Journal of Sustainable Energy & Environment
12 (2021) 115-125

# Relationships between road transport emissions and particulate matter ambient concentrations in the Bangkok Metropolitan Region during 2007-2018

Pattarapoom Phuengyaem, Agapol Junpen and Savitri Garivait*

The Joint Graduate School of Energy and Environment (JGSEE), Centre of Excellence on Energy Technology and Environment (CEE), King Mongkut's University of Technology Thonburi, 126 Prachauthit Rd, Bangmod, Tungkru, Bangkok, 10140, Thailand
*Corresponding author: Tel: +66 2 470 8309-10 # 4134; Fax: +66 2 872 9805
E-mail: savitri.gar@kmutt.ac.th; savitrigarivait@yahoo.com; savitri.jgsee@gmail.com

**Abstract:** Bangkok Metropolitan Region (BMR), one of the top world's most congested megacities, has been facing air quality problems due to incidences of particulate matter especially during the dry seasons during the past few years. To evaluate the contribution of road transport emissions on air quality in BMR, this study investigated the relationships between PM10 and PM2.5 emissions from road transport and their ambient concentrations during 2007-2018 by the linear regression model. The emissions and ambient concentrations analysis to prepare inputs for investigating their correlations showed an emission reduction of 7.96 kt equivalent to 75% from 2007 to 2018 for PM10, and 3.87 kt or about 43% for PM2.5, respectively. For the ambient air concentrations, there was a decrease of 18 $\mu g/m^3$ (31%) for PM10 and 10 $\mu g/m^3$ (28%) for PM2.5, respectively. For both PM10 and PM2.5, the correlation between emissions and ambient concentrations was significant for the overall fleet exhaust emission, and especially from diesel vehicles, while an insignificant linear relationship was observed for the case of emissions from gasoline vehicles. Using the resulting linear regression model coefficients, it was estimated that an emission reduction of 1 kt of PM10 will contribute to an approximate decrease of 1.31 $\mu g/m^3$ of ambient PM10, and 1.26 $\mu g/m^3$ in the case of PM2.5, respectively. Results from this study suggest reducing the timeframe of emission estimation from road transport, from annually to monthly or daily basis in order to improve the accuracy and precision of the emission-to-ambient concentration conversion factors.

**Keywords:** PM10, PM2.5, Road transport, Air quality, Bangkok Metropolitan Region (BMR).

## 1. Introduction

Air quality is becoming a global challenge, especially in high-density urban areas. In the 2019 Global Burden of Disease study [1], air pollution was ranked as the fourth largest risk factor for premature mortality. Also, it was found that one of the most significant increases in risk exposures was ambient particulate matter (PM) pollution. The study showed that exposures increased globally by 1.46% per year over the past decade, and large annual increases, nearly 3.8-4.0% in low- and middle-income countries.

According to the Air Quality Life Index Report-2020 [2], Thailand is one of the most polluted countries in Southeast Asia and ranked among the Top 10 most polluted countries worldwide. The annual average of particulate matter with a diameter lesser than 2.5-micron (PM2.5) reached 23.8 $\mu g/m^3$ in 2020, corresponding to about 5 times higher than the World Health Organization (WHO) air quality guideline level of 5 $\mu g/m^3$, and hence could contribute to shortening the average Thai resident's life expectancy by 1.8 years relative to what it would be if the WHO guideline were met. In addition, it was found that overall air pollution in Thailand has increased by about 23% since 2000 and that the health burden of air pollution was the highest in Bangkok, Nakhon Ratchasima, and Chiang Mai. This results in an estimate of the year of life loss (YLL) of 4.1 to 13.9 million total life years, and the average gain in life expectancy from clean air ranging from 1.5 to 2.4 years.

Regarding Bangkok and the five adjacent provinces that form the BMR, i.e. Nakhon Pathom, Pathum Thani, Nonthaburi, Samut Prakan, and Samut Sakhon, Thailand's Annual Report of the Environment indicates that air quality in BMR has been beyond the standard especially due to an incidence of particulate matter, and that road transport constitutes one of the major sources of air pollutants in this region [3]. Also, road transport activities are well recognized to be dense with high exhaust emissions, as reported by the INRIX Global Traffic Scorecard showing that Thailand was the top world's most congested country, and Bangkok was the twelfth city in the world with high traffic congestion in 2017 [4]. Air pollutants emissions from road transport are acknowledged to significantly contribute to the smog haze formation with high ambient particulates and ozone concentrations, especially in megacities [5-10]. Major air pollutants emissions from road traffic include nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbon (HC), particulate matter (PM), and others [11-12]. Road transport has significantly contributed to the emission of atmospheric pollutants in Bangkok, with consequent problems for the environment and human health [13-14]. Exposure to air pollutants is a concern in urban areas because of the high population density exposed to air pollution and the high number of emission sources with suspected harmful effects on human health [15].

This study aims to investigate the relationship between emissions from road transport and ambient particulate matter (PM10 and PM2.5) concentrations during 2007-2018, to evaluate the contribution of this emission source to air quality in BMR. Emissions and air quality monitoring used for the investigation are first described and analyzed. Correlations between emissions and ambient PM2.5 or PM10 are discussed and commented on. The results from this study are expected to contribute to/support the development of policy recommendations for the attainment of air quality in BMR by reducing air pollutants emissions from road transport, which would also help the BMR to go towards the national targets on carbon neutrality by 2050 and net zero emission by 2065.

## 2. Methodology

### 2.1 Road transport emission estimation data

The emission estimation method and data used in this study were from the research work developed by Cheewaphongphan et al. [16] in 2017. On-road vehicles were classified into four types, motorcycles (MC); light-duty vehicles (LDV) which include light-duty cars (LDC) and light-duty trucks (LDT); and heavy-duty vehicles (HDV) which involve heavy-duty bus (HDB) and heavy-duty truck (HDT). They were also specified by fuel types including gasoline (GSL) and middle distillates (MD), more commonly named diesel.

### 2.2 Air particulate matter monitoring data

The ambient particulate matter (PM10 and PM2.5) concentrations data during the period of 2007-2018 were collected from 21 air quality monitoring stations located in BMR and operated by the Pollution Control Department (PCD). There are 7 ambient air monitoring stations in Bangkok and 10 in the adjacent provinces within BMR. In addition, 4 roadside stations were set up in Bangkok. Detailed ID and name of these stations are reported in Table 1. The spatial distribution of air quality monitoring stations in BMR is mapped in Figure 1. The measurement methods used at each air quality monitoring station are summarized in Table 2.

**Table 1.** Name and ID of air quality monitoring stations in BMR.

| Province | Type | ID | Name |
|---|---|---|---|
| Bangkok | Ambient station | 02T | Bansomdejchaopraya Rajabhata |
| | | 05T | Thailand Meteorological Department |
| | | 10T | Klongjun NHA |
| | | 11T | Huaykwang NHA Stadium |
| | | 12T | Nonsi wittaya school |
| | | 59T | Public Relations Department |
| | | 61T | Badindecha School |
| | Roadside station | 50T | Chulalongkorn Hospital |
| | | 52T | Thonburi Power Substation |
| | | 53T | Chokchai 4 Police Station |
| | | 54T | Dindang NHA |
| Samut Prakan | Ambient station | 08T | Prapradang Rehabilitation for the Disabled |
| | | 16T | South Bangkok Thermal Power Plants |
| | | 17T | Residence for Department of Primary Industries and Mines |
| | | 18T | Samut Prakan City Hall |
| | | 19T | Bangplee NHA |
| Pathum Thani | | 20T | Bangkok University |
| Samut Sakhon | | 14T | Samut sakhon Highway District |
| | | 27T | Samut sakhon Wittayalai School |
| Nonthaburi | | 13T | Electricity Generating Authority of Thailand |
| | | 22T | Sukhothai Thammathirat University |

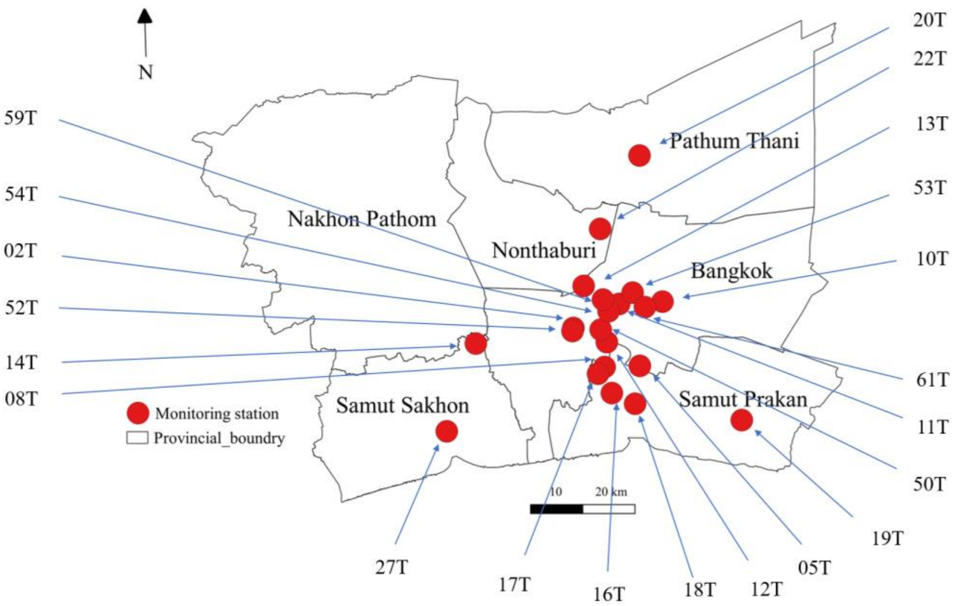


**Figure 1.** Spatial distribution of air quality monitoring stations in BMR.

**Table 2.** Measurement methods used at air quality monitoring stations in BMR

| Air quality | Methodology | Height | Detection Range |
|---|---|---|---|
| PM2.5, PM10 | Beta-ray method | 3 m | 0–1000 $\mu g/m^3$ |
| CO | Non-Dispersive Infrared Detection | 3 m | 0–50 ppm |
| $SO_2$ | UV-Fluorescence | 3 m | 0–500 ppb |
| NO, $NO_2$, $NO_X$ | Chemiluminescence | 3 m | 0–500 ppb |
| Relative Humidity | Thin Film Polymer Capacitor | 3 m | 0–100 %RH |
| Temperature | Multistage solid state thermistor, highly linearized | 3 m | (-50)–50 ℃ |
| Wind Direction | Wind Vane | 10 m | 0–360 deg |
| Wind Speed | Cup propeller | 10 m | 0–50 m/s |
| Rain | Tipping Bucket | 3 m | mm/h |

**2.3 Analysis of the relationship between total PM emission from road transport and PM ambient concentrations in BMR during 2007-2018**

In this study, we applied the linear regression method to investigate the relationship of particulate matter emission from road transport with the ambient particulate matter concentration. The linear regression model used is formulated by Equation 1.

$$Y = \alpha_1(X) + \alpha_0 \tag{1}$$

Where,

$Y = PM\ Ambient\ comcentration$

$X = PM\ emission\ from\ on - road\ transport$

$\alpha_0 = Y - Intercept$

$\alpha_1 = slope\ of\ regression\ line$

The degree of association between the road transport emissions and ambient concentrations of particulate matter, namely correlation coefficient and denoted R was also calculated. The coefficient of correlation R varies between -1 and +1, and the closer to 1 is the $R^2$ value, the stronger is the correlation.

## 3. Results and Discussions

**3.1 Emissions of $PM_{10}$ and $PM_{2.5}$ from road transport in 2007-2018**

The PM10 and PM2.5 emissions from road transport in 2007-2018 are reported in Figures 2 and 3, respectively. From these Figures, the heavy-duty trucks fueled with diesel (HDT-MD) were the top emitter of both PM10 and PM2.5, followed by light-duty trucks fueled with diesel (LDT-MD), heavy-duty buses fueled with diesel (HDB-MD), and light-duty cars fueled with diesel (LDC-MD). The road transport emissions of PM10 and PM2.5 showed an observable decreasing trend during 2007-2018, from about 10.5 kt in 2007 to 2.5 kt in 2018 for PM10, and from about 10.5 kt in 2007 to 5.5 kt in 2018 for PM2.5, respectively. The observed significant drops could be associated with the changes in the vehicle exhaust emission standards in application in Thailand shown in Table 3. Moreover, the particulate matter emissions showed a substantial diminution with the implementation of the sulfur content in fuel reduction measures. Indeed, a noteworthy decrease was observed after 2012 when the sulfur content passed from 350 ppm to 50 ppm with the putting into force of the Euro 4 for light-duty vehicles.

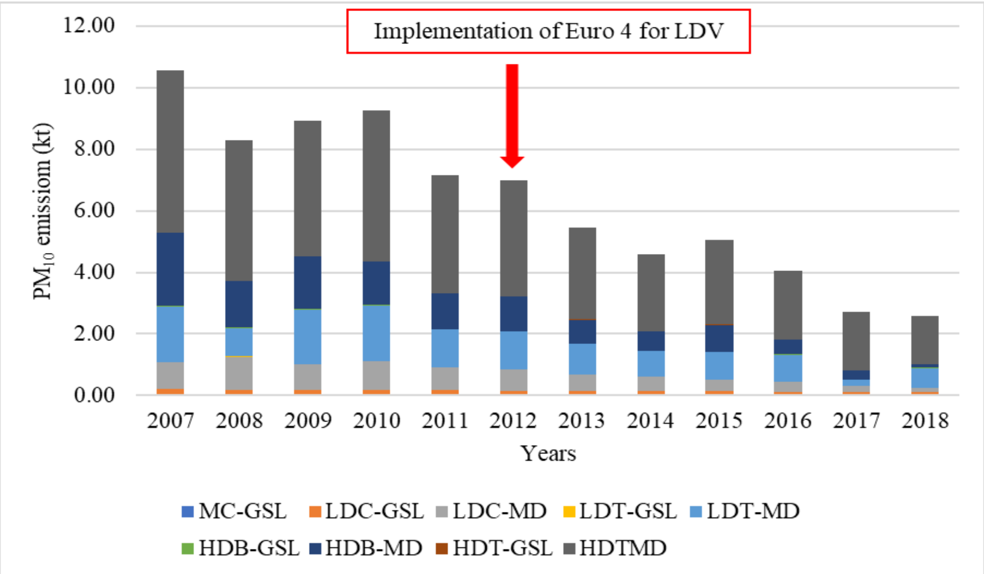


**Figure 2.** $PM_{10}$ emission from road transport in BMR in 2007-2018.

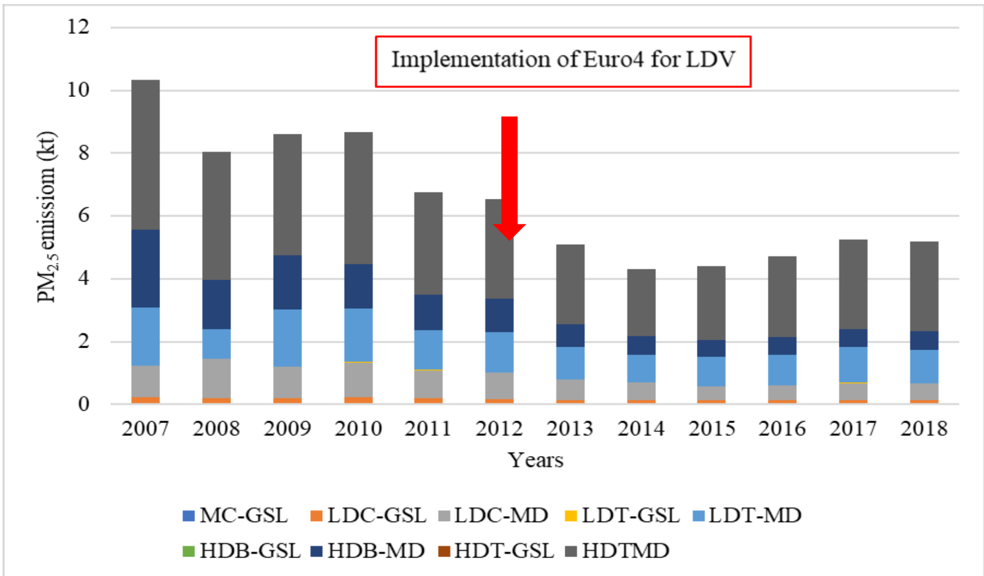


**Figure 3.** $PM_{2.5}$ emissions from road transport in BMR in 2007-2018.

 

**Table 3.** Thailand's vehicle exhaust emission standards

| Vehicle type | Reference Standard (Euro Standard) Enforcement | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Before 1995 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 - Present |
| LDC | Pre-Euro | | | Euro I | | | Euro II | | | | | Euro III | | | | | | | Euro IV | | | |
| HDV | Pre-Euro | | | | Euro I | Euro II | | | | | | | | Euro III | | | | | | | | |
| MC | ECE 40-00 | ECE 40-01 | $CO \leq 13$ g/km $HC \leq 5$ g/km | | | $CO \leq 4.5$ g/km $HC+NOx \leq 3$ g/km White Smoke $\leq$ 30% Evaporative $\leq 2$ g/test (for < 110cc.) | | | | | $CO \leq 3.5$ gm/km $HC+NOx \leq 2$ g/km White Smoke $\leq$ 15% Evaporative $\leq 2$ g/test (for $\geq$ 150cc.) | | | | | Euro III | | | | | | |

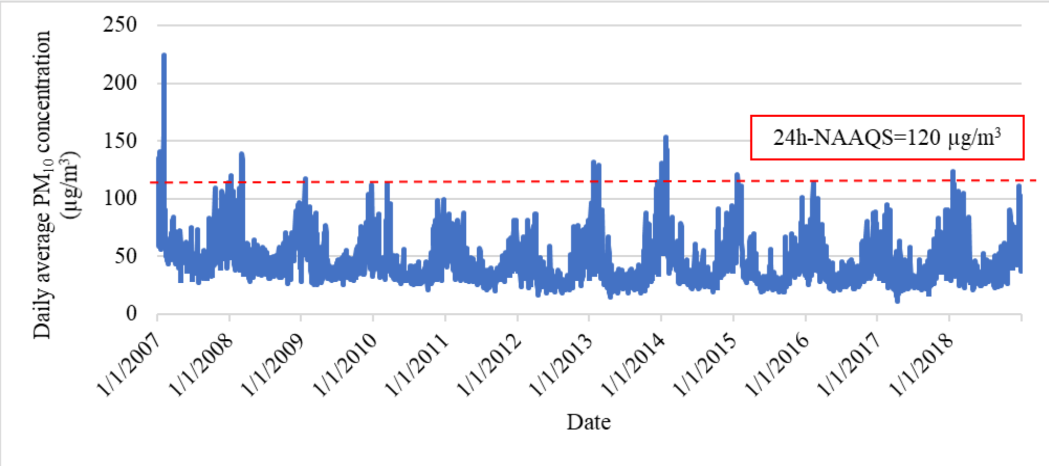


**Figure 4.** Daily average ambient $PM_{10}$ concentrations in BMR in 2007-2018.

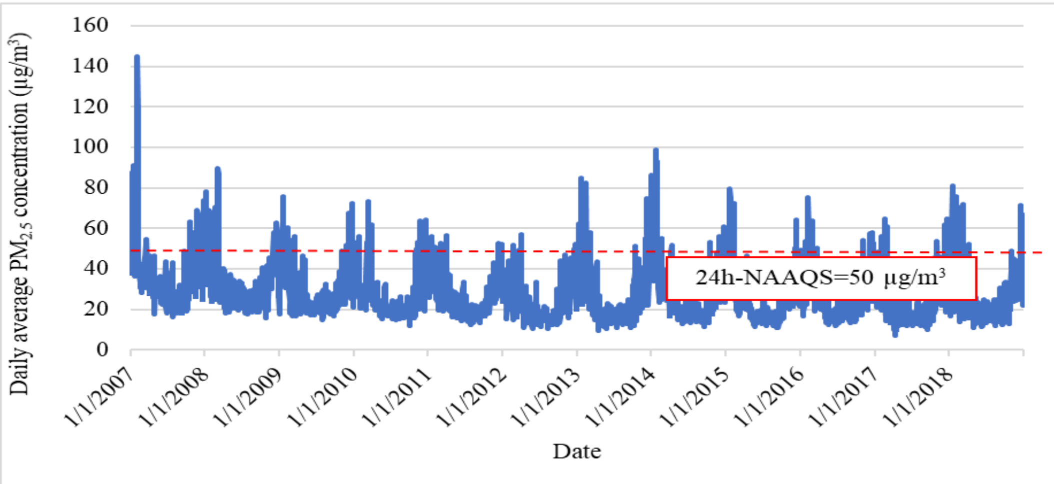


**Figure 5.** Daily average ambient $PM_{2.5}$ concentrations in 2007-2018.

### 3.2 Ambient particulate matter concentrations in BMR in 2007-2018

The particulate matter 24h-average concentrations variation from 2007-2018 is shown in Figures 4 and 5. Similar time-series profiles were observed for PM10 (Figure 4) and PM2.5 (Figure 5). The high concentrations were found during the dry season (November to April) with the peak period in January to March, while low values were detected during the rainy season (May to October). Table 4 compares the Thai national ambient air quality standards (NAAQS) with the WHO air quality guideline (AQG) level. The comparison indicates that the NAAQS values are significantly higher than WHO-AQG levels, and the air quality complying with NAAQS still presents some health risks for the exposed population. From Figures 4 and 5, the daily average of ambient PM2.5 concentrations showed exceedances compared to the 24h-national ambient air quality standards (NAAQS) during the peak periods for all years during 2007-2018, while PM10 exceeded the standard values in some years only. In addition, slight exceeding values were observed for PM10, and significant differences compared to the national standards for PM2.5 were found.

Figures 6 and 7 show the boxplots of the annual averages of PM10 and PM2.5 concentrations in 2007-2018, respectively. As for the daily averages, slight exceeding values compared to the national ambient air quality standards were observed in some years for PM10, while large exceedances were detected for PM2.5.

We also investigated the ambient particulate matter spatial variation to identify the areas where exposure may induce more severe health impacts. Maps of ambient PM10 and PM2.5 annual average concentration in 2007-2018 are displayed in Figures 8 and 9, respectively. For PM10, high concentrations were at the air quality monitoring stations in Bangkok's central and southern areas. The number of stations without exceedance increased from 2007 to 2018 in Bangkok and adjacent provinces included in BMR. This result showed air quality improvements in BMR in terms of PM10.

Regarding PM2.5, it should be noted that their monitoring started only in 2011, and therefore, we had to estimate their daily average concentrations for all the air quality monitoring stations whenever no measurement data were available, using PM10 air quality monitoring data and the PM2.5/PM10 ratio obtained by Pengjan et al. [17]. Comparing Figures 8 and 9, it was found that high PM2.5 concentrations were observed in the same areas as those of PM10. However, there were more stations with exceedances than those that complied with the national standards, and large exceedances were found in Bangkok in 2007, 2014, and 2016. For other provinces in BMR, only one exceedance in Samut Sakhon was observed for PM10, while several ones of annual average PM2.5 concentrations were detected in Pathum Thani, Samut Sakhon and Samut Prakarn, over the period of 2007-2018.

**Table 4.** Comparison of the Thai national ambient air quality standards and WHO air quality guideline level for PM10 and PM2.5.

| | AQ Annual Standard (μg/m$^3$) | | 24-hr. Standard (μg/m$^3$) | |
|---|---|---|---|---|
| | PM10 | PM2.5 | PM10 | PM2.5 |
| WHO Air Quality Guideline (AQG) Level | 15 | 5 | 45 | 15 |
| Thailand (TH) National Ambient Air Quality Standards (NAAQS) | 50 | 25 | 120 | 50 |

Note: The Thai NAAQS for PM2.5 officially entered into application in 2010

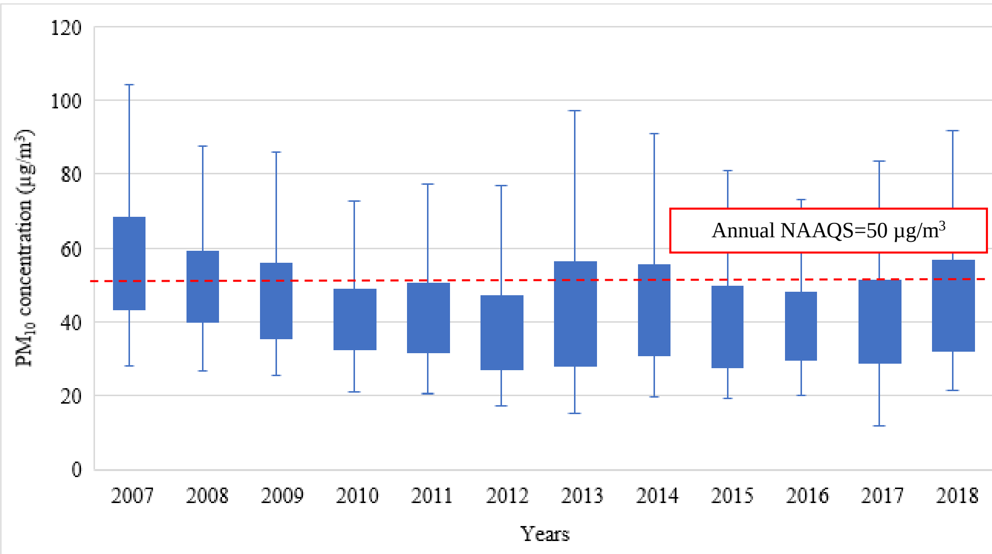


**Figure 6.** Boxplots of the annual average of ambient PM10 concentrations in BMR during 2007-2018.

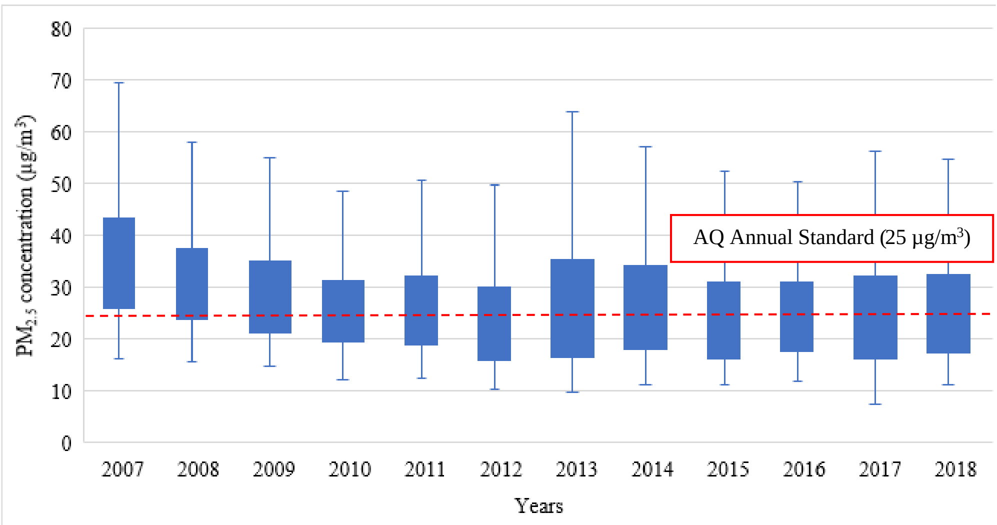


**Figure 7.** Boxplots of the annual average of ambient PM2.5 concentrations in BMR during 2007-2018.

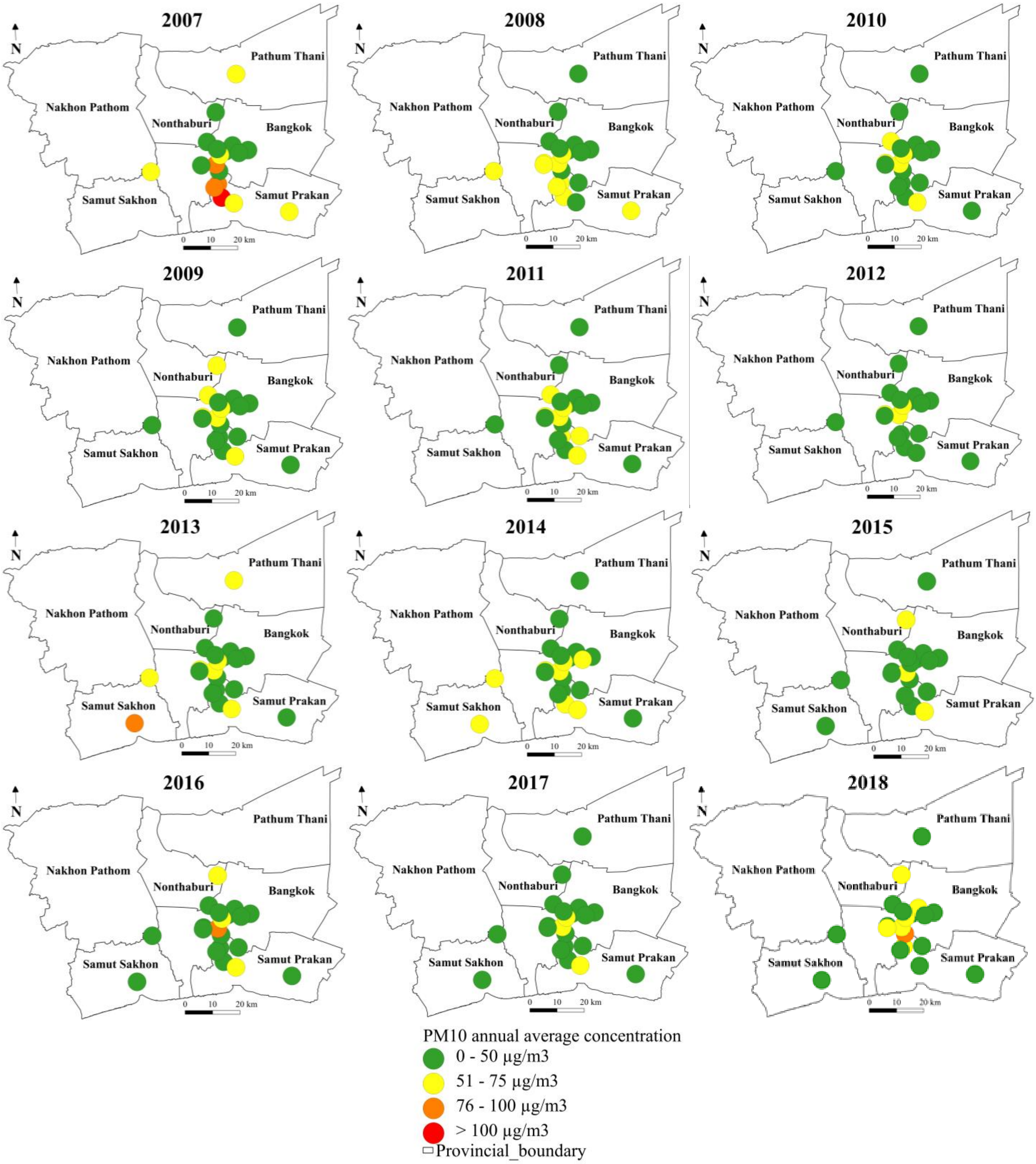


**Figure 8.** Map of $PM_{10}$ annual average concentration in BMR during 2007-2018.

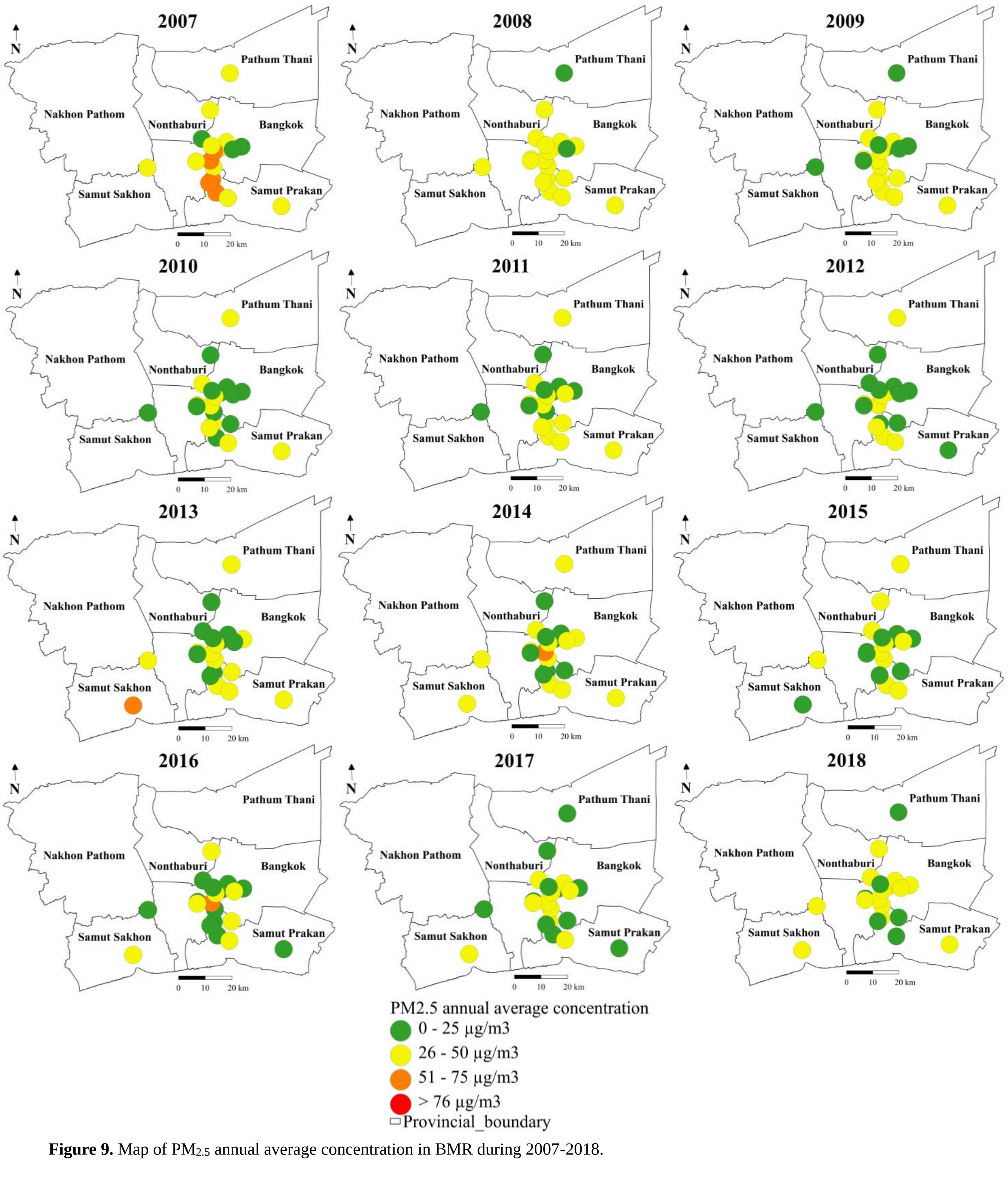


**Figure 9.** Map of $PM_{2.5}$ annual average concentration in BMR during 2007-2018.

**3.3 Relationships between total PM emission from road transport and ambient PM concentrations in BMR during 2007-2018**

The detailed analysis of the air quality monitoring data revealed that a linear correlation exists only for ambient air particulate matter and total particles emitted from vehicles fueled with diesel, and it was found a stronger correlation between ambient concentrations monitored at roadside stations than ambient air stations. The investigation results of the relationships between total PM10 emissions from road transport vehicles fueled with diesel and ambient PM10 concentrations in BMR during 2007-2018 are displayed in Figures 10-12. Based on the correlation coefficient values ($R^2$), the strongest relationship was observed for emission from heavy-duty vehicles ($R^2$=0.31), followed by all type vehicles ($R^2$=0.27), and light-duty vehicles ($R^2$=0.18), respectively. For PM2.5, the obtained results are reported in Figures 13-15, and show a stronger correlation between PM2.5 emissions and ambient concentrations comparatively to the case of PM10. Again the correlation found for PM2.5 emitted from heavy-duty vehicles fueled with diesel ($R^2$=0.54) revealed to be the strongest, followed by all type vehicles ($R^2$=0.46), and light-duty vehicles ($R^2$=0.26), respectively.

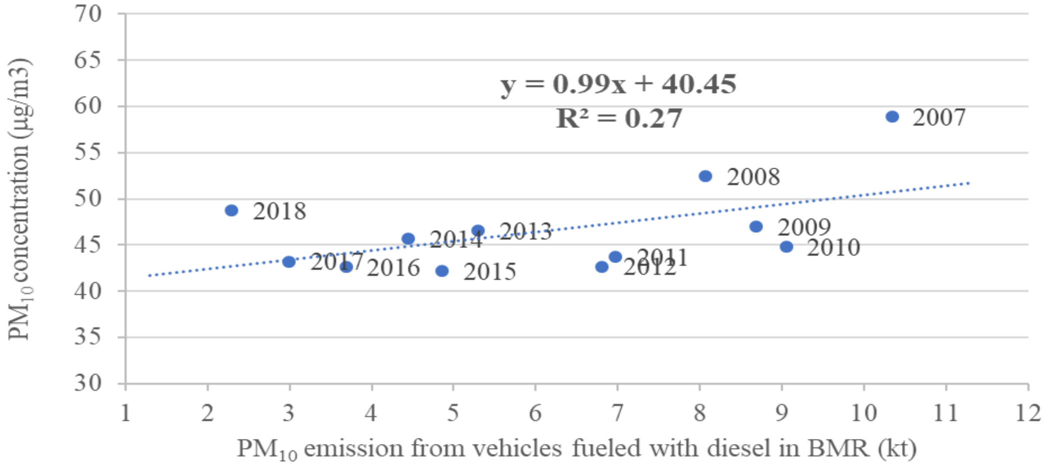


**Figure 10.** Relationship between PM10 emissions from all type vehicles fueled with diesel and ambient PM10 concentration in BMR during 2007-2018.

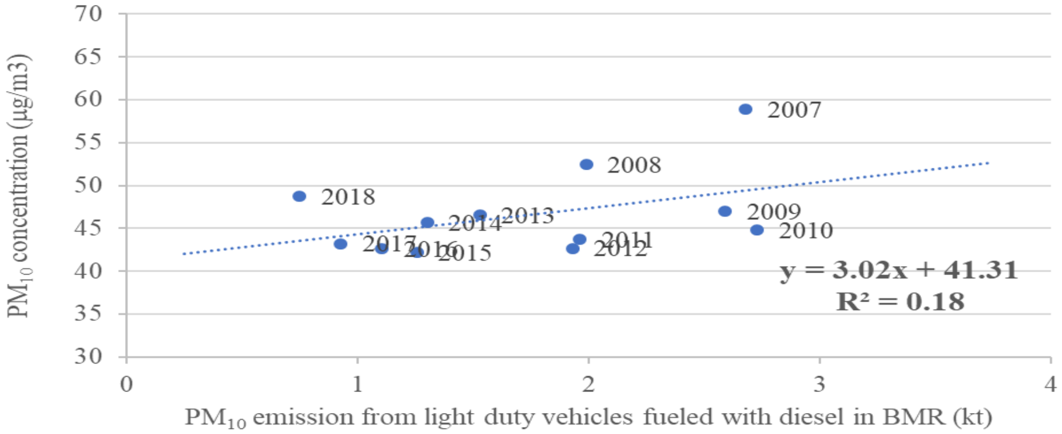


**Figure 11.** Relationship between PM10 emissions from light-duty vehicles fueled with diesel and ambient PM10 concentration in BMR during 2007-2018.

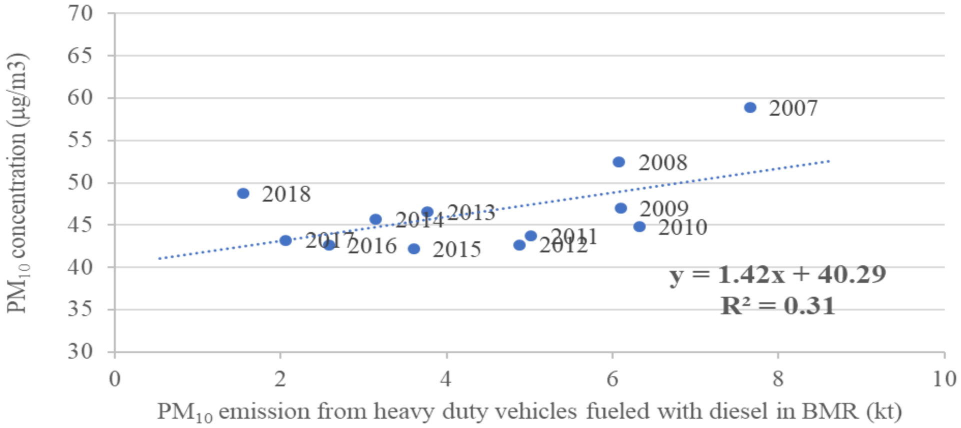


**Figure 12.** Relationship between PM10 emissions from heavy-duty vehicles fueled with diesel and ambient PM10 concentration in BMR during 2007-2018.

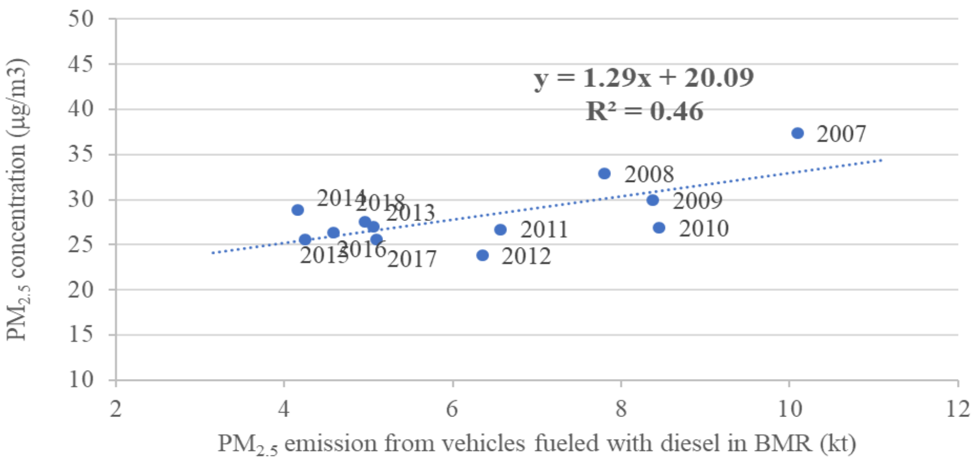


**Figure 13.** Relationship between PM2.5 emissions from all type vehicles fueled with diesel and ambient PM2.5 concentrations in BMR during 2007-2018.

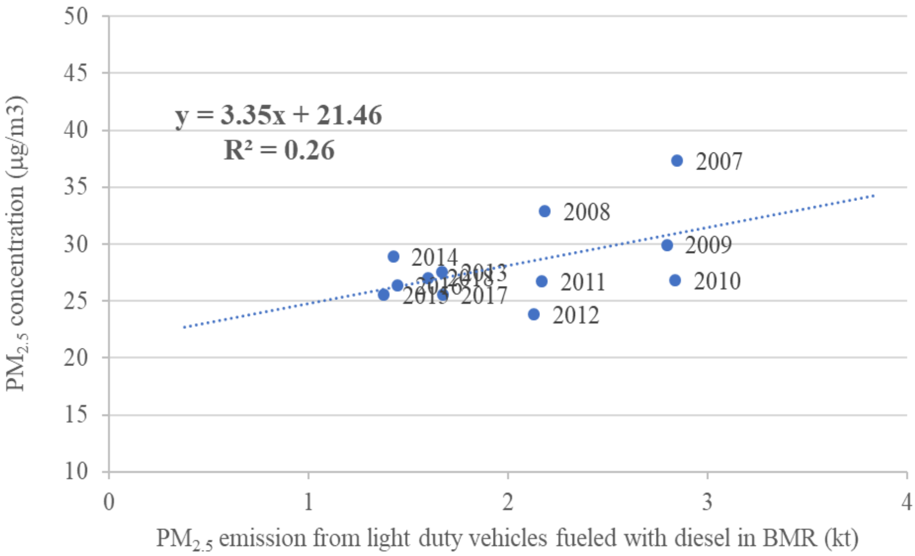


**Figure 14.** Relationship between PM2.5 emissions from light-duty vehicles fueled with diesel and ambient PM2.5 concentrations in BMR during 2007-2018.

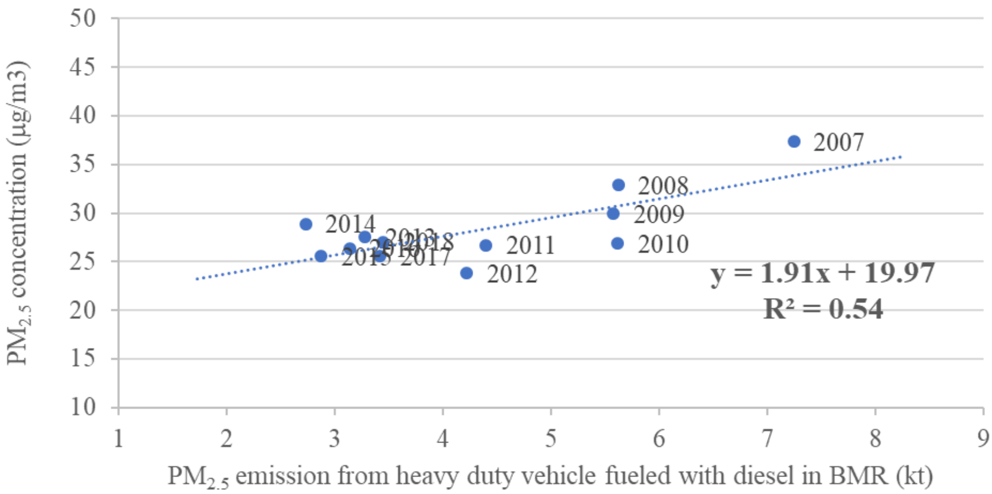


**Figure 15.** Relationship between PM2.5 emissions from heavy-duty vehicles fueled with diesel and ambient PM2.5 concentrations in BMR during 2007-2018.

**Table 5.** Summary of the resulted linear regression models to convert particulate emission from road transport vehicles into ambient particulate matter concentrations in BMR during 2007-2018.

| PM type | Air quality monitoring station type | Emission range (kt) | Concentration range $(\mu g/m^3)$ | Intercept $(\alpha_0)$ | Slope $(\alpha_1)$ | Correlation coefficient $(R^2)$ |
|---|---|---|---|---|---|---|
| $PM_{10}$ | All station | 3 - 11 | 40 - 60 | 37.91 | 1.31 | 0.39 |
| | Ambient stations | 3 - 11 | 35 - 60 | 35.94 | 1.23 | 0.27 |
| | Roadside stations | 3 - 11 | 40 - 65 | 44.96 | 1.49 | 0.39 |
| $PM_{2.5}$ | All station | 4 - 11 | 20 - 40 | 19.98 | 1.26 | 0.46 |
| | Ambient stations | 4 - 11 | 20 - 40 | 20.22 | 1.05 | 0.36 |
| | Roadside stations | 4 - 11 | 20 - 45 | 20.46 | 1.86 | 0.47 |

From the obtained results, it was found that heavy-duty vehicles constitute one of the main contributor to ambient air particulate matter in BMR, especially PM2.5. This can be partly explained by the fact that the exhaust emission standard was revised only for light-duty vehicles, passing from the Euro 3 to Euro 4 standard in 2011. Nevertheless, the upgrade fuel quality, from 350 ppm to 50 ppm sulfur content, to meet the requirements of Euro 4 standard vehicles enabled to reduce the particulate exhaust emissions from heavy-duty vehicles and, consequently, ambient air particulate matter concentrations, for both PM10 and PM2.5. To mitigate air pollution by PM2.5 to BMR, it is therefore recommended to upgrade the exhaust emission standard for heavy-duty at the same time as that for light-duty vehicles.

The resulted linear regression models to convert particulate emission from road transport vehicles into ambient particulate matter concentrations in BMR during 2007-2018, for both PM10 and PM2.5 classified by type of air quality monitoring station, are summarized in Table 5. Based on the models obtained for all stations, it was found that an emission reduction of 1 kt of PM10 will approximately contribute to a decrease of 1.31 $\mu g/m^3$of ambient PM10, and 1.26 $\mu g/m^3$ in the case of PM2.5, respectively. The linear regression models, obtained in this study, enable to approximate ambient particulate matter concentrations from the total exhaust emission from vehicles, and may therefore be used to evaluate the emission reduction from road transport measures effectiveness in terms of air quality improvement and to prioritize actions to implement.

## 4. Conclusion

This study investigated the relationships between PM10 and PM2.5 emissions from road transport and their ambient concentrations in BMR during 2007-2018 by the linear regression model. The emissions and ambient concentrations analysis to prepare inputs for investigating their correlations showed an emission reduction of 7.96 kt equivalent to 75% from 2007 to 2018 for PM10, and 3.87 kt or about 43% for PM2.5, respectively. For the ambient air concentrations, there was a decrease of 18 µg/m3 (31%) for PM10 and 10 µg/m3 (28%) for PM2.5, respectively.

For both PM10 and PM2.5, the correlation between emissions and ambient concentrations was significant for the overall fleet exhaust emission, and especially from diesel vehicles, while an insignificant linear relationship was observed for the case of emissions from gasoline vehicles. Based on the linear regression models obtained using the annual overall emissions from road transport and ambient concentrations integrated from all air quality monitoring stations in BMR for the period of 2007-2018, it was found an emission reduction of 1 kt of PM10 will contribute to an approximate decrease of 1.31 $\mu g/m^3$ of ambient PM10, and 1.26 $\mu g/m^3$ in the case of PM2.5, respectively. These emission-ambient concentration conversion factors obtained in this study may be used to evaluate how effective the emission reduction from road transport is on air quality improvement in terms of PM10 and PM2.5 concentrations.

To improve the accuracy and precision of the factors for converting emissions into ambient concentrations, the results of this study suggest reducing the periodicity of emission estimation, by moving from the annual estimate to a daily or at least monthly estimate. emissions of PM10 and PM2.5 of road origin. transport vehicles to BMR.

## 5. Acknowledgement

The authors would like to express their gratitude to The Joint Graduate School of Energy and Environment (JGSEE), King Mongkut's University of Technology Thonburi (KMUTT), and The Center of Excellence on Energy Technology and Environment (CEE), PERDO, Ministry of Higher Education, Science, Research and Innovation (MHESI) for the financial support provided to perform this study. In addition, the authors would like to thank the Thai Pollution Control Department (PCD) for air quality monitoring data to support this study.

## References

[1] Murray, C.J.L., Aravkin, A.Y., Zheng, P., Abbafati, C., Abbas, K.M., Abbasi-Kangevari, M., et al. 2020. Global burden of 87 risk factors in 204 countries and territories, 1990-2019: A systematic analysis for the Global Burden of Disease Study 2019; *The Lancet*, 396, 1223-1249.

[2] Greenstone M. and Fan, C. 2020. *Air Quality Life Index – Annual Update*, July 2020. Available online: https://aqli.epic.uchicago.edu/report-archive/?report-id=22817.

[3] Pollution Control Department. 2016. *Annual Report of the Environment*. Available online: http://infofile.pcd.go.th/mgt/report2556.pdf?CFID=3083545&CFTOKEN=93093716.

[4] Cookson, G. 2018. *INRIX Global Traffic Scorecard*. INRIX Research, February 2018. Available online: https://www.missionline.it/wp-content/uploads/2018/02/INRIX_2017_Traffic_Scorecard_Final.pdf.

[5] Im, U. and Kanakidou, M. 2012. Impacts of East Mediterranean megacity emissions on air quality, *Atmospheric Chemistry and Physics*, 12, 6335-6355.

[6] Ahanchian, M. and Biona, J.B.M. 2014. Energy demand, emissions forecasts and mitigation strategies modeled over

a medium-range horizon: The case of the land transportation sector in Metro Manila, *Energy Policy*, 66, 615-629.

[7] Hitchcock, G., Conlan, B., Kay, D., Brannigan, C. and Newman, D. 2014. *Air quality and road transport*. London: Impacts and solutions. RAC Foundation.

[8] Rutherford, D. and Ortolano, L. 2008. Air quality impacts of Tokyo's on-road diesel Emission regulations, *Transportation Research Part D: Transport and Environment*, 13(4), 239-254.

[9] Souza, C.D.R., Silva, S.D., da Silva, M.A.V., D'Agosto, M.A. and Barboza, A.P. 2013. Inventory of conventional air pollutants emissions from road transportation for the state of Rio de Janeiro, *Energy Policy*, 53, 125-135.

[10] D'Angiola, A., Dawidowski, L.E., Gómez, D.R. and Osses, M. 2010. On-road traffic emissions in a megacity, *Atmospheric Environment*, 44(4), 483-493.

[11] Jing, B., Wu, L., Mao, H., Gong, S., He, J., Zou, C., Song, G., Li1, X. and Wu, Z. 2016. Development of a vehicle emission inventory with high temporal–spatial resolution based on NRT traffic data and its impact on air pollution in Beijing–Part 1: Development and evaluation of vehicle emission inventory, *Atmospheric Chemistry and Physics*, 16(5), 3161-3170.

[12] He, J., Wu, L., Mao, H., Liu, H., Jing, B., Yu, Y., Ren, P., Feng, C. and Liu, X. 2016. Development of a vehicle emission inventory with the high temporal-spatial resolution based on NRT traffic data and its impact on air pollution in Beijing – Part 2: Impact of vehicle emission on urban air quality, *Atmospheric Chemistry and Physics*, 16, 3171-3184.

[13] Vichit-Vadakan, N., Vajanapoom, N. and Ostro, B. 2008. The Public Health and Air Pollution in Asia (PAPA) Project: estimating the mortality effects of particulate matter in Bangkok, Thailand, *Environmental Health Perspectives*, 116(9), 1179-1182.

[14] Krzyzanowski, M., Apte, J.S., Bonjour, S.P., Brauer, M., Cohen, A.J. and Prüss-Ustun, A.M. 2014. Air pollution in the mega-cities, *Current Environmental Health Reports*, 1(3), 185-191.

[15] World Health Organization. 2016. Ambient (Outdoor) Air Quality and Health. Available online: http://www.who.int/ mediacentre/ factsheets/ fs313/e.

[16] Cheewaphongphan, P., Junpen, A., Garivait, S. and Chatani, S. 2017. Emission inventory of on-road transport in Bangkok Metropolitan Region (BMR) Development from 2007 to 2015 using the GAINS Model. *Atmosphere*, 8(9), 167, https://doi.org/10.3390/atmos8090167.

[17] Pengjan, S., Fan, C., Bonnet, S. and Garivait, S. 2019. Assessment of the PM2. 5/PM10 ratio in the Bangkok Metropolitan Region during, *Journal of Sustainable Energy & Environment*, 10, 75-84.