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Emission Inventory of On-Road Transport in Bangkok Metropolitan Region (BMR) Development during 2007 to 2015 Using the GAINS Model

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Abstract: Bangkok Metropolitan Region (BMR), including the capital city and five adjacent provinces, constitutes one of the top 10 megacities experiencing serious traffic congestion in the world, leading to air quality problems with significant adverse human health risks. Previously, there have been many operations planned to influence the fuel consumption and emissions from the on-road transport sector in the BMR area. It is necessary to estimate emissions using detailed information in order to thoroughly understand the reason for changes in emission levels and their impact on air quality. This paper aims to determine the successful implementation of energy and air pollution control policies in Thailand through an investigation of the emissions inventory of on-road transport in BMR, including ozone precursors (CO, NO_X, Non-methane volatile organic compounds (NMVOCs)), greenhouse gases (CO_2, CH_4, N_2O), acidic substances (SO_2 and NH_3), and particulate matters ($PM_{2.5}$, PM_{10}, Black Carbon (BC), Organic Carbon (OC)) during the period from 2007 to 2015, using the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model based on the country-specific activity data together with the emission factor from the GAINS-Asia database. This study found that the amount of exhaust emissions over the BMR area in the year 2015 (and the trend during the period from 2007 to 2015) is approximately 139 kt of CO (−7.9%), 103 kt of NO_X (−4.1%), 19.9 kt of NMVOC (−6.7%), 15 kt of CO_2 (+1.6%), 8.6 kt of CH_4 (+6.8%), 0.59 kt of N_2O (+1.3%), 0.87 kt of SO_2 (−25.8%), 1.1 kt of NH_3 (+7.8%), 4.9 kt of $PM_{2.5}$ (−5.5%), 5.1 kt of PM_{10} (−7.9%), 3.1 kt of BC (−2.5%), and 1.4 kt of OC (−7.7%). The change in emissions in each pollutant is a result of the more stringent control of fuel and engine standards, the shift in the fuel type used, and the effects of controlling some emissions. Light duty car gasoline fuel is identified as a major contributor of CO, NH_3, N_2O, and NMVOC, whereas trucks are the greatest emitters of NO_X, SO_2, and particulate matter. This study suggests that the most powerful implementation plan for the continuous, significant reduction of ozone precursor, SO_2, and particulate matter emissions is the more stringent enforcement of fuel and vehicle standard levels, especially concerning light duty vehicles.

Keywords: mobile source; air pollution control policy; air quality; urban air pollution; GAINS

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1. Introduction

Bangkok Metropolitan Region (BMR) is a region located in the central part of Thailand, which includes the Bangkok Metropolitan Administration (BMA)—the capital city, and five surrounding provinces (Pathum Thani, Nonthaburi, Samut Prakarn, Samut Sakhon, and Nakhon Pathom), as illustrated in Figure 1. This region has a total area of 7700 km^2 and 12.6 million inhabitants (including a registered population of 8.6 million people, a non-registered population of 3.0 million people, and alien workers amounting to 1.0 million people); approximately 1636.66 people/km^2 [1]. Thailand exhibits centralized development; the majority of economic development has been conducted in the BMR, and the Gross Regional Product (GRP) per capita increased from 315,846 baht in 2007 to 410,617 baht in 2015, with an average annual increasing rate of 13,539 baht [2]. The BMR represents a megacity with a high rapid economic growth [3].

According to the "Thailand Air and Noise Pollution Situation 2015 Report" of the Air Quality and Noise Management Bureau, the overall air quality in Thailand is getting better. This can be seen from the average air monitoring information of 21 stations around the BMR during the period of 2007 to 2014, which found that the annual average of PM_{10}-24 h concentration decreased from 57.8 micrograms per cubic meter in 2007 to 44.1 micrograms per cubic meter in 2014; a decrease rate of 3.8% annually. Moreover, the annual average of O_3-1 h concentration reduced from 21.53 ppb in 2013 to 20.99 ppb in 2014, or, about a 3.0% reduction. However, it still has an air pollution problem in the BMR area, especially on the roadsides of Bangkok and Samutprakarn provinces. The concentrations of PM_{10}, $PM_{2.5}$, O_3, and N_2O in those areas still exceed the standard level of national ambient air quality and is higher than those in other areas. In addition, although the trend for the benzene concentration—a group of volatile organic compounds (VOCs)—has decreased since 2013, it is still over the national standard level for all roadside monitoring stations [4]. This information demonstrates that the BMR area is still facing an air pollution problem, with a major contributing factor to the source of emissions being in transport activity.

The total number of vehicles registered in the BMR during 2007 was approximately 6.3 million, a number that continuously increased to 10 million vehicles in the year 2015, with an annual rising rate of 6%. Taking into consideration the different vehicle types that make up the cumulative number of vehicles, in the year 2015 the most common transport mode was light duty vehicle (5.74 million vehicles or about 58%), followed by motorcycle (4.00 million vehicles or about 40%), and heavy duty vehicles (0.23 million vehicles or about 2%). The cumulative number of vehicles increased by about 5% from the previous year. The number of road motor vehicles per 1000 inhabitants was about 683 motor vehicles per 1000 people, considerably higher than the national average of 240 motor vehicles per 1000 people. Motorcycles take the largest share of vehicles, followed by light duty cars that are gasoline fueled and light duty trucks that are diesel fueled, making up 40%, 25% and 13% of the total vehicles register in the BMR area, respectively. In addition, dual fuel vehicles on the road such as liquefied petroleum gas (LPG)–gasoline vehicles amount to 0.7 million vehicles, and natural gas for vehicle (NGV)–gasoline vehicles amount to 0.25 million vehicles [5].

Energy Statistics of Thailand 2015 [6] reported that the amount of national fuel consumption in the year 2015 was about 77,881 ktoe, of which 28.5% was used in the transportation sector. A look into the type of fuel used in the transportation sector found that diesel was the most consumed, followed by benzene, NGV, LPG, and electricity at amounts of 10,298 ktoe, 7180 ktoe, 2682 ktoe, 2020 ktoe and 10 ktoe, respectively. Under the Department of Alternative Energy Development and Efficiency, the Ministry of Energy has launched the "Energy Efficiency Plan (EEP) 2015" [7]. This plan set a target to decrease 30% of energy intensity by 2036 (compared to 2010), meaning that 56,142 ktoe must be reduced by the year 2036. In this reduction, it is the responsibility of transportation sector to decrease about 69% of its total energy consumption, amounting to about 30,213 ktoe. There are many operation plans, especially in the city, being launched to support this target, including promoting energy efficient vehicle use by implementing a CO_2 tax and energy-efficiency labeling; developing transport infrastructure of mass rapid transit and double track railways; and using electric vehicles. With these plans, the energy consumption is expected to be reduced by about 6514 ktoe, or about 21% of the total energy reduction, and CO_2 emissions are expected to be reduced by about 177 Mt by 2036.

Governmental policy related to fuel consumption and emissions in the transportation sector during the period from 2007 to 2015 include:

(1) "First car buyer incentive scheme": Thailand launched this plan from 2011 to 2012. This scheme encouraged customers who did previously own a car to purchase a small engine car (less than 1500 cc engine). This scheme operated from 16 September 2011 to 31 December 2012, and the total vehicles sold under this plan was about 1.25 million; furthermore, more than half of the vehicles purchased under this plan were passenger cars (0.73 million vehicles). Of these passenger cars, about 44% (0.33 million vehicles) were registered in the BMR. It can be seen that this scheme had an impact on the sharp increase in the number of new vehicles [8].

(2) "Eco car phase 1 and phase 2": This plan operated in 2009 and 2015 for phase 1 and phase 2, respectively, with the objective of encouraging manufacturers to produce more efficient and environmental friendly vehicles, called ecology cars. Ecology cars are small cars (less than 1300 cc engine size for a gasoline engine and 1400 cc engine size for a diesel engine) which have high efficiency engines that meet the qualifications of Euro 4 engine standards. These plans influenced the sharp increase in small vehicles from 2389 cars in the year 2009 to 138, 592 cars in the year 2015 [9].

(3) "Biofuel Development under Alternative Energy Development Plan 2015 (AEDP-2015)" [10]: Biofuel has been promoted as an alternative fuel for the transportation sector since the year 2001. Under AEDP-2015, the biofuel consumption target was set to use 14.0 million liters of biodiesel per day and 11.3 million liters of ethanol per day. A way to enhance the use of biofuel is to stop selling gasoline fuel and promote gasohol products (gasohol 91, gasohol 95, gasohol E20, and gasohol E85) instead. For biodiesel, an increase in higher blend products such as diesel B7 sold in the market has been seen since 2014.

(4) "Oil Plan 2015": Oil plan 2015 [11] aimed to support the use of LPG and NGV as an alternative fuel to substitute the use of benzene and diesel. For LPG consumption, the amount of LPG consumption has increased continuously. Taking into consideration the share of LPG consumption by sector, it was found that the growth rate of LPG consumed in the household sector has reduced since the year 2013 whereas the rate in the transportation sector has increased because the price of LPG is only 2 to 4 times cheaper than all gasohol products (except gasohol E85). The multi-fuel engine vehicle, known as a dual fuel vehicle, is a vehicle capable of running on two fuel types, one being gasoline or diesel and the other being an alternate fuel such as natural gas, LPG, or hydrogen. Dual fuel vehicles running gasoline and LPG has become popular since the fluctuation of petroleum fuel products. In addition, the financial incentive for choosing a gas-fueled system for both consumers and manufacturers is one cause of the sharp increase in duel fuel (petrol and LPG) vehicles, which rose from 0.16 million vehicles in 2007 to 1.00 million vehicles in 2015; more than half of which were registered in the BMR area [5]. For NGV consumption, Thailand has various plans that support the use of NGV as an equipped gas system in public transport systems such as buses and taxis, reducing the gas system installation cost, and expanding the gas station from 166 stations to 500 stations distributed around the country. In 2015, the cumulative number of duel fuel vehicles (petrol and NGV) registered was 0.186 million vehicles, of which 0.117 million vehicles or about 63% were registered in the BMR area [5].

(5) "Fuel an Engine Quality Standard Enforcement": Thailand has improved fuel quality in order to mitigate air pollution problems since 1983. The way to improve fuel quality is to limit the sulfur content and the aromatic hydrocarbon of the fuel. From Thailand, the air and noise pollution situation report presents the decrease of particulate matter and better ambient air quality especially in the BMR area; this is the result of the more intensive enforcement of fuel and engine standard levels, from the Euro 1 standard level in 1999 to the Euro 4 standard level in 2013 for light duty vehicles [12]. The qualification of engines at the Euro 4 standard level involves a stricter limit on CO, HC, and NO_X for gasoline engines and on CO, NO_X, HC + NO_X, and PM for diesel engines compared to the previous standard. For fuel standard Euro 4, it has greater control on the content of aromatic hydrocarbon, olefin, and sulfur for gasoline fuel and polycyclic

aromatic hydrocarbon (PAH) and sulfur content for diesel fuel [13]. Controlling at the Euro 4 standard level has resulted in the decreasing sulfur content in fuel up to 7–10 times compared to the previous standard, which reduced emissions of particulate matter 1732 tons per year, declining the particulate concentration 4.05 microgram per cubic meter [14]. However, the Pollution Control Department (PCD) under the Ministry of Natural Resources and Environment has a plan to further control the fuel and the engines of light duty vehicles at the Euro 5 level standard by 2020. Under the Euro 5 standard, the content of sulfur will be lower than 10 ppm; a 5-fold reduction compared to the Euro 4 standard. For motorcycles and heavy duty vehicles, the PCD plans to skip from the Euro 3 standard to the Euro 5 standard by 2019 and 2026, respectively [12].

Moreover, Thailand developed the first national greenhouse gas (GHGs) inventory for the year 1994 [15]. This inventory reported the total amount of emissions from the transportation sector to be about 39,920.40 kt CO_2, 0.09 kt CH_4, 0.26 kt NO_X, 1.30 kt CO, and 0.70 kt NMVOC. The second national emission inventory was developed for the year 2000, with the objective of submitting the report to the United Nations Framework Convention on Climate Change (UNFCCC) [16]. This report noted that the transportation sector emitted 44,438.7 kt CO_2, 6.6 kt CH_4, 0.6 kt N_2O, 450.4 kt NO_X, 2071.1 kt CO, 393 kt NMVOC, and 6.2 kt SO_X. Furthermore, in 2015, Thailand presented the "Thailand Biennial Update Report under UNFCCC" [17]. This report estimated the emissions for the year 2011, of which the emissions from the transportation sector amounted to 60,684.84 kt CO_2, 13.32 kt CH_4, 0.46 kt N_2O, 601.66 kt NO_X, 2245.40 kt CO, 418.18 kt NMVOC, and 7.07 kt SO_X.

This information demonstrates that previous studies have developed emission inventories for specific years on the national scale. However, they lacks consideration for emission trends, specifically at the city scale, for example, for the BMR region. In addition, from 2007 to 2015, there were many operation plans to influence the emission levels from the on-road transport sector as mentioned in the session government policy. To thoroughly understand the impact of these operation plans, it is necessary to estimate emission levels using detailed information on fuel type, vehicle engine type, and vehicle engine standard, etc. in order to understand the reasons behind emission changes. The results of this study can be used as support information for policy makers to create emission mitigation plans for the road transport sector in the BMR area.

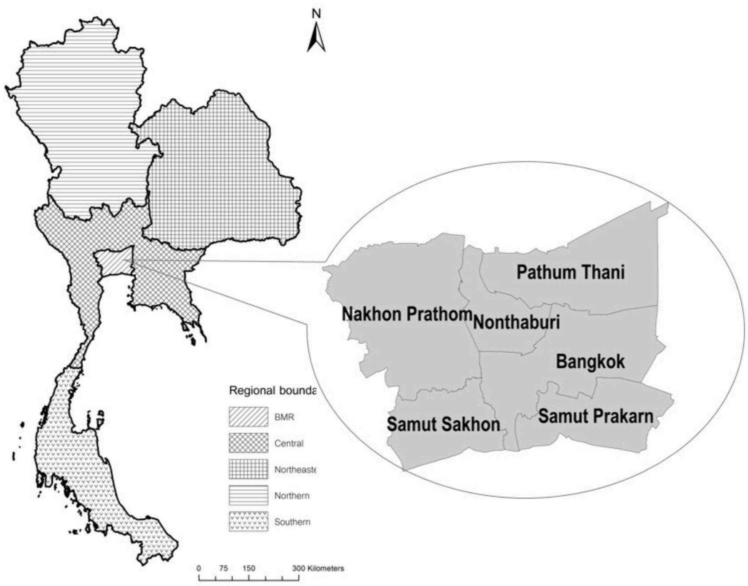
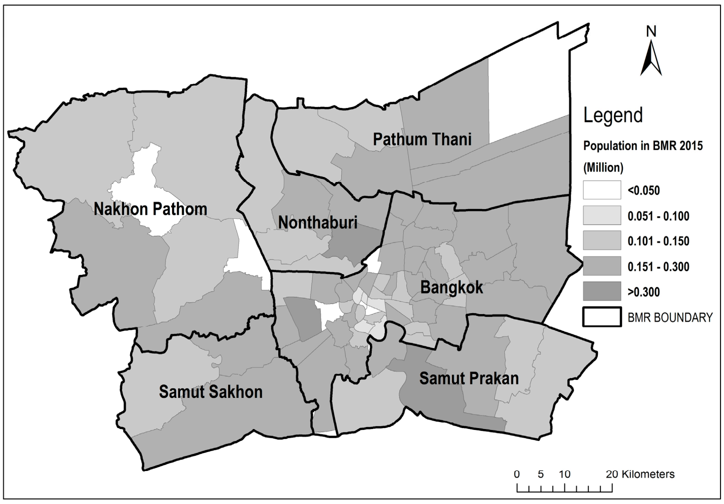


Figure 1. Map of Thailand and boundary of BMR-site study.

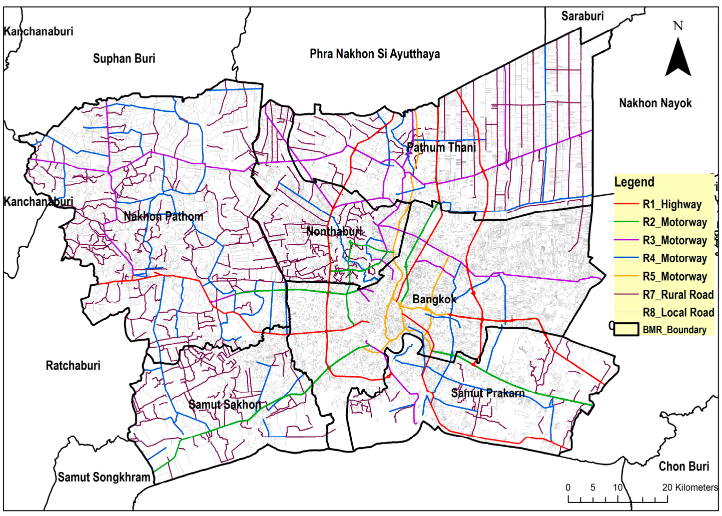
2. Methodology

2.1. Site Study

This study focuses only on the BMR area, which includes the capital city and surrounding provinces. The BMR area faces traffic problems as one of the top 10 most congested cities in the world [3]. Figure 2a presents the population density in the BMR area. Concerning the road network, Thailand is classified into five types of road, including motorways (linkages between regions, designed for high speed traffic, controlled access), national highways (connects regions, provinces, districts, and other important destinations), rural highways (connects provinces and districts, overseen by the Department of Rural Roads), local highways (local routes, overseen by local administrative organizations), and concession highways (special routes granted by local government concessions). The road network in the BMR area presented in Figure 2b; it covers all areas with a total road length of about 4400 km. It includes motorways, a network linking the metropolitan area and other regions; highways, a network linking Bangkok and the metropolitan area; major roads, a network inside the province (including small roads called "soi").



(**a**) Population density



(**b**) Road network

Figure 2. Demography and road structure in the BMR area. (**a**) Population density, (**b**) Road network.

2.2. Estimation of Emissions from the On-Road Transport Sector

Road transport is a source of air pollutants including ozone precursors CO, NO_X, and NMVOC; greenhouse gases CO_2, CH_4, and N_2O; acidifying substances NH_3 and SO_2; particulate matter; carcinogenic species such as PAHs and POPs; as well as toxic and heavy metals. According to the European Monitoring and Evaluation Programme (EMEP)/European Environment Agency (EEA) air pollutant emission inventory guidebook [18], the technical guide for emission inventory development, emissions from road transport are emitted from four sources. These include the emissions which originated from the fuel combustion process in vehicle engines, the evaporation emission which initiated from fuel evaporation in the fuel tank, the emissions from tire and brake wear originating from the abrasion process, and emissions from road surfaces originating from the abrasion between tires and road paving. For the exhaust emissions, it is divided into two sub-categories: hot emissions emitted from vehicles after the vehicle engine is warmed up and in the driving stage, and cold emissions that are emitted from vehicles during the warming-up stage. This study only focuses on the estimation of exhaust emissions during the hot stage condition.

2.2.1. Reference Method

In general, for emissions estimation, there are two sets of parameters used: a set of activity data and set of emission factors [18,19]. For exhaust emissions estimation, the set of activities is based on two parameters: fuel consumption and distance traveled, according to the available information. However, when both datasets are available, the consistency of the data must be considered based on the balancing between the fraction of fuel consumption per distance traveled and the fuel economy of each vehicle category. If the fraction associates to the possible fuel economy of each vehicle type, then the data is consistent. For sets of emission factors, they are either given in energy units or distance traveled units, corresponding to the available data.

The level of emissions estimation can be classified into three approaches; Tier 1, Tier 2, and Tier 3, each of which requires different detailed parameters. Tier 1 requires only default factors disaggregated by fuel and vehicle types, whereas Tier 2 requires more detailed disaggregation for default factors (either fuel consumed or distance traveled) such as disaggregation by fuel, vehicle, and engine types. In Tier 3, estimates are calculated from the summation of hot emissions and cold emissions; hot emission estimates can be determined from Tier 2 but are considered more by operating conditions (urban, rural, and highway driving patterns), while cold emission estimates are determined from the ratio of cold over hot emissions [18,19]. However, the Tier 1 approach of EMEP/EEA and 2006 IPCC Guidelines suggest the use of fuel consumption data, which has been recorded as national information and is thus a major driver of exhaust emissions estimation.

2.2.2. GAINS Model Method

The Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model is a scientific tool to assess the cost-effectiveness of emission control strategies for all scales that have been developed by the International Institute for Applied System Analysis (IIASA) since 2006 (extension of the Regional Air Pollution Information and Simulation (RAINS) model) [20]. The GAINS model is used to identify various emissions from various activities as well as relevant on-road transport activities such as exhaust emissions, fuel evaporation, tire and brake wear, and abrasion wear. Exhaust gas dominates as a major contributor to emissions of on-road transport activities. So, this paper aims to develop an inventory of exhaust emissions in the BMR area, including ozone precursors (CO, NO_X, NMVOC); greenhouse gases (CO_2, CH_4, N_2O); acidic substances (SO_2, NH_3), and particulate matters ($PM_{2.5}$, PM_{10}, Black Carbon (BC), Organic Carbon (OC)) during the period of 2007 to 2015 using the GAINS model based on the country-specific activity data together with the emission factors from the GAINS-Asia database, in order to identify the major source of each emission pollutant and gain a thorough understanding of the exhaust emission situation spanning from 2007 to 2015.

The general principal of emission estimation in the GAINS model is presented as Equation (1) [20,21]:

$$E_{i,p} = \sum_{m}\left[A_{i,s,f} \times ef_{i,s,f,p} \times Appl_{i,s,f,p}\right] \quad (1)$$

where

$$ef_{i,s,f,p} = ef_{is}^{NOC} \times (1 - remeff_{t,p}) \quad (2)$$

and

$$\sum_{m} Appl_{its} = 1 \quad (3)$$

i, s, f, t, p = country, sector, fuel, abatement technology, pollutant
$E_{i,p}$ is the air emission of pollutant p in country i (kt)
$A_{i,\ s,f}$ is the activity s (e.g., amount of fuel type f consumed) that produces pollutant i (PJ)
$ef_{i,s,f,p}$ is the uncontrolled emission factor (kt/PJ)
$Appl_{its}$ is the application rate of technology t to activity s (dimensionless)
ef_{is}^{NOC} is the no control emission factor for activity s (kt/PJ)
$remeff_{sm}$ is the removal efficiency of technology m when applied to activity s (dimensionless)

From Equation (1), there are three main related factors used to analyze the emissions: the activity data, the emission factor, and the emission control technology. The GAINS model applies this equation to estimate the exhaust emissions using fuel consumption disaggregated by vehicle and fuel types as an activity indicator; emission factor disaggregated by different vehicles and fuel categories and their engine types; and the share of emission control technology based on Euro standards for each vehicle and fuel categories. From the detailed information of the GAINS model (vehicle, fuel, and vehicle engine types), this method can be associated with the Tier 2 methodology as described in EMEP/EEA and 2006 IPCC Guidelines.

2.3. Data Used for the Estimation of Activity Data

The GAINS model requires the amount of fuel consumption disaggregated by vehicle and fuel type as a major driver of emissions estimation. The vehicle category relies on Nomenclature For Reporting (NFR), which classifies vehicles into six types: passenger car (LD4C), light commercial vehicle (LD4T), heavy duty vehicle for carriage goods (HDT), heavy duty vehicle for carriage passenger (HDB); motorcycle with two strokes (LD2), and motorcycle with four strokes (M4) [20]. The fuel is classified into four types: middle distillates (MD), gasoline (GSL), liquefied petroleum gas (LPG), and natural gas for vehicles (NGV). Moreover, the GAINS model also considers biofuel, requiring the information as a fraction of the bio in the fossil fuel. Because only fuel consumption by fuel type data was available, this study uses the other available parameters to allocate the fuel consumption of each fuel type into each vehicle type under the basis of the balance between the total fuel consumption and the annual distance traveled. These factors are the distance traveled classified by vehicle type, cumulative vehicle register classified by vehicle type, fuel type, and fuel economy of each vehicle type.

2.3.1. Basic Information of Fuel Consumption

The Department of Alternative Energy Development and Efficiency (DEDE)—Ministry of Energy published the "Annual Energy Statistic Report" [22]. This report provided the annual amount of fuel consumption of 11 fuel types including HSD, HSD-B5, LSD, ULG-RON 91, ULG-RON 95, gasohol E10-RON 91, gasohol E10-RON 95, gasohol E10-RON 95, gasohol E85, LPG, and NGV for road transport activities. This information is grouped into four fuel types: MD, GSL, LPG, and NGV, and is used as initial data to prepare the database of emissions calculation in this study. In addition, for a group of biofuels, which are also counted in MD and GSL, including HSD-B5 (a mix of 5% palm-oil and 95% diesel), gasohol E10-RON 91 (a mix of 10% ethanol and 90% gasoline-octane 91), gasohol E10-RON 95 (a mix of 10% ethanol and 90% gasoline-octane 95), and gasohol E85 (a mix of 85% ethanol and 15% gasoline octane 95), the mixing fraction between the bio (ethanol or bio-palm) and fossil fuel is taken into account in each fuel type. Each fuel in a group of biofuels was deducted by the bio-fraction, so only a part of the fuel that was produced from the petroleum product is counted in the emissions calculation. To quantify the fuel consumption in the BMR area, the total national fuel consumption is downscaled by using the related parameters of distance traveled, number of vehicles, and fuel economy classified by vehicle and fuel types.

Figure 3 presents the annual fuel consumption by five fuel types from 2007 to 2015 in the BMR area. The overall fuel consumption was raised from 213 PJ in 2007 to 265 PJ in 2012, and then slightly decreased to 225 PJ in 2015. However, during the year 2011, the fuel consumption showed a significant decrease due to the flooding situation which occurred in Thailand, including in the BMR area. Taking into consideration the fuel consumption by fuel type, we found that diesel was the most consumed fuel for every year, but its consumption slightly dropped from 123 PJ in 2007 to 95 PJ in 2015. Gasoline was the second highest consumed, showing a slight increase from 70 PJ to 82 PJ in the year 2015. NGV and LPG, the alternative fuels of diesel and gasoline, were the third and fourth ranked for fuel consumption, and tended to increase significantly from 2008 to 2014 and then drop down considerably. The increasing gas demand resulted from the fluctuation of crude oil prices (changing between 60.86 and 109.45 U.S. dollars per barrel [23]) and the subsidization through government policy. Due to the government's aid in gas prices, many consumers—both individual and industry consumers—switched from petroleum to gas. LPG became popular for taxi vehicles, whereas NGV was mostly used in passenger cars and trucks. After 2014, crude oil price dropped to lower than 60 U.S. dollars per barrel, while gas prices rose. Due to the floating gas prices, most gas consumer switched back from gas to petroleum, which was the reason for the observed gas consumption reduction. These situations demonstrates that crude oil price has an influence on both fuel demand and fuel type. In addition, the subsidization of the government to promote the use of alternative fuels instead of petroleum products for transportation over the period of 2003–2008 was also a cause of the increase in gas demand.

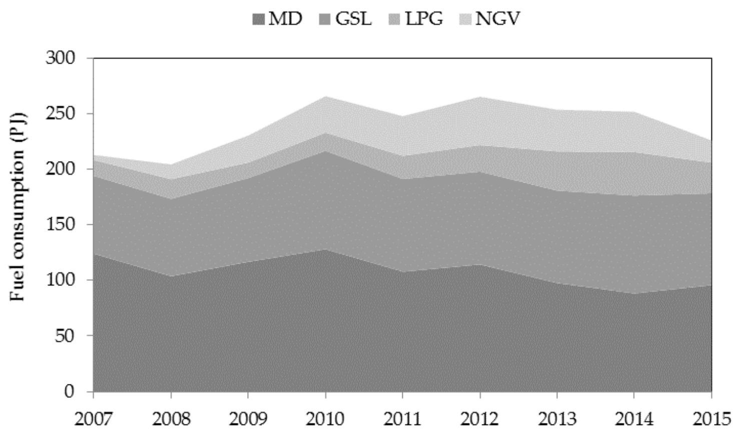


Figure 3. Fuel consumption of on-road transport activity in the BMR area from 2007 to 2015. Remark: MD stands for diesel (including HSD, HSD-B5, and LSD); GSL stands for gasoline fuel (including ULG-RON 91, ULG-RON 95, gasohol E10-RON 91, gasohol E10-RON 95, gasohol E10-RON 95, and gasohol E85), LPG stands for liquefied petroleum gas; NGV stands for natural gas for vehicles.

2.3.2. Cumulative Number of Vehicles Registered Classified by Vehicle and Fuel Types

All vehicles in Thailand must be registered with the Department of Land Transport (DLT)—Ministry of Transport [5]. The DLT records the number of five vehicle types under the Motor Vehicle Act (including motorcycles, passenger cars, pickups, buses, and trucks) in each province. The cumulative number of vehicles registered in the BMR area from 2007 to 2015, presented in Figure 4, shows that this value increased from 6.2 million vehicles in 2007 to approximately 10 million vehicles in 2015, with an average annual growth rate of 5.7%. The average growth rate by vehicle type was around 4%, 9%, 4%, 7% and 4% for motorcycles, light duty cars, light duty trucks, buses, and trucks, respectively. Passenger cars had the highest growth rate which, and represents the major mode of transport on the road network in the BMR, followed small-engine and medium-engine cars.

Taking into consideration the new vehicles registered with the DLT [24,25], the number of new vehicles registered over the BMR area was in the range between 0.61 and 1.1 million vehicles. More than 50% of new vehicles were motorcycles, followed by light duty cars and light duty trucks with an average share of 33% and 13%, respectively, as presented in Figure 5. The number of new vehicles registered especially increased during 2012 and 2013, which constituted mostly small size engine (<1300 cc) and medium engine (between 1300 cc and 1800 cc) cars, as demonstrated in Figure 6. The high increase at that period is a result of the governmental "first car rebate policy," which gave tax rebates to customer who purchased light duty vehicles with less than 1500 cc engines during 2011 and 2012.

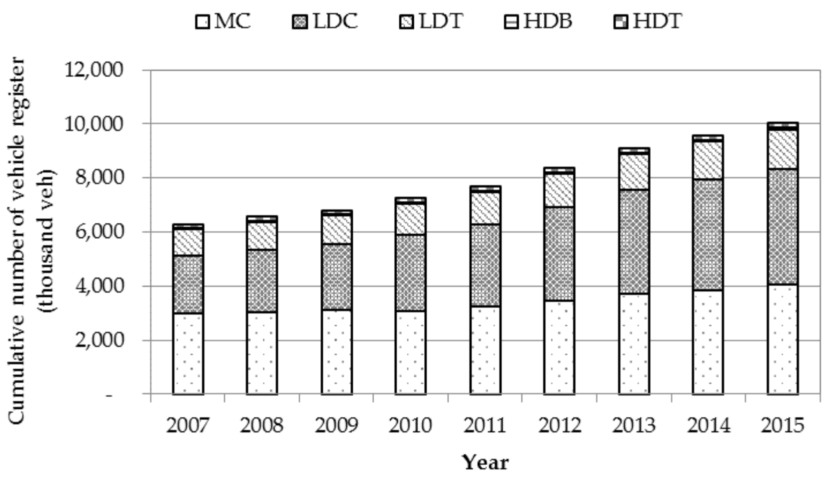


Figure 4. Cumulative number of vehicles registered in the BMR area from 2007–2015. Remark: MC stands for motorcycles; LDC stands for light duty cars (including passenger cars less than seven seats and passenger cars over seven seats); LDT stands for light duty trucks; HDB stands for heavy duty buses (including fixed-route, non-fixed route, and private buses); and HDT stands for heavy duty trucks (including non-fixed route and private trucks).

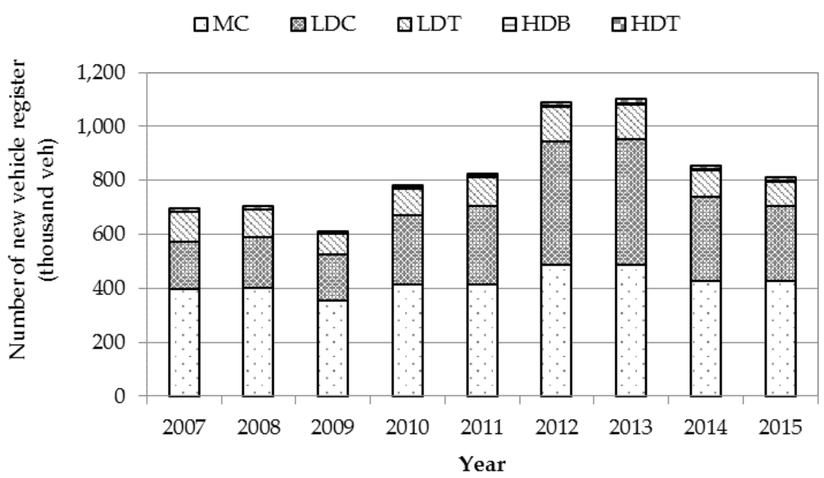


Figure 5. Number of new vehicles registered, classified by vehicle type, from 2007–2015 in the BMR area.

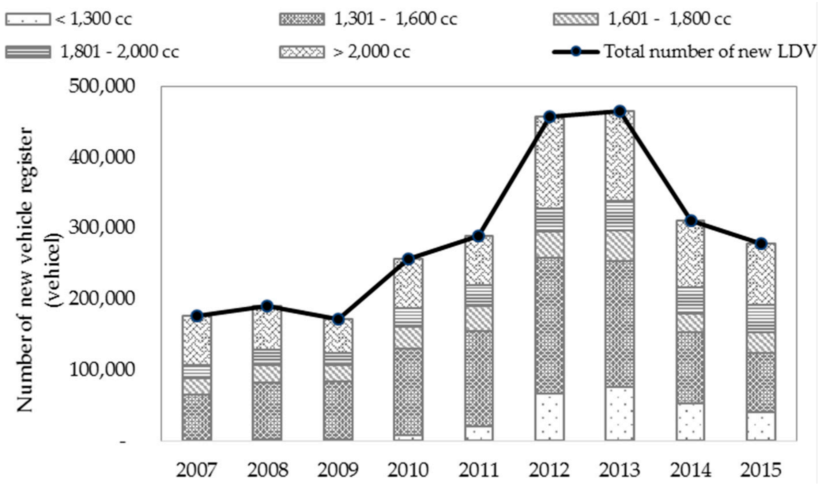


Figure 6. Number of new light duty vehicles registered, classified by engine size.

2.3.3. Distance Traveled by Vehicle Type

The Department of Highway (DOH)—Ministry of Transport annually publishes the "Statistics of Highway Travel Report" [26]. This report provides the annual distance traveled by 11 vehicle types (including motorcycles, passenger cars less than seven seats, passenger cars over seven seats, light duty trucks, mini-buses, medium-buses, coaches, semi-trucks, trucks, semi-trailers, and trailers) in each province, as assessed according to the number of vehicles on the road and the average distance traveled for each vehicle type.

Figure 7 presents the annual distance traveled by vehicle type from 2007 to 2015 in the BMR area. From the information found, the distance traveled of vehicles in the BMR increased continuously from 30,040 million vehicle-kilometers in 2007 to 43,200 million vehicle-kilometers in 2015, with an average increase of 5.4% annually. Light duty cars take the largest share, which represents approximately half of the total distance traveled in each year, followed by light duty trucks, heavy duty trucks, motorcycles, and buses. Evidence shows that light duty vehicles take a high share on the road network in the urban area.

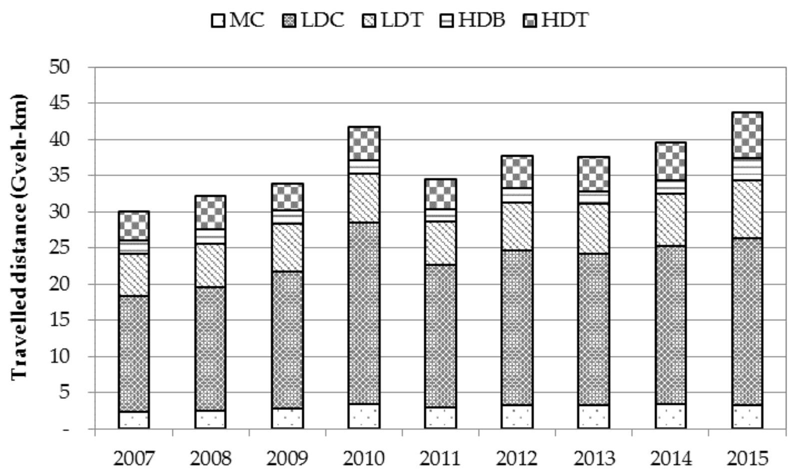


Figure 7. Distance traveled on highway roads in the BMR area from 2007–2015. Remark: MC stands for motorcycle; LDC stands for light duty car (including passenger cars less than seven seats and passenger cars over seven seats); LDT stands for light duty truck; HDB stands for heavy duty bus (including mini-buses, medium-buses, coaches); and HDT stands for heavy duty truck (including semi-trucks, trucks, semi-trailers, and trailers).

2.3.4. Fuel Economy of Each Vehicle Type

Fuel economy varies by each vehicle type and traffic situation (urban and rural areas); this study uses the average fuel economy of each vehicle type driving in an urban area as a reference level to disaggregate fuel consumption by vehicle type from "A Study of Motor Vehicle and Fuel Usage Pattern in Bangkok Metropolitan and Suburb Areas" [27]. The range of fuel economy for each vehicle type used in this study is summarized in Table 1.

Table 1. Fuel economy of each vehicle type used in this study.

Vehicle Types	Fuel Economy (km/L)
Light duty cars	10–12.3
Light duty trucks	10–13.5
Heavy duty trucks	3.0–6.2
Heavy duty buses	7.3–8.5
Motorcycles	25.5

2.3.5. Fuel Consumption Disaggregate by Vehicle and Fuel Types

According to the optimized balance between total fuel consumption and annual distance traveled, the cumulative number of vehicles registered, classified by vehicle and fuel types as presented in Section 2.3.2, as well as the distance traveled, classified by vehicle type as presented in Section 2.3.3, and the fuel economy, classified by vehicle type as presented in Section 2.3.4, are analyzed to quantify the share of fuel consumption by vehicle and fuel types. Thus, the total fuel consumption must be equal to the total amount of fuel consumption by fuel type as presented in Section 2.3.1. The result is demonstrated in Figure 8 and Table 2.

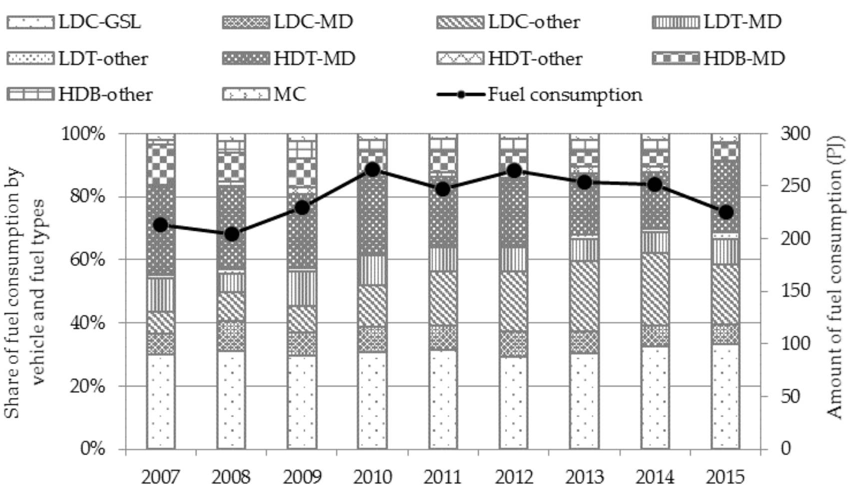


Figure 8. Amount of fuel consumption by vehicles and fuel types of on-road transport in the BMR from 2007–2015. Remark: LDC-other included LDC with LPG and NGV; LDT-other included LDT with gasoline, LPG, and NGV; HDT-other included HDT with LPG and NGV; HDB-other included HDB with LPG and NGV.

The results show that light duty vehicles represent the major consumer, taking the share of around 60% of the total fuel consumed in the BMR, and half of this consumption is gasoline-fueled. The following consumers were heavy duty trucks (diesel fueled) and light duty trucks (diesel fueled), which represent approximately 18% and 6% of the total fuel consumed, respectively. However, gas fuels such as LPG and NGV represent a higher share compared to diesel, especially for passenger cars and heavy duty trucks from 2008 to 2014, which was influenced by the fluctuation of crude-oil prices.

Table 2. Amount of fuel consumption classified by vehicle and fuel types.

Fuel Type	Fuel Consumption by Vehicle Type (PJ)				
	MC	LDC	LDT	HDB	HDT
Total of FC 2007	4.40	92.39	24.96	30.49	60.80
MD	-	14.15	22.71	27.02	60.06
GSL	4.40	63.81	1.81	0.31	0.05
LPG	-	12.56	0.41	1.22	0.13
NGV	-	1.86	0.03	1.95	0.56
Total of FC 2008	4.75	101.32	14.80	26.30	57.36
MD	-	19.49	12.21	17.97	54.08
GSL	4.75	63.24	1.62	0.29	0.06
LPG	-	15.25	0.89	1.30	0.25
NGV	-	3.34	0.09	6.74	2.97
Total of FC 2009	5.40	104.45	27.35	34.26	58.94
MD	-	16.76	24.67	21.09	54.14
GSL	5.40	68.33	1.66	0.24	0.05
LPG	-	12.16	0.80	0.79	0.15
NGV	-	7.20	0.22	12.14	4.60
Total of FC 2010	5.81	138.28	26.88	27.57	67.30
MD	-	21.50	24.54	18.45	63.54
GSL	5.81	81.43	1.30	0.15	0.05
LPG	-	14.70	0.82	0.63	0.20
NGV	-	20.65	0.22	8.34	3.50
Total of FC 2011	4.64	139.23	21.03	25.62	57.27
MD	-	19.53	19.06	16.33	52.91
GSL	4.64	77.69	1.05	0.14	0.05
LPG	-	19.87	0.54	0.35	0.12
NGV	-	22.15	0.37	8.80	4.19
Total of FC 2012	4.92	148.82	23.11	27.32	61.12
MD	-	21.05	20.75	16.78	55.75
GSL	4.92	77.48	1.07	0.15	0.05
LPG	-	22.71	0.77	0.37	0.09
NGV	-	27.59	0.52	10.03	5.23
Total of FC 2013	5.18	151.20	20.70	21.94	54.63
MD	-	17.85	17.79	12.81	49.18
GSL	5.18	76.88	1.05	0.13	0.05
LPG	-	33.34	1.32	0.48	0.13
NGV	-	23.13	0.54	8.53	5.27
Total of FC 2014	5.53	156.64	19.21	20.51	49.82
MD	-	16.49	16.05	11.32	44.44
GSL	5.53	81.41	1.07	0.13	0.05
LPG	-	36.94	1.54	0.49	0.13
NGV	-	21.80	0.55	8.57	5.20
Total of FC 2015	6.09	131.69	23.03	23.17	58.07
MD	-	13.89	18.14	12.21	51.49
GSL	6.09	75.24	1.31	0.15	0.06
LPG	-	24.40	2.93	0.84	0.20
NGV	-	18.15	0.66	9.98	6.31

2.4. Emission Factors

The emission factors of the transportation sector vary according to vehicle, fuel, engine type, and engine standard [17,28]. An emission factor is defined as the emission rate relative to the fuel consumed or distance traveled, based on the available activity data. This study used emission factors from the GAINS-Asia database [29] as a default value to estimate exhaust emissions, as it provided a comprehensive list of vehicle and engine fleets associated with the current vehicles used on the road network in Thailand, and also covered all emission species investigated in this study. The emission factors of the GAINS-Asia database are presented in terms of the weight of emission (kiloton) per heating value of fuel (PJ) classified by vehicle type, fuel type, and engine-standard (Euro standard), as demonstrated in Table A1(a–d) for ozone precursors, greenhouse gases, acidic substances, and particulate matters, respectively. The value of emission factor (EF) relates to the controlling of emission levels in each engine-standard.

2.5. Control Technology

Vehicle engine technology is a major factor employed to control emission levels. In order to estimate emissions using the GAINS model, data on the share of each vehicle type by vehicle engine based on the Euro standard is required. This study assumes that all engines of new vehicles reach the exhaust emission standard level controlling at that year. To quantify the share of control technology for each fleet under this assumption, three pieces of information are required, including (1) exhaust emission regulation enforcement; (2) the number of new vehicles; and (3) the number of cumulative vehicles. The number of new vehicles and cumulative vehicles is presented above in Section 2.3.2, and the information on first parameters is presented in the following section.

2.5.1. Exhaust Emission Regulation Enforcement

The vehicle engine emission standard is a device to limit the amount of exhaust emission released. Thailand relies on the European emission standard (Euro standard) to limit the amount of pollutants released for new vehicles, enforced by the Thai Industrial Standards Institute (TISI) agency under the Ministry of Industry and the PCD under the Ministry of Natural Resources and Environment [30]. Focusing on light duty vehicles (both diesel and gasohol engines), the major mode of transport in urban areas has been controlled by the Euro 1 standard since 1995, followed by the more intensive control of Euro 2, 3 and 4 in 1999, 2005 and 2012, respectively [11]. A summary of the exhaust emission standards and engine regulations for each fleet in Thailand is presented in Table 3.

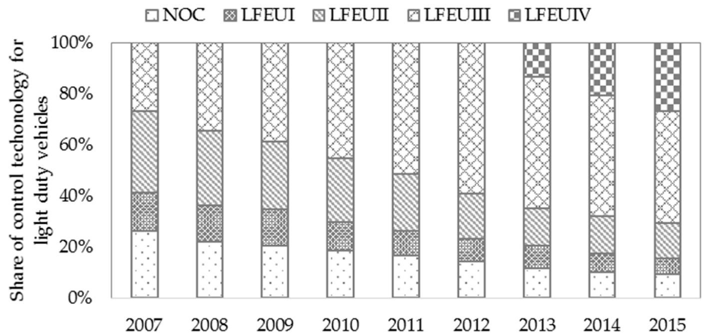
Table 3. Euro Emission standard for each mode type (g/km).

Vehicle Types	Euro Standard	CO		HC		NOx		HC + NOx		PM		Year Enforced
		GSL	MD	GSL	MD	GSL	MD	GSL	MD	GSL	MD	
LDV < 1305 kg	Euro 1	2.72	2.72	-	-	-	-	0.97	0.97	-	0.14	1995
	Euro 2	2.20	1.00	-	-	-	-	0.50	0.70	-	0.08	1999
	Euro 3	2.30	0.64	0.20	-	0.15	0.50	-	0.56	-	0.05	2005
	Euro 4	1.00	0.50	0.10	-	0.08	0.25	-	0.30	-	0.025	2011
LDV 1305–1760 kg	Euro 1	5.17	5.17	-	-	-	-	1.40	1.40	-	0.19	1995
	Euro 2	4.00	1.25	-	-	-	-	0.60	1.00	-	0.12	1999
	Euro 3	4.17	0.80	0.25	-	0.18	0.65	-	0.72	-	0.07	2005
	Euro 4	1.81	0.63	0.13	-	0.10	0.33	-	0.39	-	0.04	2011
LDV 1760–3500 kg	Euro 1	6.90	6.90	-	-	-	-	1.70	1.70	-	0.25	1995
	Euro 2	5.00	1.50	-	-	-	-	0.70	1.20	-	0.17	1999
	Euro 3	5.22	0.95	0.29	-	0.21	0.78	-	0.86	-	0.10	2005
	Euro 4	2.27	0.95	0.16	-	0.11	0.39	-	0.46	-	0.06	2011
HDV	Euro 1	-	4.50	-	1.10	-	8.0	-	-	-	0.36	1998
	Euro 2	-	4.00	-	1.10	-	7.0	-	-	-	0.150	1999
	Euro 3	-	2.10	-	0.66	-	5.0	-	-	-	0.10/0.13 [a]	2007
MC	Euro 1	>4.50	-	-	-	-	-	3.00	-	-	-	1999
	Euro 2	<3.50	-	-	-	-	-	<2.00	-	-	-	2004
	Euro 3	<2.00	-	<0.80	-	<0.15	-	-	-	-	-	2009

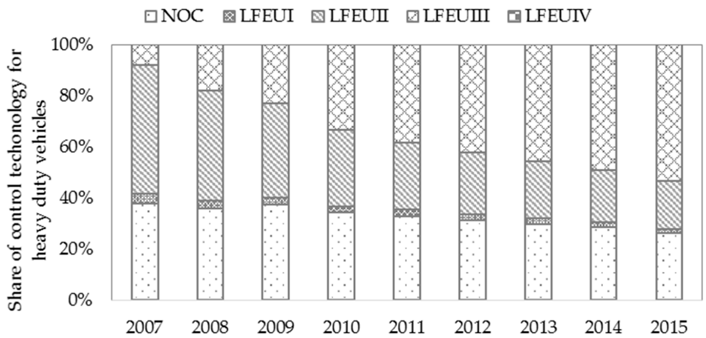
Remark: LDV stands for light duty vehicles; HDV stands for heavy duty vehicles; MC stands for motorcycles. For light duty vehicles, emission measures are based on the European Driving Cycle (EDC) and the New European Driving Cycle (NEDC). [a] for heavy duty vehicle engines, <0.75 dm^3 and power >3000 round/min.

2.5.2. Share of Control Technology

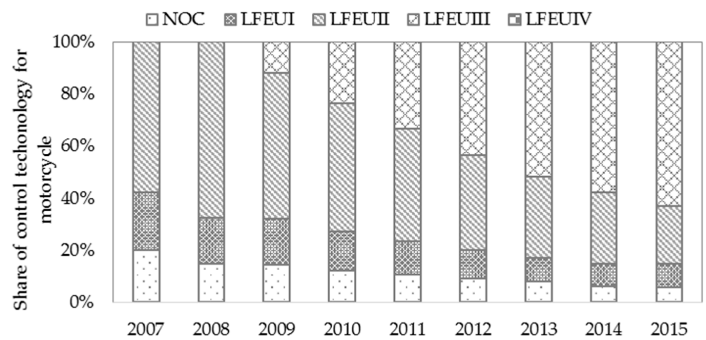
Euro standards have been used to control exhaust emissions for new vehicles in Thailand since 1995, starting with Euro 1 for light duty vehicles and reaching Euro 4 in 2013. In the case of heavy duty vehicles, they have been controlled under Euro 1 since 1998 and under Euro 2 and Euro 3 in 1999 and 2007, respectively. For motorcycles, they has been controlled under Euro 1 since 1999 and under Euro 2 and Euro 3 in 2004 and 2009, respectively. According to the assumption used to assess the share of control technology that all engines of new vehicles meet the exhaust emission standard level controlling at that year, in the case of light duty vehicles, the new vehicles registered in 2013 are assumed to be equipped with Euro 4 engines; the new vehicles registered from 2005 to 2012 are assumed to be equipped with Euro 3 engines; the new vehicles registered before 2005 are assumed to be equipped with Euro 2, Euro 1, and non-controlled emissions in descending order by the vehicle age and the engine standard stage enforcement. The share of vehicle engine standards has changed year by year, with the share of high efficiency light duty vehicles growing larger as new vehicles have entered the system, as presented in Figure 9a. The same concept used is to assess the share by engine for heavy duty vehicles and motorcycles, and the results presented in Figure 9b,c, respectively.



(**a**) Share of emission control technology of light duty vehicles



(**b**) Share of emission control technology of heavy duty vehicles



(**c**) Share of emission control technology of motorcycles

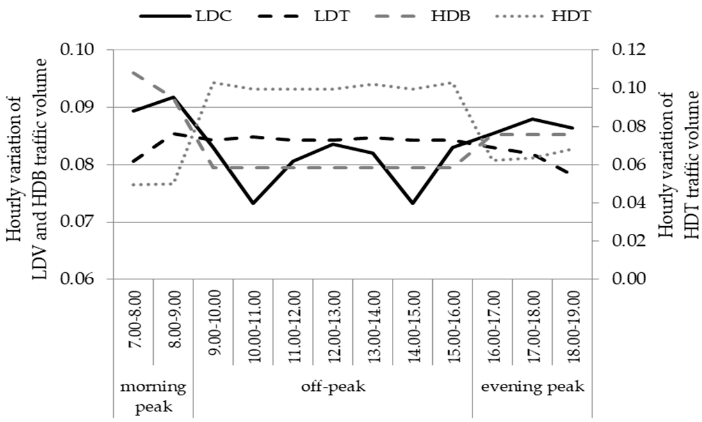
Figure 9. Share of emission control technology by mode in the BMR area from 2007 to 2015: (**a**) light duty vehicles; (**b**) heavy duty vehicles; (**c**) motorcycles.

2.6. Temporal and Spatial Variation of Exhaust Emission Determination

The modal share of traffic volume varies by time and area, which influences the level of emissions [31]. In order to understand the emission variation, this study uses information on the traffic volume from the Division of Policy and Planning under the Department of Transport and Planning—Bangkok Metropolitan (BMA), which record traffic volume on 286 intersections and 628 routes on the road network in the BMR area during morning peak period (7.00–9.00), evening peak period (16.00–19.00), off-peak period (9.00–16.00); furthermore, it classifies traffic by vehicle type into four categories (light duty cars, light duty trucks, heavy duty buses, and heavy duty trucks) [32]. Traffic count was completed from 1 January to 31 December 2015. The distribution of CO and NO_X emissions, the main emissions from road transport activity, are assessed on the basis of the trip distribution of the key contributors of each emission type.

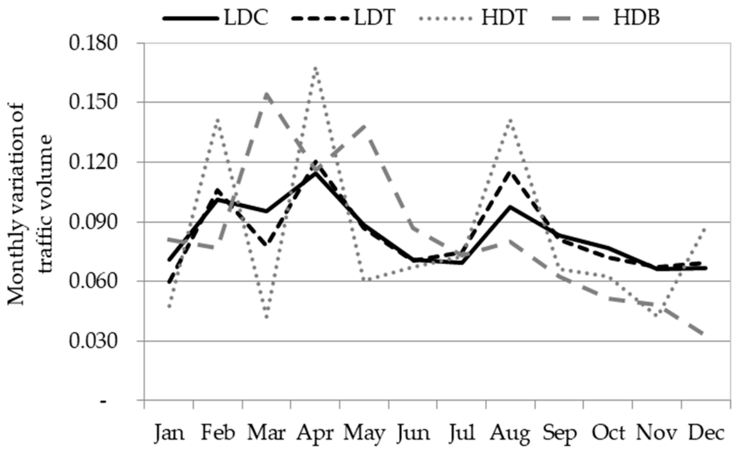
2.6.1. Temporal Variation of Traffic Demand

Figure 10a,b present the hourly and monthly variation of each transport mode, respectively. According to hourly temporal variation, we found that the timing of travel can be classified into two groups: the timing of passengers and freight transports, which obviously vary at different times. Passengers, transported by light duty vehicles (LDC) and heavy duty buses (HDB), have the highest travel demand during the morning peak, followed by the evening peak, and the off-peak session. However, the variation during the peak is quite close to the off-peak, meaning that passenger travel may be generated all day. Freight transport, in the form of light duty trucks (LDT) and heavy duty trucks (HDT), mostly travelled after 9.00 am, starting at the off-peak session, until evening. It is obvious that the transport of heavy duty trucks dramatically increases during the off-peak period due to the enforcement of timing limitations for heavy duty trucks, which are not allowed to drive on BMR road networks from 6.00–9.00 am and 16.00–20.00, except on Sunday, in order to reduce traffic congestion.



(**a**) Hourly variation

Figure 10. *Cont.*



(**b**) Monthly variation

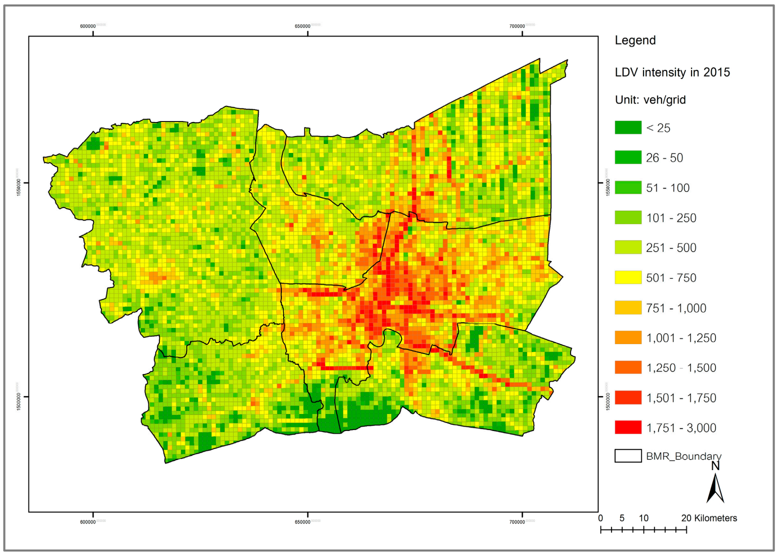
Figure 10. Temporal variation of traffic in the BMR area: (**a**) hourly variation; (**b**) monthly variation.

Travelling varies by month. The overall trip generation in the BMR has three peaks in April, August, and February, whereas low demand commences during the end of the year in November and December. Taking into consideration the monthly variation in each vehicle type, these can be categorized into two groups: private and public vehicles. Private vehicles such as light duty cars and light duty trucks have a narrow range of variation in each month, with the range of 0.07–0.11 for light duty cars and 0.06–0.12 for light duty trucks. The largest share of light duty vehicle demand is in April and August, whereas the lowest share is in November, December, and January. For public vehicles such as heavy duty trucks and heavy duty buses, they have a wide range of variation, especially heavy duty buses, with a range of 0.04–0.16 for heavy duty trucks and 0.03–0.15 for heavy duty buses. The monthly temporal pattern for heavy duty trucks is similar to that of light duty vehicles, meaning that its highest demand can be seen in April and its lowest in November. For heavy duty buses, it is quite different compared to other modes, as it sees a peak in March and a downturn in December and April. The variation of heavy duty buses is associated with the holiday seasons, such as the New Year holiday in December and Thailand's New Year (Songkran day) holiday in April.

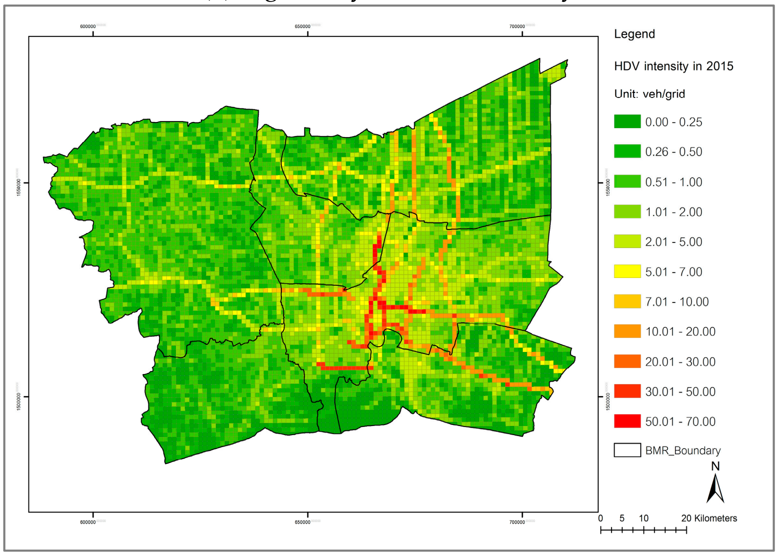
2.6.2. Spatial Variation of Traffic Demand

Trip generation has a spatial heterogeneous characteristic according to the land use in each area, such as business areas, industrial estate areas, residential areas, etc. The allocation variation of traffic volume has an influence on the amount of emissions. This study uses the gridded map of traffic intensity at a resolution 1 km × 1 km to study the characteristic of spatial variation of emissions over the road network in the BMR area. The gridded map was created from the road network information together with road physical characteristics (number of lanes and road distance) and the traffic volume of each mode on the major roads, as reported by the Division of Policy and Planning under the Department of Transport and Planning—Bangkok Metropolitan (BMA) [32] and the Department of Highway (DOH) [26]. From the report, we found that the average daily traffic of the BMR is in the range between 94 and 210,153 vehicles per day. Distributed into the grid cell, these values represented the traffic intensity on the road network across the BMR area for light duty vehicles and heavy duty vehicles, shown in Figure 11a,b, respectively.

According to the geography of the BMR, as demonstrated in Figures 1 and 2, Bangkok is in the center; north of Bangkok is Nonthaburi province; northeast is Pathum thani province; south is Samutprakarn province; west is Samutsakorn province; and northwest is Nakhonpathom province. The traffic intensity map demonstrates that the high congestion traffic is found in the center of Bangkok, which is classified as a downtown area, the provincial connection area (between Bangkok and Nonthaburi, and between Bangkok and Pathumthani), and the linkage network between Bangkok and Samutprakarn. It can be noted that the further away from the center of Bangkok, the lower the traffic intensity.



(**a**) Light duty vehicles intensity



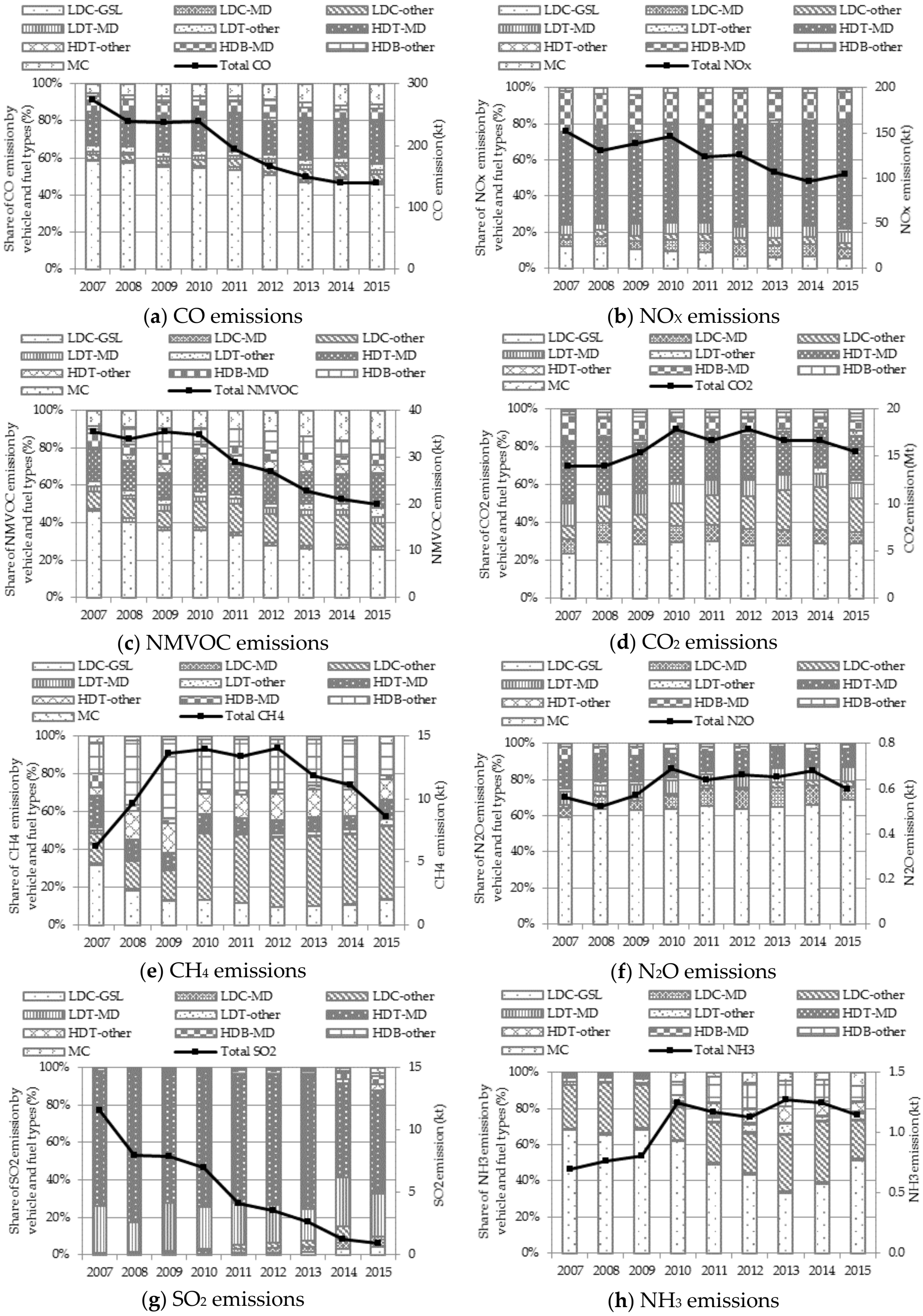
(**b**) Heavy duty vehicles intensity

Figure 11. Gridded map of traffic intensity on the road network in the BMR, 2015: (**a**) light duty vehicles intensity; (**b**) heavy duty vehicles intensity.

3. Results and Discussion

3.1. Emission Inventory from On-Road Transport in the BMR

Twelve emission species from on-road transport activities from 2007 to 2015 are reported as graphs in Figure 12a–l. The stack-graphs represent the shares of emissions according to vehicle and fuel types, and the line-graphs represent the quantities of emissions recorded from 2007 to 2015.



(**a**) CO emissions (**b**) NO_x emissions

(**c**) NMVOC emissions (**d**) CO_2 emissions

(**e**) CH_4 emissions (**f**) N_2O emissions

(**g**) SO_2 emissions (**h**) NH_3 emissions

Figure 12. *Cont.*

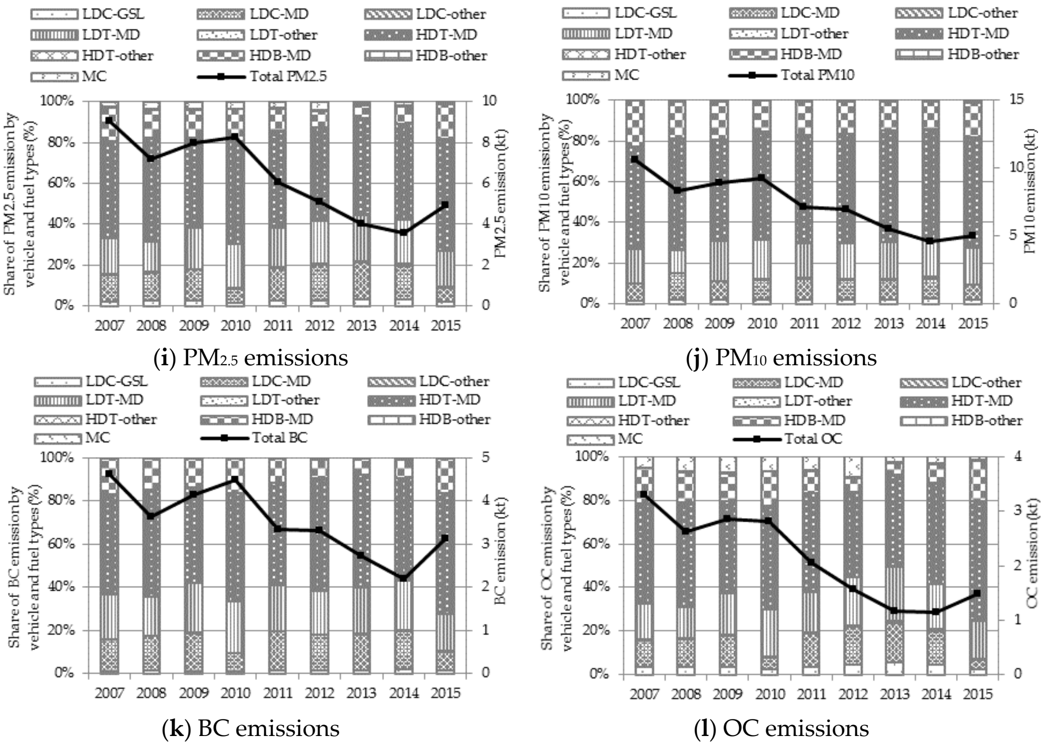


Figure 12. Share of emissions by vehicle and fuel types and trend of emissions from 2007 to 2015 for each emission species: (**a**) CO emissions; (**b**) NO_X emissions; (**c**) NMVOC emissions; (**d**) CO_2 emissions; (**e**) CH_4 emissions; (**f**) N_2O emissions; (**g**) SO_2 emissions; (**h**) NH_3 emissions; (**i**) $PM_{2.5}$ emissions; (**j**) PM_{10} emissions; (**k**) BC emissions; (**l**) OC emissions.

3.1.1. CO Emissions

CO emissions emit from the incomplete combustion of fuel, and increases with speed [18]. From 2007 to 2015, the average CO emissions totaled approximately 197 kt/year. Passenger cars using gasoline dominated as the major contributor of CO emissions in the BMR area, which contributed around half of the total CO emissions, followed by heavy duty trucks and motorcycles at the average portion of around 19% and 8% of total CO emissions, respectively. CO emissions tended to decrease continuously by the average reduction rate of 7.9% annually, which mainly resulted from the reduction of CO emissions from light duty vehicles. This decrease was a result of the increasing share of high efficiency light duty vehicles due to the more controlled exhaust emission standard of light duty vehicles from Euro 3 to Euro 4 at the beginning of year 2013. The EF of the higher standard contributed approximately 42% of CO emission reductions compared to the previous standard. These results demonstrate the success of the government policy instigating a more intense exhaust emission standard for light duty vehicles. Thank to this regulation, all new light duty vehicles since the year 2013 must meet the Euro 4 standard, and with the higher share of high efficiency engine vehicles in the transport system, the trend of CO is expected to decline continuously.

3.1.2. NO_X Emissions

NO_X emits from the oxidation of non-combustible species in the combustion chamber. The quantity of NO_X emissions released varies depending on the vehicle engine temperature. The driving-speed affects the temperature of vehicle engines, which influences the amount of NO_X emissions [18]. From 2007 to 2015, the average NO_X emissions totaled approximately 125 kt/year; heavy diesel-fueled trucks are a major emitter of NO_X in the BMR area, and emit around 53% of the total NO_X emissions. Buses and light duty gasoline-fueled cars are the second and third emitters with shares of around 18% and 8% of the total NO_X emissions, respectively. NO_X emissions fluctuated with a downward trend by the average reduction rate 4.1% annually, mainly due to the reduction of NO_X emissions from buses and light duty vehicles. The reduction of NO_X emissions from buses resulted from the decreasing diesel consumption, as diesel was replaced with alternative fuels such as gases. In addition, the reduction of NO_X emissions from light duty vehicles was a result of the increased share of high efficiency vehicles (EU 4), as the EF of high efficiency vehicles accounts for approximately 50% of the NO_X reduction from Euro 3 engines. However, the rate at which NO_X declined is rather low due to the less stringent policies to control emission from heavy duty vehicles, which are the major contributors of NO_X emissions. The phase-out rate of heavy duty vehicles is quiet low, as seen from the share of low efficiency engine heavy duty vehicles (non-control to Euro 2) that accounts for nearly a half of the cumulative heavy duty vehicles. So, to control NO_X emissions in the BMR area, old heavy duty vehicle should be phased out of the road network system, or the more intense engine standard for heavy duty vehicles should be enforced.

3.1.3. NMVOC Emissions

NMVOC is a group of organic compounds, including carbon, hydrogen, and other varieties of chemical species with different characteristics such as benzene and toluene in the group of aromatic hydrocarbon compounds; formaldehyde in the group of carbonyl compounds, etc. [33] In the transport sector, NMVOC emits from the combustion of fossil fuels and gas as well as from the evaporation of fuel in the tank, mostly produced from a gasoline engine. The average NMVOC emissions from 2007 to 2015 were approximately 28.8 kt/year. Light duty vehicles that are gasoline-fueled are key emitters that account for around 32% of the total NMVOC emissions; heavy duty trucks represent the second contributor of NMVOC, but contributed only half that from light duty vehicles (about 16% of total NMVOC emissions); motorcycles are the third contributor of NMVOC emissions, emitting approximately 12%, similar to the amount contributed by light duty cars that are fueled by gas. NMVOC emissions tended to decrease continuously by an average reduction rate of 6.7%, which mainly resulted from the reduction of NMVOC emissions from light duty cars fueled by gasoline and buses. This decrease was a result of the increase of the share of high efficiency vehicles, as the EF of high efficiency vehicles represents approximately a 50% and 17% reduction compared with Euro 3 engines for light duty cars and buses, respectively.

3.1.4. CO_2 Emissions

CO_2 emits from a complete combustion process of fuel, and depends upon the amount of fuel consumed [18,19]. The average CO_2 emissions from 2007 to 2015 reached approximately 16 Mt/year. Gasoline-fueled passenger cars are is a major contributor of CO_2 emissions in the BMR area, which contribute around 28% of the total CO_2 emissions; heavy duty trucks and light duty trucks represent the second and third contributors with the average shares of approximately 24% and 8% of total CO_2 emissions, respectively. CO_2 emissions vary with the upward trend by the rate of 1.6% annually, which results from the increase of fuel consumption of all modes, especially heavy duty trucks and buses.

3.1.5. CH_4 Emissions

CH_4 is a main component of natural gas. The average CH_4 emissions from 2007 to 2015 were approximately 11.4 kt/year. Light duty cars (especially gasoline- and natural gas-fueled cars) are a major contributor of CH_4, with an average share of around 29% of the total CH_4 in the BMR area, whereas gas-fueled buses and gas-fueled heavy duty trucks take the second and third place contributors at the average shares of 26% and 12% of total CH_4, respectively. The trend of CH_4 between 2007 and 2015 showed a rapid increase from 2007 to 2009; after that, you can see a narrow change from 2010 to 2012, and then a continuous decline. This information indicated that the pattern of CH_4 emissions is consistent with the amount of NGV consumption (as seen from the trend of NGV consumption from

Figure 3). The more NGV that is consumed, the higher the CH_4 emissions. Using the alternative fuel substitution, the use of benzene and diesel has a higher impact on CH_4 emissions than oil fuels.

3.1.6. N_2O Emissions

N_2O emits from the urea additive in catalytic converters. The amount of N_2O contribution depends on the combustion and the control technology present in the vehicle engines [19]. From 2007 to 2015, the average N_2O emissions amounted to 0.62 kt/year, which were mainly emitted from light duty gasoline vehicles (averaging around 64% of the total N_2O emissions), followed by heavy duty trucks and light duty diesel vehicles with shares of 11% and 8%, respectively. The trend of N_2O sees a narrow fluctuation in the range between 0.52 and 0.69 kt/year.

3.1.7. SO_2 Emissions

SO_2 emits from the oxidation of fuel containing sulfur in the combustion chamber, especially from diesel engines [34]. The more intensive control of sulfur in fuel quality of Euro 2, Euro 3, and Euro 4 fuel standards induced the lower rates of 500 ppm, 350 ppm, and 50 ppm, respectively [13,35]. From the estimation of SO_2 emissions from 2007 to 2015, it was found that approximately 5.2 kt of SO_2 was emitted annually, mostly from heavy duty trucks, with a share of 62%. Light duty trucks are the second contributor of SO_2 in the BMR with a share of 21%; the third contributor is light duty cars and buses which have similar shares at 2% of the total SO_2 emissions each. Trends of SO_2 reduced significantly by the average reduction rate of around 25% annually, which mainly resulted from the reduction of SO_2 emissions from diesel vehicles (both heavy duty trucks and light duty trucks). These results demonstrated the effectiveness of the intensive control on the sulfur content of fuel.

3.1.8. NH_3 Emissions

NH_3 emits from the burning of the emission reduction device through catalytic converters and diesel particles filters (DPFs) [17], which typically occur when the catalyst reaches equilibrium temperature [36]. Approximately 1.05 kt of NH_3 is emitted from road transport in the BMR area, which is mainly (78% of NH_3 emissions) from light duty vehicles. NH_3 emissions tended to increase slightly by the average rate of 7.8% annually, which mainly was due to the increase of NH_3 from heavy duty vehicles. The possible reason for the increase of NH_3 relates to the low sulfur content fuel. From previous study, we found that the amount of NH_3 inversely relates to the sulfur content in the fuel [36].

3.1.9. Particulate Matter ($PM_{2.5}$, PM_{10}, BC, and OC)

Particulate matter such as $PM_{2.5}$, PM_{10}, BC, and OC emit from the incomplete combustion of fuels, especially in diesel engine vehicles [17]. The resultant particulate matter is presented in Figure 12i–l, respectively, which are described in detailed as followed:

(1) For $PM_{2.5}$, the annual average from 2007 to 2015 was approximately 6.24 kt, the major contributor of which is heavy duty trucks, emitting an annual average 3.00 kt or a share of about 48% of the annual average of $PM_{2.5}$; followed by light duty trucks (1.20 kt or 19% of the annual average), and light duty cars with diesel engine (0.83 kt or 13% of the annual average), and lastly heavy duty buses (0.82 kt or 13% of the annual average). The trend of $PM_{2.5}$ showed a decrease from 9.07 kt in 2007 to 4.92 kt in 2015, with an average dropping rate of 5.5% annually.

(2) For PM_{10}, the annual average during the study period was about 7.38 kt. Heavy duty trucks dominates as the major emitter (3.88 kt or 53% of the annual average), followed by heavy duty buses (1.29 kt or 17.5% of the annual average) and light duty trucks (1.28 kt or 17.3% of the annual average). The trend of PM_{10} showed a decrease from 10.58 kt in 2007 to 5.05 kt in 2015, with an average dropping rate of 7.9% annually.

(3) For BC, the annual average was about 3.51 kt, the major source of which is heavy duty trucks, followed by light duty trucks, and light duty cars with diesel engines at the average values of 1.73 kt (49% of the annual average), 0.74 kt (21% of the annual average), and 0.52 kt (15% of the annual average), respectively. The trend of BC showed a decrease from 4.62 kt in the year 2007 to 3.12 kt in the year 2015, with an average reduction rate of 2.5% annually.

(4) For OC, the annual average was about 2.1 kt, the largest share of which comes from heavy duty trucks (0.96 kt or 45% of the annual average), followed by light duty trucks (0.39 kt or 18% of the annual average), and heavy duty buses (0.27 kt or 13% of the annual average), as well as light duty cars with diesel engine (0.26 kt or 13% of the annual average). The trend of OC showed a decrease from 3.92 kt in the year 2007 to 1.48 kt in the year 2015, with an average annual decreasing rate of 7.7%.

Taking into consideration the fraction of BC to $PM_{2.5}$, it was found that diesel engines had the fraction in the range of 0.5–0.8, whereas gasoline engines had the fraction in the range of 0.06–0.3. The highest share derived from heavy duty trucks, meaning that trucks contribute the largest amount of BC. The fraction of OC to $PM_{2.5}$ found quite similar shares for diesel and gasoline engines, with the largest share occupied by motorcycles (the fraction is in the range between 0.45 and 0.71), meaning that motorcycles contribute the high amount of OC.

These results demonstrate that the reduction of particulate matter comes from the higher control on sulfur content in the fuel and the higher intensive standards of vehicle engines. With the major source of particulate matter being emitted from heavy duty vehicles, the mitigation plan is to enforce more intense engine standards for heavy duty vehicle.

3.2. Temporal Distribution of Emissions from On-Road Transport

Figure 13a,b demonstrate the temporal variation of CO and NO_X emissions, which are the major emissions from road transport. In the BMR area, CO emissions, mainly emitted from light duty cars, are highest during the morning peak and evening peak classified as rush hour. However, CO emissions during the morning peak are slightly higher than those in the evening because the period of traffic congestion in the morning is shorter than that in the evening due to the characteristic behavior of urban people, who tend to hurry more in the morning. For NO_X emissions, mainly from heavy duty vehicles, they are mostly emitted during off-peak time. This pattern comes from the permitted time and area restrictions for truck trips. In the BMR area, the operating time for trucks on the BMR road network is from 9.00 a.m.–4.00 p.m. and after 8.00 p.m., except in the inner area of Bangkok, where the operating time for trucks is only at night (11.00 p.m. till 5.00 a.m. the following day). The trend of monthly variation of emissions is very similar for all emission species. The peak of emissions is in April, February, and August, which is related to the monthly distribution of traffic volume classified by vehicle type as detailed in Section 2.6.1

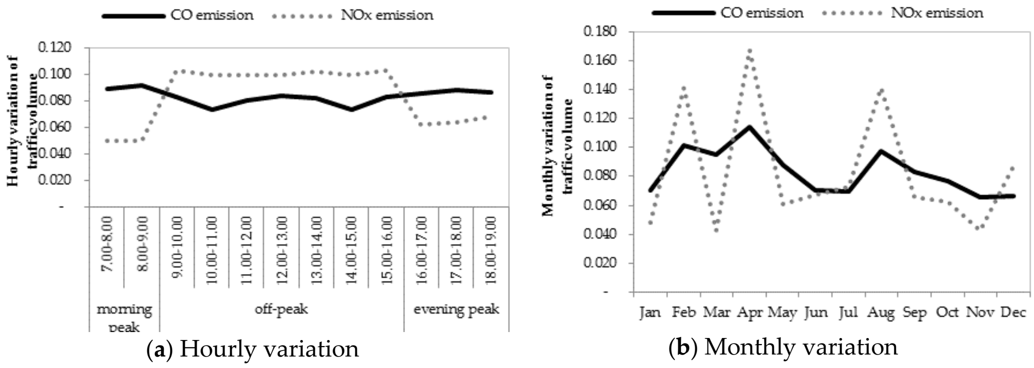
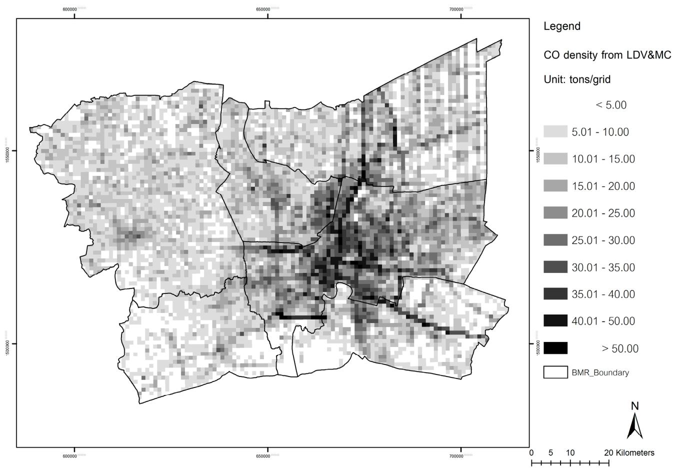


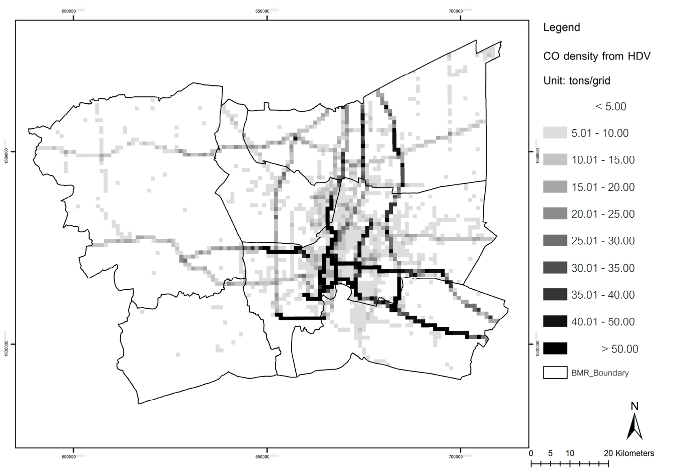
Figure 13. Temporal variation of CO and NO_X emissions in the BMR, 2015: (**a**) hourly variation; (**b**) monthly variation.

3.3. Spatial Distribution of Emissions from On-Road Transport

The allocation of each emission species is determined from the trip distribution of the modal share, as presented in Figures 14–16. From the traffic distribution information of each mode, the high congestion of light duty vehicles was found in the center of Bangkok, a downtown area, as well as at the boundary between provinces, the provincial connection area. These areas have a high intensity of CO emissions, as presented in Figure 14a. Meanwhile, a high volume of trucks was found on the ring road motorway, which is the road network of suburb areas, and on the highway, which is network linkage between provinces, and especially in the western side of Bangkok, which is the industrial estate area. These areas are facing a high intensity of NO_X and PM_{10} emissions, as presented in Figures 15b and 16b. These results demonstrate the allocation of each emission species, which relates to the amount and mode of traffic as well as the land use area.

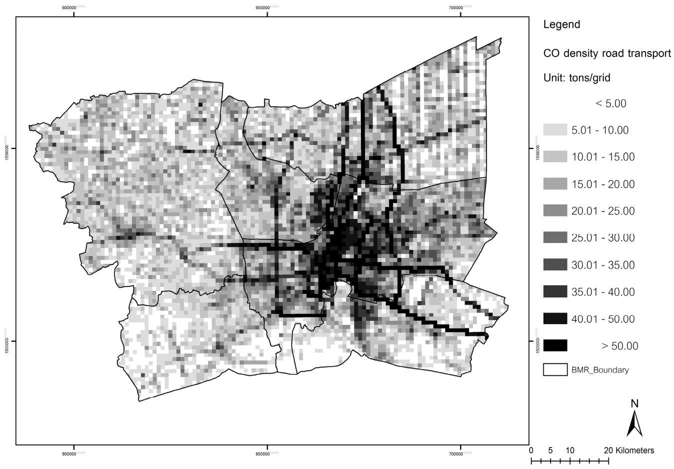


(**a**) CO emission density from light duty vehicles and motorcycles



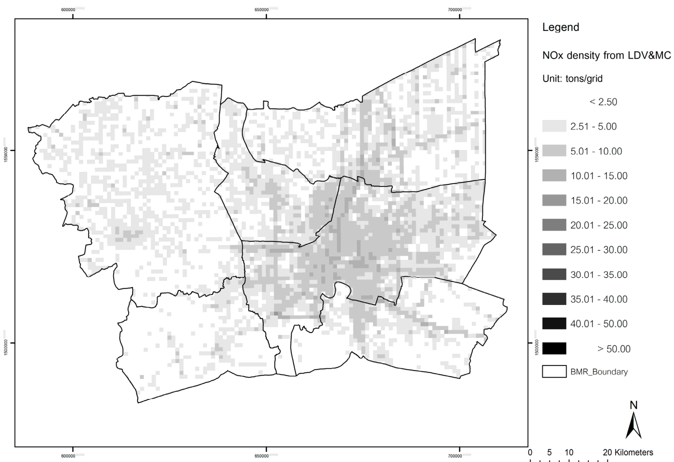
(**b**) CO emission density from heavy duty vehicles

Figure 14. *Cont.*

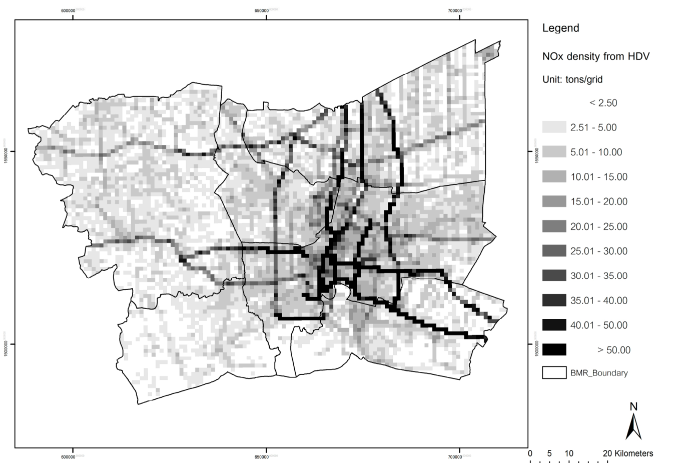


(**c**) CO emission density from road transportation

Figure 14. Spatial allocation of CO emission in the BMR, 2015: (**a**) light duty vehicles and motorcycles; (**b**) heavy duty vehicles; (**c**) road transportation.

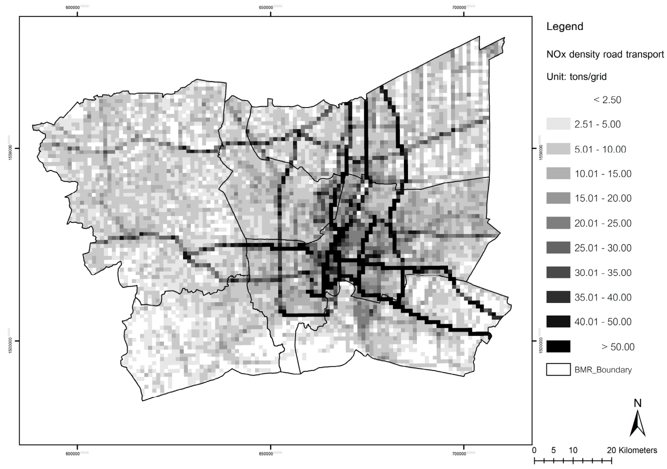


(**a**) NOx emission density from light duty vehicles and motorcycles



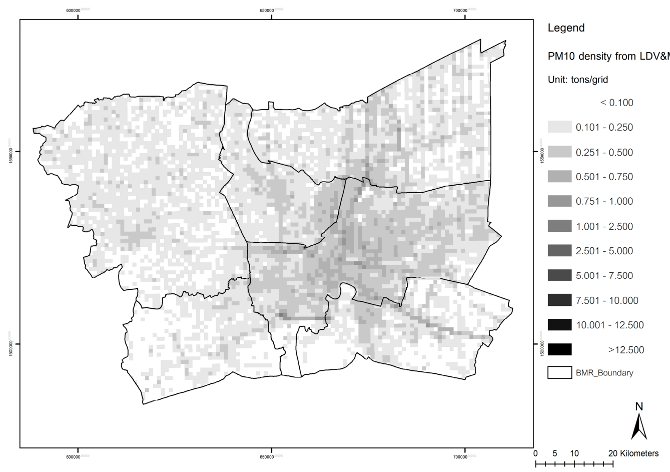
(**b**) NOx emission density from heavy duty vehicles

Figure 15. *Cont.*

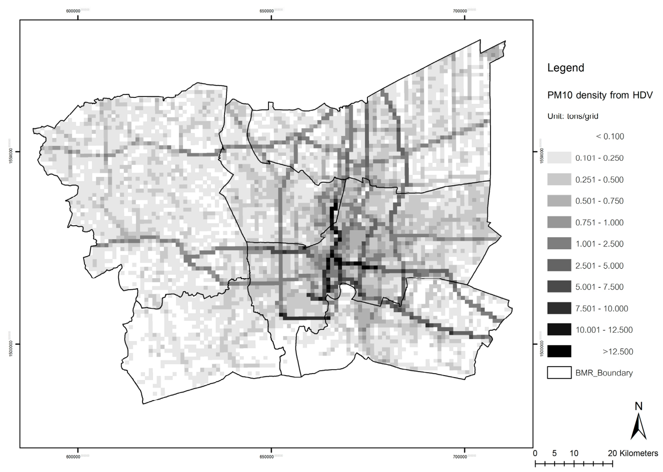


(**c**) NO_X emission density from road transportation

Figure 15. Spatial allocation of NO_x emission in the BMR, 2015: (**a**) light duty vehicles and motorcycles; (**b**) heavy duty vehicles; (**c**) road transportation.

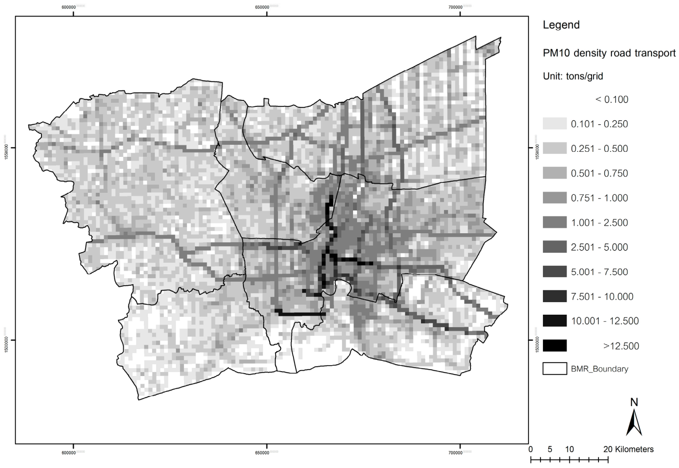


(**a**) PM_{10} emission density from light duty vehicles and motorcycles



(**b**) PM_{10} emission density from heavy duty vehicles

Figure 16. *Cont.*



(**c**) PM10 emission density from road transportation

Figure 16. Spatial allocation of PM_{10} emission in the BMR, 2015: (**a**) light duty vehicles and motorcycles; (**b**) heavy duty vehicles; (**c**) road transportation.

3.4. Comparison with Other Studies

From the literature review related to emission inventories from road transport in the BMR area, there are several studies on the emission inventory of Thailand [37,38]. However, there are two studies that are closely associated with this study, including the study of Kim Oanh, N.T. et al. [39], and the study of GAINS-Asia [29].

Kim Oanh, N.T. et al. [39] studied ground-level ozone in the Bangkok Metropolitan Region by Advanced Mathematical Modeling for Air Quality Management. A part of this study develops emission inventory in two activities, including road transport and fuel station over the BMR area for the base year 2010 using a bottom-up approach with the International Vehicle Emissions (IVE) model. This study uses distance traveled as a main driver for emissions estimation, taken from the e-bum traffic model that provides the annual kilometers traveled (VKT) for each type of vehicle at different road junctions, excluding small roads, for the year 2010. Primary data from the sampling of parking lot surveys; GPS surveys, and traffic videos are used as inputs for the IVE model to quantify the EF that represents the driving pattern conditions of Bangkok. The result of this study is summarized and presented in Table 4, which demonstrates that the results of this study are in line with those obntained by Kim Oanh, N.T., et al., although different drivers and dissimilar emission factors are used.

GAINS-Asia [29] developed an emission inventory for all sectors over five regions of Thailand for the period of 1990–2050, and reports in five-year intervals using a top-down approach to quantify the activity data. The emission inventory is developed under two scenarios including a Current Legislation (CLE) scenario and a Maximum Feasible Reduction (MFR) scenario. The activity data related to energy for the period 1990–2010 were obtained from the statistics of the International Energy Agency (IEA), whereas the projection from 2010 to 2050 was taken from the Energy Technology Projection (ETP 2012). The emission inventory of the CLE scenario for road transport activity over the BMR area in the year 2010 is presented in Table 4, which shows that emissions related to fuel and vehicle engine standard such as CO, NO_X, and particulate matter are lower than the results of this study. This demonstrates that GAINS-Asia expects that Thailand's vehicle-technology efficiency will be higher than indicated in this study. For CO_2 emissions related to the amount of fuel consumption, the CO_2 from GAINS-Asia is also lower than that recorded in this study, because GAINS-Asia expects the use of high efficiency of vehicle engines following the information from Energy Technology Perspective. In addition, GAINS-Asia provides the consumptions of LPG and NGV that are lower than the real situation, which results in the lower estimation of CH_4 emissions compared to this study.

From this information, it can be seen there are several factors that influence the distinction of emission estimation such as methodology, emission driver factors, source of information, and so on. Some previous studies, especially on the small scale (city or regional scales), use a bottom-up approach (using primary information), as did the study of Kim Oanh, N.T. et al., whereas other studies, especially on the large scale (national, international or continental scales) use a top-down approach (using secondary information), as did the study of GAINS-Asia. Either fuel consumption or distance traveled can be used as drivers for exhaust emission estimation. In addition to the method and driver factor used in the emissions calculation, the information that is associated with the study site is very important.

Table 4. Comparison of the emission inventory over the BMR area in the year 2010 between other studies and this study.

Emission Species	Emission from Other Studies (kt)		This Study
	Kim Oanh, N.T. et al. [39]	GAINS-Asia [29]	
CO	246	112	239
NO_X	149	35	147
NMVOC	27	21.1	34.7
CO_2	18,278	4980	17,800
CH_4	49.83	4.6	13
N_2O	0.54	0.17	0.69
SO_2	2.5	0.2	7
NH_3	-	0.3	1.2
$PM_{2.5}$	-	2.9	8.2
PM_{10}	-	3.4	9.3
BC	-	-	4.5
OC	-	-	2.8

4. Conclusions

This study develops an inventory of ozone precursors, greenhouse gases, acidic substances, and particulate matter—in total 12 emissions—from on-road transport during the period from 2007 to 2015 over the BMR area using actual data with the GAINS model in order to investigate the major contributor of each exhaust emission. The factors considered in the emission estimation are equal to Tier 2 of the EMEP/EEA handbook. There are three main factors used for emission estimation in this study. The first factor is activity data, which uses fuel consumption as a major parameter in conjunction with a number of cumulative vehicles, distance traveled, and fuel economy as an indication of the distribution of fuel consumption by fuel and vehicle type. The second factor is the share of control technology, which uses the number of new vehicles, cumulative of vehicles, and the enforcement of vehicle engine standard to quantify the share of control technology for each mode. The last factor is the emission factor obtained from the GAINS-Asia database. The total amount of emissions is allocated to 1 km $\times$ 1 km resolution and varied according to hourly and monthly distributions using the modal share of traffic as a factor.

The results show that the amount of exhaust emissions over the BMR area in the year 2015 and the trend from 2007 to 2015 is about 139 kt of CO (−7.9%), 103 kt of NO_X (−4.1%), 19.9 kt of NMVOC (−6.7%), 15 kt of CO_2 (+1.6%), 8.6 kt of CH_4 (+6.8%), 0.59 kt of N_2O (+1.3%), 0.87 kt of SO_2 (−25.8%), 1.1 kt of NH_3 (+7.8%), 4.9 kt of $PM_{2.5}$ (−5.5%), 5.1 kt of PM_{10} (−7.9%), 3.1 kt of BC (−2.5%), and 1.4 kt of OC (−7.7%). Some of the emissions have a downward trend, such as SO_2, ozone precursor emissions, and particulate matter, due to the higher control of sulfur content in the fuel and the vehicle engine standard. Some of them have an upward trend, such as NH_3 and GHG emissions, which come from the increase of fuel consumption, especially alternative fuels. In addition, using additives to control some emissions also affects to the high release of other emissions. In particular, light duty cars fueled by gasoline represent a major contributor of CO, NH_3, N_2O, and NMVOC (accounting for an average of 52% of CO, 53% of NH_3, 64% of N_2O, and 29% of NMVOC), whereas trucks were the largest emitter of NO_X, SO_2, and particulate matter (accounting for an average of 53% of NO_X, 53% of NH_3, 67% of SO_2, 48% of $PM_{2.5}$, 52% of PM_{10}, 49% of BC, and 45% of OC).

Taking into consideration the temporal and spatial variation of traffic density by modal share, information that reflects the exhaust emission contribution, in the BMR area, CO emissions are mainly emitted during early morning, with the risk area being the center of Bangkok and the provincial boundary area especially between Bangkok and Nonthaburi province, as well as Bangkok and Pathumthani province. NO_X emissions are mainly emitted during the off-peak period, with the risk area being in the suburbs, especially the area around the highway network linkage between provinces.

The result of this study shows the pattern of exhaust emissions over the BMR area. This information contributes to a thorough understand of the influence of related policy on the trends and type of fuel consumption in road transport activity. It can be seen that the trend of fuel consumption has decreased since the year 2012, which is associated with the implementation of the Energy Efficiency Development Plan (EEP-2015) [6], encouraging the use of high efficiency vehicles, electric vehicles, etc. The shift from petrol fuel to gas fuel during the period of 2008 to 2013 and the shift back from gas fuel to petrol fuel during 2014 and 2015 corresponded to the crude oil price situation and the floating gas price policies. The changing amounts and types of fuel consumption also influenced the level of emissions of each species. Moreover, the most powerful implementation plan leading to the continuous reduction of ozone precursor, SO_2, and particulate matter emissions was the more stringent enforcement of fuel and vehicle standard levels. In order to further control emissions in the BMR area, more stringent of vehicle standards for heavy duty vehicles, the major contributor of particulate matter and NO_X emissions, are needed. As the regulation of heavy duty vehicle standards skip from Euro 3 standard to Euro 4 standard in the future, it is expected that the emission factors of CO, NO_X, and particulate matter will be reduced by approximately 20%, 28% and 77%, respectively.

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Author Contributions: Penwadee Cheewaphongphan and Agapol Junpen devised the project, the main conceptual ideas and proof outline. They worked out almost all of the technical details, and performed the numerical calculations. Savitri Garivait supervised the findings of this work. Penwadee Cheewaphongphan proposed the result in discussions with Satoru Chatani. All authors discussed the results and contributed to the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Emission factor used in this study.

(a) Emission Factor of Ozone Precursors (Unit: kt Emission/PJ)				
Vehicle-Fuel Types	**Engine Standard**	**CO**	**NO_X**	**NMVOC**
LDC/LDT-GSL	Pre-Euro	6.9000	0.8600	0.7500
	Euro 1	2.7600	0.2494	0.2175
	Euro 2	0.8280	0.1118	0.0975
	Euro 3	0.8280	0.0688	0.0600
	Euro 4	0.4830	0.0344	0.0300
LDC/LDT-MD	Pre-Euro	0.3100	0.3500	0.0600
	Euro 1	0.2573	0.3675	0.0384
	Euro 2	0.1116	0.3850	0.0342
	Euro 3	0.1116	0.4025	0.0276
	Euro 4	0.1116	0.3850	0.0204

Table A1. *Cont.*

(a) Emission Factor of Ozone Precursors (Unit: kt Emission/PJ)				
LDC/LDT-LPG	Pre-Euro	1.4500	0.8600	0.6375
	Euro 1	0.5800	0.2494	0.1848
	Euro 2	0.1740	0.1118	0.0828
	Euro 3	0.1740	0.0688	0.0510
	Euro 4	0.1015	0.0344	0.0255
LDC/LDT-NGV	Pre-Euro	0.7200	0.6500	0.6500
	Euro 1	0.2880	0.1885	0.1885
	Euro 2	0.0864	0.0845	0.0845
	Euro 3	0.0864	0.0520	0.0520
	Euro 4	0.0504	0.0260	0.0260
HDT/HDB-GSL	Pre-Euro	7.9000	0.8600	0.6500
	Euro 1	1.1850	0.1548	0.1300
	Euro 2	0.9480	0.0860	0.0520
	Euro 3	0.9480	0.0602	0.0195
	Euro 4	0.9480	0.0602	0.0195
HDT/HDB-MD	Pre-Euro	0.9000	1.3000	0.1200
	Euro 1	0.8550	1.2350 (HDT)/1.3000 (HDB)	0.0840
	Euro 2	0.7560	1.1700 (HDT)/1.3000 (HDB)	0.0612
	Euro 3	0.4050	1.1700 (HDT)/1.3000 (HDB)	0.0516
	Euro 4	0.3240	0.8450 (HDT)/1.3000 (HDB)	0.0516
HDT/HDB-LPG	Pre-Euro	1.5200	0.8600	0.5525
	Euro 1	0.2280	0.1548	0.1105
	Euro 2	0.1824	0.0860	0.0442
	Euro 3	0.1824	0.0602	0.01657
	Euro 4	0.1824	0.0602	0.01657
HDT/HDB-NGV	Pre-Euro	0.7400	0.6500	0.5600
	Euro 1	0.1110	0.1170	0.1120
	Euro 2	0.0888	0.0650	0.0448
	Euro 3	0.0888	0.0455	0.0168
	Euro 4	0.0888	0.0455	0.0168
MC	Pre-Euro	12.000	0.1300	1.3430
	Euro 1	7.2000	0.1300	1.2758
	Euro 2	3.0000	0.1157	0.5506
	Euro 3	1.2000	0.0585	0.1745

Table A1. *Cont.*

(b) Emission Factor of GHG Emissions (Unit: kt Emission/PJ)				
Vehicle-Fuel Types	**Engine Standard**	**CO_2**	**N_2O**	**CH_4**
LDC/LDT-GSL	Pre-Euro	68,600	0.0031	0.0690
	Euro 1	-	0.0136	0.0150
	Euro 2	-	0.0055	0.0210
	Euro 3	-	0.0055	0.0160
	Euro 4	-	0.0055	0.0110
LDC/LDT-MD	Pre-Euro	73,400	0.0018	0.0093
	Euro 1	-	0.0018	0.0056
	Euro 2	-	0.0018	0.0023
	Euro 3	-	0.0018	0.0016
	Euro 4	-	0.0052	0.0000
LDC/LDT-LPG	Pre-Euro	68,600	0.0006	0.0332
	Euro 1	-	-	0.0332
	Euro 2	-	-	0.0332
	Euro 3	-	-	0.0332
	Euro 4	-	-	0.0332
LDC/LDT-NGV	Pre-Euro	55,800	0.0001	0.7000
	Euro 1	-	-	0.1518
	Euro 2	-	-	0.2067
	Euro 3	-	-	0.1400
	Euro 4	-	-	0.0913
HDT/HDB-GSL	Pre-Euro	68,600	0.0031	0.0541
	Euro 1	-	-	0.0117
	Euro 2	-	-	0.0160
	Euro 3	-	-	0.0108
	Euro 4	-	-	0.0108
HDT/HDB-MD	Pre-Euro	73,400	0.00180	0.0176
	Euro 1	-	0.00106	0.0176
	Euro 2	-	0.00102	0.0176
	Euro 3	-	0.00061	0.0176
	Euro 4	-	0.00310	0.0176
HDT/HDB-LPG	Pre-Euro	68,600	0.0006	0.0092
	Euro 1	-	-	0.0092
	Euro 2	-	-	0.0092
	Euro 3	-	-	0.0092
	Euro 4	-	-	0.0092
HDT/HDB-NGV	Pre-Euro	55,800	0.0001	0.6531
	Euro 1	-	-	0.1419
	Euro 2	-	-	0.1930
	Euro 3	-	-	0.1306
	Euro 4	-	-	0.1306
MC	Pre-Euro	68,600	0.0031	0.0590
	Euro 1	-	-	0.0590
	Euro 2	-	-	0.0590
	Euro 3	-	-	0.0590

Table A1. *Cont.*

(c) Emission Factor of Acidic Substance (Unit: kt Emission/PJ)			
Vehicle-Fuel Types	**Engine Standard**	**SO_2**	**NH_3**
LDC/LDT-GSL	Pre-Euro	0.0091	0.00073
	Euro 1	0.0004	0.03000
	Euro 2	-	0.01200
	Euro 3	-	0.01200
	Euro 4	-	0.00210
LDC/LDT-MD	Pre-Euro	0.4608	0.00045
	Euro 1	0.0921	0.00045
	Euro 2	0.0207	0.00040
	Euro 3	0.0004	0.00040
	Euro 4	-	0.00100
LDC/LDT-LPG	Pre-Euro	0.0042	0.00073
	Euro 1	-	0.03000
	Euro 2	-	0.01200
	Euro 3	-	0.01200
	Euro 4	-	0.00210
LDC/LDT-NGV	Pre-Euro	-	0.00050
	Euro 1	-	0.00490
	Euro 2	-	0.00490
	Euro 3	-	0.00300
	Euro 4	-	0.00250
HDT/HDB-GSL	Pre-Euro	0.0091	0.00026
	Euro 1	0.0004	0.01100
	Euro 2	0.0004	0.01000
	Euro 3	0.0004	0.00500
	Euro 4	0.0004	0.00500
HDT/HDB-MD	Pre-Euro	0.4608	0.00029
	Euro 1	0.0921	0.00029
	Euro 2	0.0207	0.00025
	Euro 3	0.0004	0.00025
	Euro 4	0.0004	0.00045
HDT/HDB-LPG	Pre-Euro	0.0042	0.00026
	Euro 1	-	0.01100
	Euro 2	-	0.01000
	Euro 3	-	0.00500
	Euro 4	-	0.00500
HDT/HDB-NGV	Pre-Euro	-	0.00050
	Euro 1	-	0.01000
	Euro 2	-	0.00500
	Euro 3	-	0.00500
	Euro 4	-	0.00500
MC	Pre-Euro	0.0091	0.00100
	Euro 1	0.0004	0.03500
	Euro 2	-	0.01500
	Euro 3	-	0.01500

Table A1. *Cont.*

(d) Emission Factor of Particulate Matter (Unit: kt Emission/PJ)					
Vehicle-Fuel Types	Engine Standard	$PM_{2.5}$	PM_{10}	BC	OC
LDC/LDT-GSL	Pre-Euro	0.00597	0.00630	0.00099	0.00330
	Euro 1	0.00328	0.00347	0.00091	0.00162
	Euro 2	0.00328	0.00347	0.00091	0.00162
	Euro 3	0.00107	0.00113	0.00052	0.00036
	Euro 4	0.00107	0.00113	0.00049	0.00036
LDC/LDT-MD	Pre-Euro	0.10467	0.10940	0.05757	0.03977
	Euro 1	0.10467	0.10940	0.05757	0.03977
	Euro 2	0.08897	0.09299	0.05354	0.03182
	Euro 3	0.01995	0.02085	0.01693	0.00251
	Euro 4	0.01945	0.02033	0.01692	0.00217
LDC/LDT-LPG	Pre-Euro	0.00184	0.00198	0.00300	0.00100
	Euro 1	0.00101	0.00109	0.00028	0.00049
	Euro 2	0.00101	0.00109	0.00028	0.00049
	Euro 3	0.00033	0.00036	0.00016	0.00049
	Euro 4	0.00033	0.00036	0.00016	0.00011
LDC/LDT-NGV	Pre-Euro	0.00184	0.00200	0.00300	0.00100
	Euro 1	0.00101	0.00110	0.00028	0.00049
	Euro 2	0.00101	0.00110	0.00028	0.00049
	Euro 3	0.00033	0.00036	0.00016	0.00049
	Euro 4	0.00033	0.00036	0.00015	0.00011
HDT/HDB-GSL	Pre-Euro	0.02396	0.02531	0.00398	0.01325
	Euro 1	0.01318	0.01392	0.00364	0.00649
	Euro 2	0.00431	0.00456	0.00210	0.00143
	Euro 3	0.00407	0.00430	0.00198	0.00135
	Euro 4	0.00407	0.00430	0.00198	0.00135
HDT/HDB-MD	Pre-Euro	0.10659	0.10857	0.05330	0.03731
	Euro 1	0.07142	0.07274	0.05276	0.01865
	Euro 2	0.04415	0.04497	0.03031	0.01006
	Euro 3	0.02665	0.02714	0.02532	0.00666
	Euro 4	0.00713	0.00726	0.00533	0.00117
HDT/HDB-LPG	Pre-Euro	0.00184	0.00200	0.00030	0.00100
	Euro 1	0.00101	0.00110	0.00028	0.00049
	Euro 2	0.00033	0.00036	0.00016	0.00011
	Euro 3	0.00031	0.00034	0.00015	0.00010
	Euro 4	0.00031	0.00034	0.00015	0.00010
HDT/HDB-NGV	Pre-Euro	0.00184	0.00200	0.00030	0.00100
	Euro 1	0.00101	0.00110	0.00028	0.00049
	Euro 2	0.00033	0.00036	0.00016	0.00011
	Euro 3	0.00031	0.00034	0.00015	0.00010
	Euro 4	0.00031	0.00034	0.00015	0.00010
MC	Pre-Euro	0.00597	0.00630	0.00099	0.00330
	Euro 1	0.00537	0.00567	0.00091	0.00162
	Euro 2	0.00358	0.00378	0.00052	0.00036
	Euro 3	0.00179	0.00189	0.00049	0.00034

Remark: LDC stands for light duty vehicles; LDT stands for light duty trucks; HDT stands for heavy duty trucks; HDB stands for heavy duty buses; MC stands for motorcycles.

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