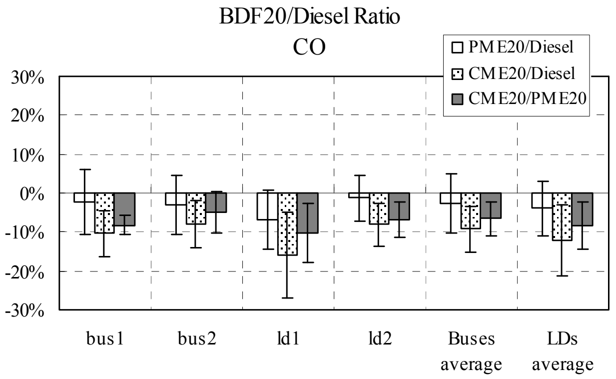

Fig. 8. Ratio between CO emissions by different fuel types.

Total Hydrocarbon (THC)

Figures 9 and 10 show the THC emissions for each vehicle and the ratio of THC emissions between different fuel types.

THC emission was highest for BKK2 driving cycles, especially for buses. CME20 reduced THC emissions in most of the test cases. Compared with diesel, the overall test results show that THC emissions from CME20 are 8.1% and 6.8% lower on average for buses and light duty trucks, respectively. This value is significantly lower than that of the EPA study showing 21.0% for B20 [20]. For PME20, since the emissions vary significantly as indicated by the error bars, it is difficult to conclude whether PME20 reduced the emissions or not. Other studies have shown that biodiesel decreases THC emissions [9], [12], [20].

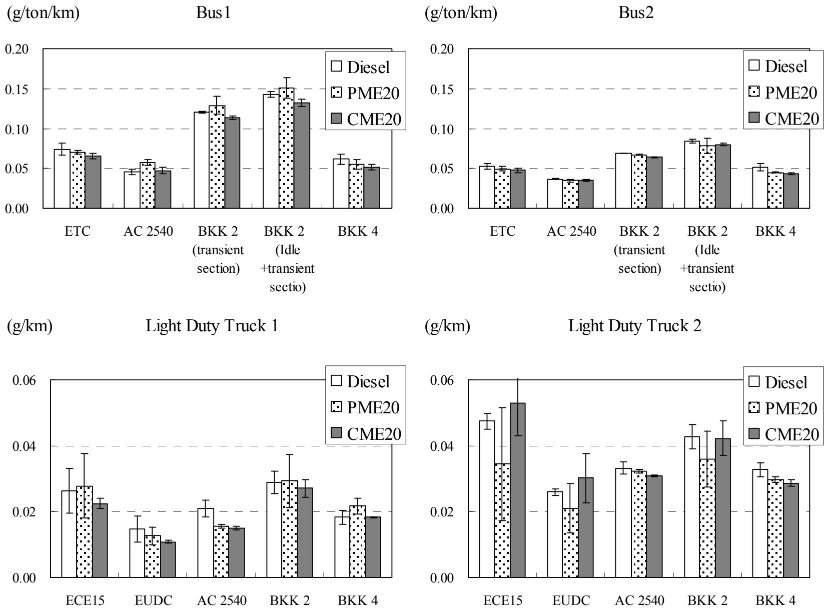

Fig. 9. THC emissions by type of vehicle and driving cycle.

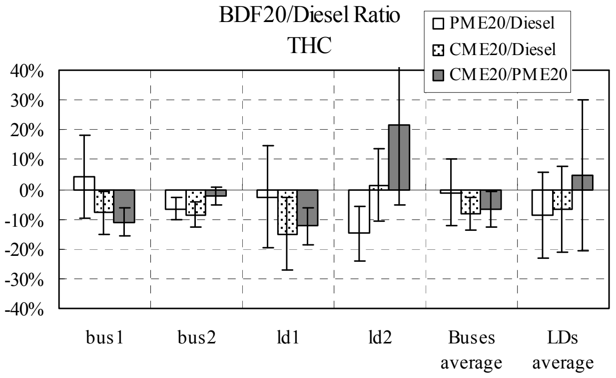

Fig. 10. Ratio between THC emissions by different fuel types.

Carbon Dioxide (CO_2)

Figures 11 and 12 show the CO_2 emissions for each vehicle and the ratio of CO_2 emissions between different fuel types.

The results for each vehicle show that CO_2 emissions for the BKK2 driving cycle are highest among all cycles tested in this experiment. CO_2 emissions were almost comparable, with no significant difference among the different fuel types.

As a reference, compared with diesel, the overall test results show that CO_2 emissions from PME20 are 0.5% and 0.2% higher on average for buses and light duty trucks, respectively; on the other hand, for CME20 on overall average, 0.6% higher for buses and 0.6% lower for light duty trucks.

Since biodiesel has less carbon content compared with petroleum diesel, it is supposed that CO_2 emissions from biodiesel per fuel volume are less than that from petroleum diesel. However, the calorific value of biodiesel is lower than that of petroleum diesel; therefore, it is supposed that CO_2 emissions from biodiesel per vehicle kilometer are almost comparable with that of petroleum diesel.

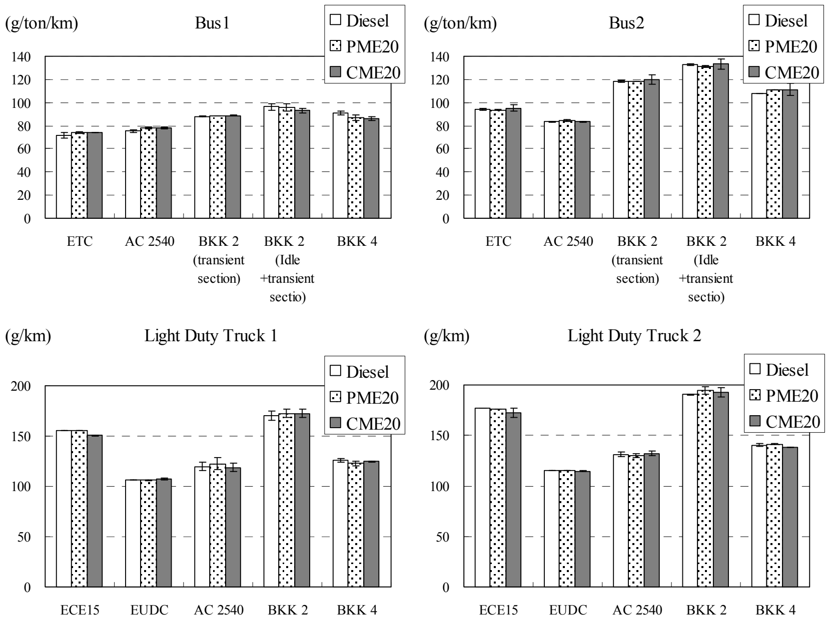

Fig. 11. CO_2 emissions by type of vehicle and driving cycle.

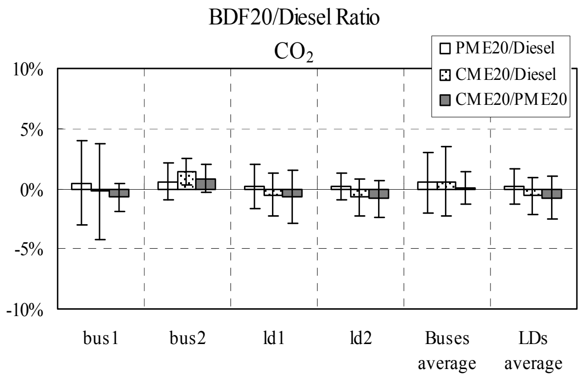

Fig. 12. Ratio between CO_2 emissions by different fuel types.

Particulate Matter (PM)

Figures 13 and 14 show the PM emissions for each vehicle and the ratio of PM emissions between different fuel types.

PM emissions are generally higher for BKK driving cycles. Emissions from vehicles fueled with biodiesel were significantly reduced in most tests. For PME20 and CME20, the reduction rate was highest for the Bus 2 – BKK2 (Transient Section) cycle at 30.9% and 58.8%, respectively. Compared with diesel, the overall test results show that PM emissions from PME20 are 7.5% and 9.8% lower on average for buses and light duty trucks, respectively. For CME20, the reduction rate is much higher than that for PME20, at 28.6% and 16.7% lower on average for buses and light duty trucks, respectively. Compared with the EPA's comprehensive study showing a reduction rate of 10.1%, PME20 is almost comparable and CME20 has a much higher reduction rate [20]. Other studies have also shown that biodiesel can decrease PM emissions [9]-[19].

Biodiesel use reduces PM emissions in vehicles mainly because it has higher oxygen content than petroleum diesel. This is the same reason as for CO reduction. The presence of fuel oxygen allows the fuel to burn more completely. Another possible reason is that biodiesel has no aromatic content and much lower sulfur content than petroleum diesel.

The difference in PM emissions between PME20 and CME20 can be explained by the differences in oxygen content of these fuels, since results of other studies indicate that the PM reduction is proportional to the oxygen content of the fuel [35], [38].

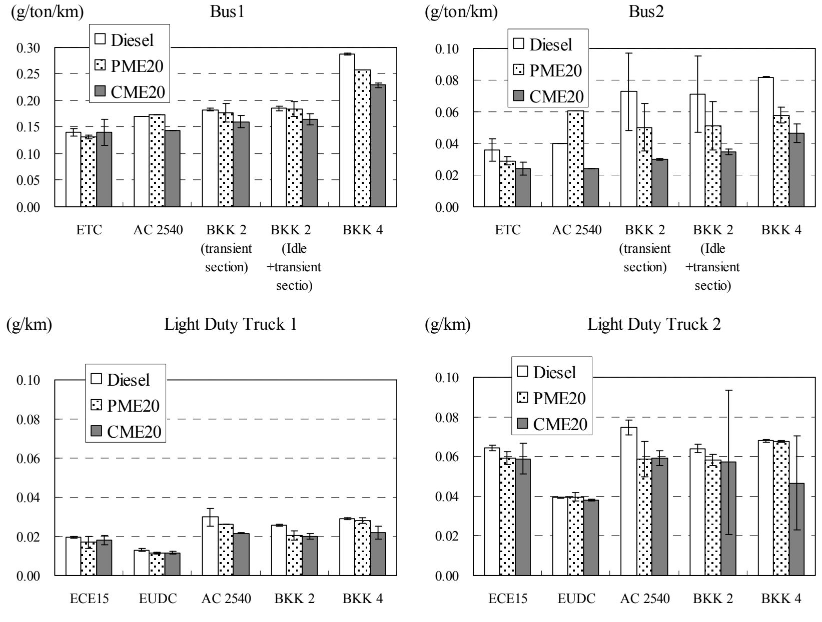

Fig. 13. PM emissions by type of vehicle and driving cycle.

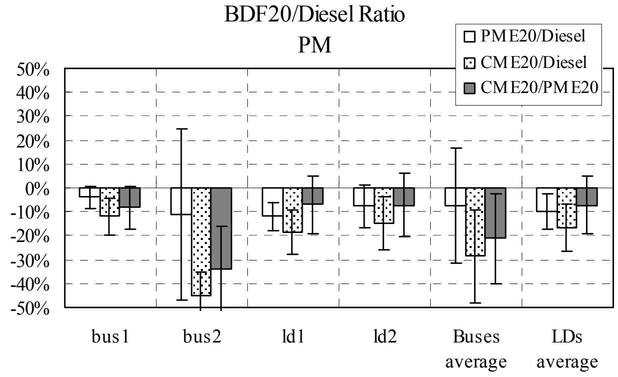

Fig. 14. Ratio between PM emissions by different fuel types.

4. CONCLUSION

This paper presented an overview of exhaust emission characteristics of PME and CME. Emission tests were performed at chassis dynamometer testing facilities using in-use diesel vehicles in Thailand. Various test cycles were selected to evaluate the difference in emission characteristics between test cycles.

The emissions were compared with that of petroleum diesel and the results showed that both PME20 and CME20 reduced major air pollutant emissions such as CO and PM. CO_2 emissions from these biodiesel fuels were almost comparable with petroleum diesel. PME20 increased NOx emissions compared with petroleum diesel as reported in previous studies. However, NOx emissions from CME20 show no significant difference compared with diesel. One of the noteworthy results in this study is that CME20 shows large amount of emission reductions than PME20 for most air pollutants and vehicle types and test cycles. One of the reasons that large amount of emission reductions occur for CME is the difference of molecular structure between PME and CME.

Although more emission tests are required in order to improve the precision of test results and to confirm the test results, this study indicates that in terms of exhaust emission characteristics, PME and CME have a potential as promising alternative fuels. To further evaluate these fuels from the aspect of total environment, it is important to assess lifecycle greenhouse gas emissions and air pollutant emissions as well as energy consumption.

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