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EMISSION FACTORS OF CH_4 AND CO_2 EMITTED FROM VEHICLES

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ABSTRACT

The study of the Emission Factors (EF) of methane (CH_4) and Carbon Dioxide (CO_2) emitted from vehicle exhaust is the study of greenhouse gases that are crucial to climate change. These gases are part of a fuel known as Compressed Natural Gas (CNG) or as Natural Gas for Vehicles (NGV) in Thailand. This fuel is used as an alternative to oil, which has decreased the amount of gasoline and diesel oil used in the transportation sector of Thailand. This study used different types of cars that were tested on a chassis dynamometer with a Bangkok driving cycle to measure the emissions of CH_4 and CO_2 and then to calculate the averages of EF-CH_4 and EF-CO_2, which are associated with speed and fuel consumption, respectively. This study was conducted in 3 vehicle types that are actually used in Thailand, namely, Heavy Duty Diesel Vehicles (HDDV), Light Duty Diesel Vehicles (LDDV) and Light Duty Gasoline Vehicles (LDGV). Our results showed that of the three vehicle types, HDDV produced the highest EF-CH_4 and EF-CO_2 averages at 7.22 and 919.6 g km^{-1}, respectively. LDDV produced the lowest EF-CH_4 (0.17 g km^{-1}) and LDGV produced the lowest EF-CO_2 (153.8 g km^{-1}). In addition, the EF-CH_4 and EF-CO_2values of LDDV and LDGV were comparable even though the engine types of these vehicles were different. With respect to fuel consumption, the EF-CH_4 and EF-CO_2 of HDDV indicated a higher fuel consumption, which differed from those of LDDV and LDGV. Nevertheless, LDGV or taxis, which account for a large portion of the transportation sector in Thailand, emitted higher proportions of CH_4 and CO_2 than the other vehicle types, as shown by the CH_4:CO_2 ratio. Therefore, according to the results, the EF-CH_4 and EF-CO_2 values can be applied for the effective evaluation of CH_4 and CO_2 emissions from vehicles in Thailand.

Keywords: Emission Factors, Methane, Carbon Dioxide, Compressed Natural Gas, Vehicle

1. INTRODUCTION

Compressed Natural Gas (CNG) or Natural Gas for Vehicles (NGV) is a fossil fuel that can be used as an energy source for traffic and transportation. The natural gas sales have risen for vehicles in Thailand and NGV engines are being installed in vehicles each day, mostly in Heavy Duty Diesel Vehicles (HDDV), trucks and new cars. Today, the compressed natural gas used in vehicles is considered an alternative energy source, which reduces the consumption and import of any type of oil and has physical properties that normally result in low pollution emissions compared with other fuels. Nonetheless, in the current situation, greenhouse gases (GHGs) are combusted and emitted as exhaust gas from vehicles (Bauer and Forest, 2001), especially methane (CH_4) and Carbon Dioxide (CO_2), which are key components of compressed natural gas and have a tendency to emit from the exhaust (Crane and Scot, 1992; Zarante and Sodre, 2009). In particular, methane

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has a higher potency as a greenhouse gas than carbon dioxide and both gases may result in climate change (Parry, 2007). As a result, compressed natural gas is an alternative fuel for vehicles that has been increasingly and widely used in metropolitan areas (Guo *et al*., 2011). Therefore, the evaluation of greenhouse gas emission can be calculated from the relationship between the exhaust gas emission activity and the Emission Factors (EF) of a certain vehicle. Furthermore, each factor is different, such as the vehicle type, fuel type used and driving patterns at various speeds. However, current EF information is only available for some factors. In Thailand, there has not been an emission factor study that could be used to properly evaluate the emissions of greenhouse gases from the combustion in vehicles using compressed natural gas (Akansu *et al*., 2007). Accordingly, conducting a study of emission factor methane (EF-CH_4) and carbon dioxide (EF-CO_2) from different types of vehicles actually used in Thailand is necessary. The purpose of this study, which was conducted in an automotive emission laboratory, was to measure the EF-CH_4 and EF-CO_2 of various vehicles with different driving patterns in Thailand. The results of the test vehicles that use CNG as fuel and the patterns of driving in the studied areas from the laboratory (PCD, 2000) will be used to calculate the EF-CH_4 and EF-CO_2 to find a relationship between the evaluated vehicle greenhouse gas emissions and the actual conditions and to apply the results to the effective planning of air pollution management in Thailand.

2. MATERIALS AND METHODS

2.1. Experiment Planning

The vehicles used in the current experiment were categorized into 3 types, namely, Heavy Duty Diesel Vehicles (HDDV), Light Duty Diesel Vehicles (LDDV) and Light Duty Gasoline Vehicles (LDGV) or taxis. The latter types are used most often and are abundant in Thailand. The LDGV were also classified according to the number of kilometers the vehicle traveled because they are used extensively for transportation in metropolitan regions. For the calculations of EF-CH_4 and EF-CO_2, all of these vehicle types were compared with respect to their greenhouse gas emissions, which result from the combustion of the compressed natural gas in the internal combustion engine. These experiments were performed as part of an experimental project of the automotive emission laboratory, Pollution Control Department, Ministry of Natural Resources and Environment. All three vehicle types use Compressed Natural Gas (CNG) or Natural Gas for Vehicles (NGV), use the bi-fuel system and are equipped with a fumigation system. The vehicles were inspected and their engines were in the conditions specified by the manufacturers. There were no leaks in the exhaust system. The tested vehicles were in actual use and used fuels in Thailand. The suitability of this test is shown in detail below **Table 1**.

2.2. Exhaust Gas Testing and Analysis

The pollution emission from the vehicles as emission factors was evaluated by analyzing pollutants from the exhaust pipes in a laboratory that simulated any force occurring during actual driving. Driving pattern simulations with controlled temperature and humidity were performed according to the testing standards or were similar to actual conditions. Each type of vehicle was tested on a chassis dynamometer to adjust the conditions of the vehicles at each speed range to replicate the actual road conditions and the test vehicles used the metropolitan driving pattern that was a simulation of the Bangkok driving cycle. The average speeds panned from low speed ranges to high speed ranges and the calculated average speed was used as a representative to calculate the pollutants produced in the studied areas and in various situations, such as congested areas or during rush hour. The vehicles were tested while their engines were still hot (hot emission tested), which represented the simulation of the traffic conditions at the low speed range to high speed range during the congested period. This congested period involves frequent switches between acceleration and braking during the high traffic flow period of one driving cycle. This analysis was performed to determine the amounts of a variety of pollutants. The pollution emitted was measured by the bag sampling system and during the test, the exhaust gas was collected throughout the entire driving cycle by Constant Volume Sampling (CVS). The test was started by diluting exhaust gas with air and measuring the amount of the diluted exhaust gas in the system. The test consisted of the following steps: (1) receiving the total flow of the vehicle exhaust gas, (2) diluting the exhaust gas with air, (3) constantly suctioning out and collecting the exhaust gas and (4) correctly measuring the total amount of diluted exhaust gas. Then, the exhaust gas sample was sent to a methane analyzer and to a Flame Ionization Detector (FID) to determine the methane concentration in the laboratory. Carbon dioxide was analyzed by a Non-Dispersive Infrared analyzer (NDIR) to determine the concentration of CO_2. The infrared energy will be absorbed and transformed into an electrical signal that is then compared to a reference gas to determine the concentration of the analyzed CO_2. The pollution was measured in grams/kilometer (g/km) and was calculated to determine the fuel consumption rates and the speeds of the tested vehicles according to the defined driving patterns.

Table 1. Vehicles of the three types tested in the emission laboratory

In-use Vehicle types	Engine type	Odometer	Engines capacity (cubic centimeters, cc.)	Vehicle types with CNG fuel used
HDDV	Diesel	442,257	12,000	Buses and Trucks
LDDV	Diesel	40,850	3,000	Pick-ups and Vans
LDGV-1	Gasoline	44,765	1,600	Passenger cars
LDGV-2	Gasoline	44,790	1,600	Passenger cars
LDGV-3	Gasoline	61,337	1,600	Passenger cars
LDGV-4	Gasoline	61,361	1,600	Passenger cars
LDGV-5	Gasoline	72,178	1,600	Passenger cars
LDGV-6	Gasoline	103,906	1,600	Passenger cars
LDGV-7	Gasoline	103,930	1,600	Passenger cars
LDGV-8	Gasoline	125,399	1,600	Passenger cars
ldgv-9	Gasoline	125,422	1,600	Passenger cars

2.3. Emission Factor Calculation

The relationship in terms of the emission factor was determined from the relationship between the average concentration of CH_4 and CO_2 from the vehicles and the number of kilometers traveled by the vehicle (Angiola *et al*., 2009). The statistical significance for all vehicles was determined using Equation 1 and 2, respectively:

$$\text{EF CH}_4(\text{g/km}) = \frac{\text{Total CH}_4\,\text{Emission (g)}}{\text{VKT (km)}} \quad (1)$$

$$\text{EF CO}_2(\text{g/km}) = \frac{\text{Total CO}_2\,\text{Emission (g)}}{\text{VKT (km)}} \quad (2)$$

Where:

EF CH_4 = The emission factor of CH_4 in g/km
EF CO_2 = The emission factor of CO_2 in g/km
Total CH_4 = Emission is the average amount of CH_4 in grams
Total CO_2 = Emission is the average amount of CO_2 in grams
VKT = The average vehicle kilometers traveled in km

3. RESULTS AND DISCUSSION

3.1. Emission Factors of CH_4 and CO_2 from the Tests of the Three Vehicle Types

The EFs of CH_4 and CO_2 from all three vehicle types are given in g/km in **Table 2**. The average speeds are provided in m/sec and the CNG consumption rates are provided in km/L. The HDDV produced the highest EF, followed by LDGV and LDDV. The LDDV and LDGV had similar EF levels. Furthermore, according to the test results of each vehicle that used CNG, the EF-CH_4 and EF-$CO_2$of the different vehicles were different. The HDDV had the highest EF-CH_4 and EF-CO_2 at 7.22 and 919.6 g km^{-1}, respectively. The LDDV had the lowest EF-CH_4 at 0.17 g km^{-1} and LDGV-2 had the lowest EF-CO_2 at 153.8 g km^{-1}. The results of this test correspond with the results from the chassis dynamometer in the study by Nilrit and Sampanpanish (2012).

When considering only EF-CH_4, the HDDV had the highest EF, which was different from the EFs of both the LDGV and LDDV. The LDDV produced an EF-CH_4 that was similar to that of the LDGV. When considering only EF-CO_2, the HDDV had the highest EF, which differed from the EFs of both the LDDV and LDGV. The LDDV had an EF-CO_2similar to that of the LDGV. However, when considering the kilometers traveled and fuel consumption, testing the variance revealed that the latter two vehicle types had EF-CH_4 and EF-CO_2values that were not significantly different.

In addition, a test was conducted with one LDDV and 9 LDGVs, which had 3,000 cc. and 1,600 cc. engines, respectively. When considering the number of kilometers traveled (40,850-125,422 km), as determined using odometers, theEF-CH_4 and EF-CO_2values were similar. When considering the average speeds, which ranged from 29.8-34.3 km h^{-1}, the EF-CH_4 and EF-CO_2 values were not significantly different. With regard to fuel consumption, the EF-CH_4 of LDDV did not differ from the EF of LDGV. In contrast, the tests for the EF-CO_2 of both vehicle types revealed that the differences in the EF were significant ($p<0.05$). The fuel combustion in the different types of engine is shown in detail in **Table 2** and the results can be summarized as follows.

Table 2. Emission factors of CH4 and CO_2 with average speeds and fuel consumption for the three vehicle types compared with the emission factors of CH4 and CO_2 in each LDGV type

Vehicles types	Average speeds (km/hr)	Fuel consumption (km/L)	$EF_{average}$ of CH_4 g/km (g/km)	g/L (g/L)	$EF_{average}$ of CO_2 g/km (g/km)	g/km (g/L)	EF ratio of CH_4/CO_2
HDDV*	23.5	1.7	7.22	12.8	919.6	259.8	0.05
LDDV	34.3 ±3.75	9.1 ±0.62	0.17 ±0.42	0.11 ±0.13	169.8 ±4.87	3.21 ±0.88	0.03 ±0.10
LDGV-1	26.3 ±3.75	10.8 ±0.62	1.24 ±0.42	0.39 ±0.13	162.0 ±4.87	0.93 ±0.88	0.42 ±0.10
LDGV-2	33.4 ±3.75	11.4 ±0.62	0.93 ±0.42	0.27 ±0.13	153.8 ±4.87	0.88 ±0.88	0.31 ±0.10
LDGV-3	26.3 ±3.75	9.9 ±0.62	1.03 ±0.42	0.35 ±0.13	168.1 ±4.87	1.70 ±0.88	0.21 ±0.10
LDGV-4	33.4 ±3.75	10.4 ±0.62	0.42 ±0.42	0.14 ±0.13	164.2 ±4.87	0.63 ±0.88	0.22 ±0.10
LDGV-5	33.4 ±3.75	10.8 ±0.62	0.43 ±0.42	0.13 ±0.13	163.9 ±4.87	0.61 ±0.88	0.21 ±0.10
LDGV-6	26.3 ±3.75	10.1 ±0.62	1.14 ±0.42	0.02 ±0.13	162.2 ±4.87	0.10 ±0.88	0.2 ±0.10
LDGV-7	33.4 ±3.75	10.3 ±0.62	0.34 ±0.42	0.38 ±0.13	162.9 ±4.87	1.58 ±0.88	0.24 ±0.10
LDGV-8	26.3 ±3.75	10.2 ±0.62	1.30 ±0.42	0.11 ±0.13	171.0 ±4.87	0.67 ±0.88	0.16 ±0.10
LDGV-9	33.4 ±3.75	10.6 ±0.62	0.55 ±0.42	0.17 ±0.13	165.6 ±4.87	0.63 ±0.88	0.27 ±0.10

Remarks: *; The HDDV was not compared to standard deviation value because it was much higher than any of the other samples

Table 3. Trends of emission factors compared by NGV fuel type for CH_4 and CO_2

In-use vehicles by NGV Fuel Type	Greenhouse Gas Study of EF Average $EF-CH_4$ ($g-CH_4$/km)	Average $EF-CO_2$ ($kg-CO_2$/km)	US EPA (2008) Average $EF-CO_2$ ($kg-CO_2$/km)	EU (2009) Average $EF-CO_2$ ($kg-CO_2$/km)
HDDV	7.22	0.92	2.78	0.11
LDDV	0.17	0.17	0.83	0.27
LDGV	0.55	0.17	0.58	0.21

For the HDDV at a speed of 23.5 km h^{-1} and a fuel consumption of 1.7 km L^{-1}, the $EF-CH_4$ and $EF-CO_2$ were 7.22 and 919.6 g km^{-1}, respectively. These results correspond with those of Gatts *et al*. (2012) and Graham *et al*. (2008), who studied the emission of CH_4 and Carbon Monoxide (CO) from vehicles on a chassis dynamometer. Their studies found that the compressed natural gas combustion and CH_4 emissions of the HDDV were low but that CO was emitted at a larger proportion because of the incomplete combustion of the engines.

At a speed of 34.3 km h^{-1} and a fuel consumption of 9.1 km L^{-1}, the LDDV had $EF-CH_4$ and $EF-CO_2$ values of 0.17 and 169.8 g km^{-1}, respectively. Comparing these results with those of the LDGV showed that the $EF-CH_4$ of LDDV was lower than that of the LDGV, but the $EF-CO_2$ of the LDDV was higher than that of the LDGV. This result was due to the different types of engine. The air compressor system during the fuel combustion of a diesel engine causes a higher pressure and temperature than those of the combustion system of a gasoline engine, resulting in a higher conversion rate of combusted fuel to CO_2. These results correspond to those of Ceper *et al*. (2009) and Chiang *et al*. (2012), who performed the tests on a chassis dynamometer.

The tests on the LDGV utilizing the Bangkok Driving Cycle driving pattern used 2 average speeds, which were 26.3 and 33.4 km h^{-1}. When categorizing the samples according to the kilometers traveled, as determined by an odometer, LDGV-1, with an odometer value of 44,765 km and a fuel consumption of 10.8 km L^{-1}, produced average $EF-CH_4$ and $EF-CO_2$ values of 1.24 and 162 g km^{-1}, respectively. LDGV-2, with an odometer value of 44,790 km and a fuel consumption of 11.4 km L^{-1}, produced average $EF-CH_4$ and $EF-CO_2$ values of 0.93 and 153.8 g km^{-1}, respectively. The LDGV-3, with an odometer value of 61,337 km and a fuel consumption of 9.9 km L^{-1}, produced average $EF-CH_4$ and $EF-CO_2$ values of 1.03 and 168.1 g km^{-1}, respectively. LDGV-4, with an odometer value of 61,361 km and a fuel consumption of 10.4 km L^{-1}, produced average $EF-CH_4$ and $EF-CO_2$ values of 0.42 and 164.2 g km^{-1}, respectively. LDGV-5, with an odometer value of 72,178 km and a fuel consumption of 10.8 km L^{-1}, produced average $EF-CH_4$ and $EF-CO_2$ values of 0.43 and 163.9 g km^{-1}, respectively.

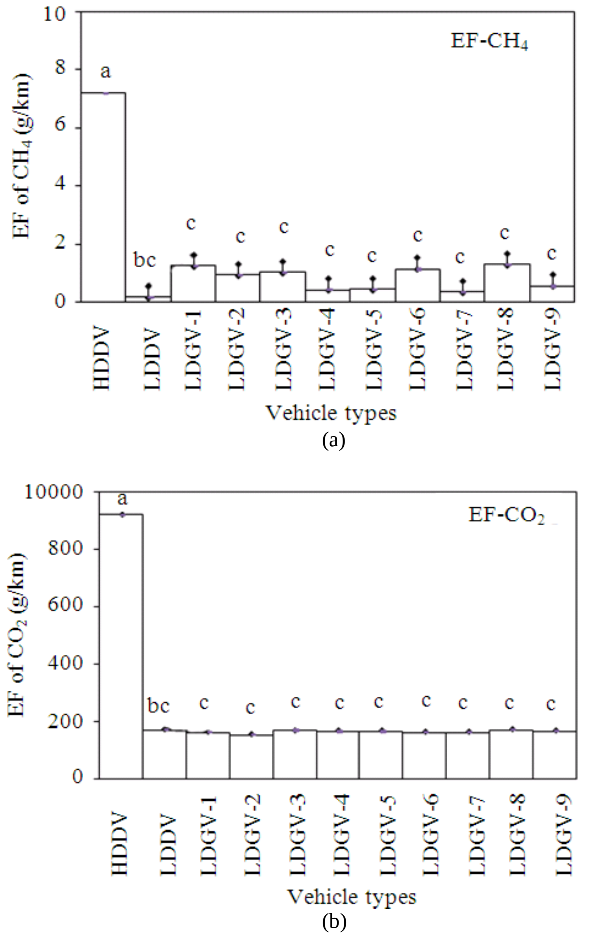

Fig. 1. Comparison of the average EF in g/km among the vehicle types EF-CH4 (a) and (b) EF-CO2

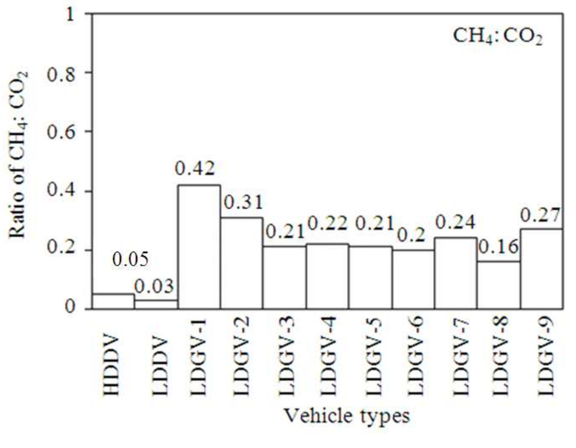

Fig. 2. Comparison of the CH_4: CO_2 ratio among the vehicle types

LDGV-6, with an odometer value of 103,906 km and a fuel consumption of 10.1 km L^{-1}, produced average EF-CH_4 and EF-CO_2 values of 1.14 and 162.2 g km^{-1}, respectively. LDGV-7, with an odometer value of 103,903 km and a fuel consumption of 10.3 km L^{-1}, produced average EF-CH_4 and EF-CO_2 values of 0.34 and 162.9 g km^{-1}, respectively. LDGV-8, with an odometer value of 125,339 km and a fuel consumption of 10.2 km L^{-1}, produced average EF-CH_4 and EF-CO_2values of 1.30 and 171.0 g km^{-1}, respectively. LDGV-9, with an odometer value of 125,422 km and a fuel consumption of 10.6 km L^{-1}, produced average EF-CH_4 and EF-CO_2 values of 0.55 and 165.6 g km^{-1}, respectively. The EF-CH_4 values from these tests correspond to those from the tests of Heeb *et al*. (2003); Weilemann *et al*. (2005) and Choi and Frey (2009), whereas the EF-CO_2values from these tests corresponded to those from the tests of Porpatham *et al*. (2008).

3.2. Emission Factor of CH_4 and CO_2 Compared with the Odometer Values, Average Speeds and CNG Fuel Consumption

The findings of this study comparing the EF-CH_4 and EF-CO_2 with the odometer value and CNG fuel consumption are detailed as follows.

The HDDV, compared with the LDDV and LDGV, had higher average EF-CH_4 and EF-CO_2 values than those of the other vehicle types because its engine was larger and its odometer value was higher. Additionally, its driving speed was lower and its fuel consumption was higher.

The LDDV had average EF-CH_4 and EF-CO_2 values of 0.17 and 169.8 g km^{-1}, respectively. These values are similar to those of the LDGV, which had average EF-CH_4 and EF-CO_2 values ranging from 0.34-1.24 and 153.8-168.1 g km^{-1}, respectively. Categorized by odometer, the comparison of the sample group of LDDV, LDGV-1 and LDGV-2 (with odometer values of 40,850, 44,765 and 44,790 km, respectively), the sample group of LDGV-3 and LDGV-4 (with odometer values of 61,337 and 61,361 km, respectively) and the sample group of LDGV-5 (with an odometer value of 72,178 km) revealed that the EF-CH_4 and EF-CO_2 values were not different from those of the LDGV-3 and LDGV-4 sample group but were significantly different ($p<0.05$) from those of the LDDV, LDGV-1 and LDGV-2 sample group. The sample group of LDGV-6, LDGV-7, LDGV-8 and LDGV-9, with odometer values of 103,906, 103,930, 125,339 and 125,422 km, respectively, had EF-CH_4 and EF-CO_2 values that were not different from each other but were significantly different from those of the other odometer groups ($p<0.05$), as shown in **Fig. 1**.

The HDDV had average EF-CH_4 and EF-CO_2 values of 12.8 and 259.8 g L^{-1}, respectively. These values were higher than those of the LDDV, which had average EF-CH_4 and EF-CO_2 values of 0.11 and 3.21 g L^{-1}, respectively. The former were also higher than those of the LDGV, which had average EF-CH_4 and EF-CO_2 values ranging from 0.11-0.39 and 0.10-1.58 g L^{-1}, respectively.

In terms of the ratio of EF-CH_4 to EF-CO_2in all 3 vehicle types, the LDGV produced the highest value, ranging from 0.20-0.42 with an average of 0.27, which was higher than the values of HDDV and LDDV, which were 0.05 and 0.03, respectively. The results of this experiment demonstrated that the LDGV emitted CH_4 and CO_2 at higher proportions than did the other vehicle types. The details are shown in **Fig. 2**.

In terms of the relationship between average speed and the EF-CH_4 and EF-CO_2 values in all 3 vehicle types, that the average speed for the HDDV differed from those of the LDDV and LDGV. The average speed of the LDDV was also different from that of the LDGV. Although the HDDV had the lowest average speed, its EF-CH_4 and EF-CO_2 values were the highest due to its larger engine.

In terms of the fuel consumption, the EF-CH_4 and EF-CO_2 values of the HDDV, LDDV and LDGV were different. With respect to EF-CH_4, the LDDV produced the lowest value compared with that of the HDDV and LDGV. The reason for this difference is that based on the size and type of the engines. The engines in the LDDV and HDDV are classified as diesel engines in which air is compressed in the pistons before combustion at a high pressure and temperature. This allows CH_4 to be combusted and converted to CO_2 at a higher rate than can be achieved in the similarly sized gasoline engine of a LDGV. The HDDV produced high EF-CH_4 and EF-CO_2values due to its larger and heavier engine.

3.3. Emission Factors of CH_4 and CO_2 Compared with International Data

The emission factors of CH_4 and CO_2 (expressed in g/km) of all 3 vehicle types used in Thailand that were used in this experiment were compared with the factors determined by international agencies. The EF-CH_4 values for vehicles using compressed natural gas were not compared in kilometers (CH_4/km) because the quantity was small and this type of study was not prevalent in Thailand. For EF-CO_2 in kilometers-CO_2/km, according to the study, it is found that the EF-CO_2values corresponded to the emission factors of the European Union (DEFRA, 2012) but were lower than those of the guideline of emission factor from the United State of America Transportation (USEPA, 2008), which is shown in **Table 3**.

4. CONCLUSION

The EF-CH_4 and EF-CO_2 of the HDDV were higher than those of the other vehicles. The EF-CH_4 of the LDDV and LDGV were different due to the different types of engine, whereas the EF-CO_2 of both vehicle types were comparable, which affected the emission of the greenhouse gases. The study of these EF-CH_4 and EF-CO_2 values of different vehicle types in the emission laboratory found that the average emission factors from this study were the actual values derived from the tests of vehicles actually used in Thailand. These factors differed according to the vehicle type. The results from this study can be used to evaluate greenhouse gas emissions by any method that requires emission factor values, especially in terms of the CH_4 and CO_2 emitted from vehicles.

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