AIR POLLUTION CHARACTERISTICS IN BANGKOK AND PM2.5 EMISSION IN ON-ROAD TRANSPORT SECTOR FOR CONTROL POLICY IMPLICATIONS

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ABSTRACT

Title of Dissertation AIR POLLUTION CHARACTERISTICS IN BANGKOK AND PM2.5 EMISSION IN ON-ROAD TRANSPORT SECTOR FOR CONTROL POLICY IMPLICATIONS

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In Thailand, the air pollution situation is one of the severe environmental issues. Particularly, the major sources of $PM_{2.5}$ in Thailand are normally caused by forest fire, biomass open burning, and vehicles. Bangkok, where is the capital city of Thailand, has faced the severe $PM_{2.5}$ episode. According to the Pollution Control Department (PCD) annual reports, they revealed that the main causes of $PM_{2.5}$ highly come from transportation and open burning, respectively. Thus, this study focused on the $PM_{2.5}$ air quality in on-road transport sector in Bangkok by using Emission Inventory (EI) tool to identify the distinct source of vehicle types and fuels associated $PM_{2.5}$ portions. The main aim is to establish the database of $PM_{2.5}$ from on-road transport sector in Bangkok during 2010 to 2019. The types of vehicles were considered into seven types based on Department of Land and Transport that consist of personal cars, motorcycles, vans, public pick-up transport, buses, trucks, pick-ups, and tuk-tuk. The results showed that the largest vehicle which contributed to the high level of $PM_{2.5}$ emission was trucks with the use of Pre-Euro diesel engines had the portion of emission up to 49%. Followed by Pickups with Pre-Euro diesel engines which had 38% of $PM_{2.5}$ emission.

However, to implement the policy for reducing $PM_{2.5}$ concentration, the prediction of $PM_{2.5}$ concentration in ambient air quality need to be considered. Thus, the relationship between $PM_{2.5}$ and factor affecting $PM_{2.5}$ concentration were correlated to estimate future $PM_{2.5}$ prediction in Bangkok. Two models were developed in different variables by using the data of 2017 to 2019. The results demonstrated that the performance of $PM_{2.5}$ model prediction in this study had high correlation with R^2 0.84 and 0.86 for Model I and Model II, respectively. In addition, to verify the concentration

of $PM_{2.5}$ prediction in this section box model was applied. Finally, the implication of $PM_{2.5}$ reduction policy were recommended based on the results of major sources of on-road $PM_{2.5}$ emission and the future emission control standards for the next ten-years (2020-2030).

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CHAPTER 1

INTRODUCTION

1.1 Background and Significance of the Research

The rapid growth of Bangkok in terms of physical, economic, and social aspects entails a lot of residences and employment sources in the inner area of Bangkok with gradual expansion to the suburban areas due to urban congestion. As Bangkok is an economically important city, many people move in and reside in urban communities generating increased demand in travelling. For people living in Bangkok, the factor of travelling to perform various activities is crucial for the urban people. The increased uses of automobiles and roads have resulted in traffic problems. Therefore, the policy was formulated for urban development by rail system as indicator of the government's development leading to the establishment of BTS Skytrain. After the development of rail system or Skytrain, the area around the Skytrain became a high potential area for access. The private sector made more investment in real estate, including office buildings, residential buildings or condominiums, and large commercial buildings or shopping malls to respond to the needs of the residents around the Skytrain. Consequently, there had been changes in the density of land use, increasing land prices in business areas. More people started to move to new residential areas in outer areas, notably the suburban areas in the west and east of Bangkok. There were investments in housing estate projects in the outer areas of Bangkok. As the suburban areas still had empty space and potential to develop the areas into residential areas with lower land prices than in the urban areas, the urban expansion to the suburban areas contributed to the change in land use the land use for agriculture to produce food to urban communities was changed into mixed land use consisting of land use for agriculture, residence, commerce, and industry. Therefore, at present, there have been great changes in the landcover. The green zone is increasingly used for residences, commerce, government offices, industries, academic institutions, warehouses, and religious institutions, etc. These buildings hinder the horizontal movement of wind (Advection) which is one of the reasons for air pollution in Bangkok. Whenever air pollutants are discharged and blown by wind in any direction, the air pollutants will gradually spread to the side. The intensity of the pollutants will be the highest at the center of the group of air pollutants. The intensity at the side will be less due to the influence of the blow in the direction of the wind (Convection), the value of which is more than the Diffusion of the direction against the wind. For example, when the air pollutants are blown by the wind in the direction of the city and are met with buildings, there will be the Wake of the air pollutants behind the buildings due to the fluid viscosity. If there are a lot of buildings, air pollutants may be slowly blown by the wind so they may not be well dispersed.

Moreover, it is found that the urban areas consist of congested buildings and edifices including roads and surfaces modified into paved roads which will be exposed to sunlight and greatly absorb heat. The ability of general construction materials such as concrete can contain heat as much as 2,000 times the ability of air for heat capacity with the same volume (Lee, 1993). The buildings will start continuously releasing heat into the surrounding air which is the general quality of materials to maintain the temperature of the materials similarly to the temperature of the surrounding air. In daytime, the release of heat of buildings in urban areas will have lower capacity compared with suburbs or outskirts with more natural features. Natural features consist of trees, soil, water sources which will contribute to major factors of the mechanism to release heat from natural features through evaporation in the air. It efficiently lowers the temperature of the areas. It is found that at the center of urban areas especially urban shopping malls and business centers consist of a lot of high-rises. These high-rises have more building surface than other types of buildings nearby. The more building surface will absorb more infrared of the building due to much space to absorb heat. At the same time, the layout of these buildings is arranged in parallel with the roads. Therefore, the building surface that receives infrared from sunlight will reflect the infrared with both buildings of the roads rendering higher temperature of the air around the roads and adjacent areas. This phenomenon is called “Urban heat Island”.

All features as mentioned above generate air pollution in Bangkok. In terms of the information of air quality in Bangkok between 1998-2021, it was found that the pollutants posing major problems of exceeding the standards were the particulate matter (PM_{10} and $PM_{2.5}$) around the roads of inner city and ozone (O_3) in general areas. They were mainly caused by diesel vehicles. At for 2022, all types of cars registered in Bangkok amount to over 11.61 million (3.18 million cars run on diesel: information as per December 31, 2022, Land Transport Department). If the motors of these vehicles are not regularly maintained, air pollution can be released (Air Quality and Noise Management Division, Environment Department, BMA). In the past, the government formulated the policy to limit the use of diesel vehicles emitting black smoke that exceeded the standards to reduce PM_{10} along the roads. In 2012, the requirement was issued that small diesel vehicles and benzene vehicles must comply with the Euro 4 standards and the fuel used must comply with the Euro 4 standards as well. The overall situation of particulate matter revealed that the measures to control the PM for the past 20 years were successful. But the $PM_{2.5}$ tended to increase recently which showed that pollution sources from the transport sector increased, impacting people’s health. Therefore, more stringent measures are needed to reduce the PM within the standard. For the past 2-3 years, Bangkok has continuously encountered the crisis of PM_{10} and $PM_{2.5}$. The main factor that has caused the problem of $PM_{2.5}$ or 70% derived from land transport in Bangkok (Kim Oanh, 2017). At the same time, the “Temperature inversion", usually occurring in winter, means the cold layer is kept under the hot layer, resulting in the feature like room ceiling that keeps dust or pollutant formed at the earth level and prevents it from floating up in the air. Moreover, common factors include Bangkok's geographical features which is a basin, and which does not facilitate pollution dilution, as well as the city plan, and the lay-out of construction that do not efficiently ventilate the air. The researcher was therefore interested in studying the formation of air pollution in Bangkok for the past ten years and the trend of particulate matter (PM_{10} and $PM_{2.5}$) with the aim to analyze the factors impacting air pollution in Bangkok and develop the database of particulate matter not exceeding 2.5 microns ($PM_{2.5}$) from the land transport sector, as well as forecast of situations of the $PM_{2.5}$ from the land transport sector in Bangkok, leading to the formulation of policy of efficient management to control, prevent, and monitor air quality.

1.2 Research Questions

1) The characteristics of the formation of air pollution in Bangkok for the past 10 years

2) The factors that impact the formation and the spread of particulate matter (PM_{10} and $PM_{2.5}$) in Bangkok

1.3 Research Objectives

1) Explain the characteristics of the formation of air pollution in Bangkok for the past ten years

2) Analyze the factors that impact the formation and the spread of particulate matter (PM_{10} and $PM_{2.5}$) in Bangkok

3) Develop the database of $PM_{2.5}$ from land transport sector in Bangkok

4) Forecast the situations of the emission of $PM_{2.5}$ from land transport sector in Bangkok

1.4 Research Scope

1.4.1 Scope of Content

1) Data of air quality from air quality monitoring stations around roads in Bangkok from Air Quality and Noise Management Bureau, Pollution Control Department between 2007-2016 by determining the parameters of the study as follows:

(1) SO_2 measured by the equipment to measure UV fluorescence system

(2) NO_2 measured by the equipment of Chemiluminescence

(3) O_3 measured by the method of Ultraviolet Absorption Photometry

(4) CO measured by the method of non-Dispersive infrared Detection

(5) PM_{10} and $PM_{2.5}$ used the data between 2007-2020 to measure using the method of Beta Ray Attenuation and according to the Federal Equivalent Method (FEM) determined by the US Environmental Protection Agency (US EPA)

(6) Wind speed and Wind direction

2) Data of air quality from air quality monitoring stations of Bangkok from Air Quality and Noise Management Division, BMA during 2017-2020 by determining the parameter of the study as follows:

(1) $PM_{2.5}$ is measured by the method of Beta Ray Attenuation and according to the Federal Equivalent Method (FEM) as determined by US Environmental Protection Agency (US EPA)

(2) Wind speed and Wind direction

(3) Data of all types of cars registered in Bangkok from Land Transport Department between 2010-2019

(4) Data of meteorological situations from Thai Meteorological Department consisted of wind direction, wind speed, temperature, humidity, and atmospheric pressure between 2017-2020

(5) Data of the quantity of hotspots from MODIS satellite from Geo-Informatics and Space Technology Development Agency (Public Organization) between 2017-2020

(6) Data of yearly agricultural produces and rice output from Office of Agricultural Economics between 2017-2020

1.4.2 Scope of Area

1) Use the data of air quality from Air Quality and Noise Management Bureau, Pollution Control Department from 12 stations as follows:

Table 1.1 Air Quality Monitoring Stations of Pollution Control Department

Rank	Stations	Locations
1	Ministry of Science and Technology.	Rama 6 Road, Phaya Thai District
2	King Chulalongkorn Memorial Hospital.	Rama 4 Road, Pathum Wan District
3	Chokchai Metropolitan Police Station.	Lat Phrao Road, Wang Thonglang District
4	Land Transport Department.	Phaholyothin Road, Chatuchak District
5	MEA Substation Thonburi.	Intharaphithak Road, Thonburi District
6	National Housing Authority Dindaeng.	Din Daeng Road, Din Daeng District

Rank	Stations	Locations
7	On Highway No. 3902.	On Kanchanaphisek Road, Bang Khun Thian District
8	Thai Meteorological Department Bang Na.	Bang Na Subdistrict, Bang Na District
9	National Housing Authority Klongchan.	Klongchan Subdistrict, Bang Kapi District
10	National Housing Authority Huai Khwang.	Din Daeng Subdistrict, Din Daeng District
11	Public Relations Department.	Phaya Thai Subdistrict, Phaya Thai District
12	Bodindecha (Sing Singhaseni) School.	Phlabphla Subdistrict, Wang Thonglang District

2) Use the data of air quality from Air Quality and Noise Management Division, BMA from 24 stations. The areas under the study were divided into six district groups as follows:

(1) Central Bangkok consisted of Phra Nakhon District, Samphanthawong District, Phaya Thai District, Ratchathewi District, and Wang Thonglang District

(2) Central Bangkok consisted of Pathum Wan District, Bang Rak District, Sathon District, Bang Kho Laem District, Yan Nawa District, and Khlong Toei District

(3) North Bangkok consisted of Chatuchak District, Bang Sue District, Lak Si District, and Bang Khen District

(4) East Bangkok consisted of Bang Kapi District, Bueng Khum District, and Lad Krabang District

(5) North Thonburi consisted of Thonburi District, Khlong San District, Bangkok Noi District, and Bang Phlat District

(6) South Thonburi consisted of Phasi Charoen District, and Bang Khun Thian District

Table 1.2 Air Quality Monitoring Stations of Bangkok Metropolitan Administration

Rank	Stations	Locations
Central Bangkok		
1	Phra Nakhon District	Within Phra Nakhon District Office
2	Samphanthawong District	At the corner of Royal Jubilee Gate (Odeon Circle)
3	Phaya Thai District	In front of Army Flat near Vichaiyut Hospital opposite Ministry of Finance
4	Ratchathewi District	Within Ratchathewi District Office
5	Wang Thonglang District	In front of Esso gas station, Soi Lat Phrao 95
South Bangkok		
6	Pathum Wan District	In front of Samyan Mitrtown
7	Bang Rak District	Next to police booth at the yard in front of Bang Rak Lovely Plaza
8	Sathon District	Intersection in front of Sathon District Office at Soi Saint Louis
9	Bang Kho Laem District	Area of police booth at Thanon Tok Intersection
10	Yan Nawa District	Near Krungsri Bank Head Office
11	Khlong Toei District	Within Khlong Toei District Office
North Bangkok		
12	Chatuchak District	Area in front of Kasetsart University
13	Bang Sue District	Within Bang Sue District Office
14	Lak Si District	Within Lak Si District Office
15	Bang Khen District	Within Bang Khen District Office
East Bangkok		

Rank	Stations	Locations
16	Bang Kapi District	Next to police booth opposite Bang Kapi District Office
17	Bueng Kum District	Within Bueng Kum District Office
18	Lat Krabang District	In front of Lat Krabang Hospital next to police booth

Table 1.3 Air Quality Monitoring Stations of Bangkok Metropolitan Administration

	North Thonburi	
19	Thonburi District	At bus stop at Mahaisawan Intersection
20	Khlong San District	In front of the library under the Taksin Bridge
21	Bangkok Noi District	In front of Bangkok Noi Railway Police Station
22	Bang Phlat District	Within Bang Phlat District Office
	South Thonburi	
23	Phasi Charoen District	In front of Siam University (near Soi Phet Kasem 36) at the University entrance
24	Bang Khun Thian District	Within Bang Khun Thian District Office

1.4.3 Period of the Study was Divided into Two Phases as Follows:

1) Phase 1: Period of study between 2007-2016

2) Phase 2: Period of study between 2017-2020

1.5 Definition of Terms

1) Air pollution means atmosphere with contaminant higher than usual for a long period of time that can harm humans, animals, plants, or various asset whether natural or manmade.

2) Particulate matter less than 10 microns (PM_{10}) is dust with the diameter not exceeding 10 microns from engine combustion, open air burning, industrial processes, grinding, milling, or crushing into powder from construction which will impact health when breathing as it can be accumulated in the respiratory system.

3) Particulate matter less than 2.5 microns ($PM_{2.5}$) is dust with the diameter not exceeding 2.5 microns from combustion from vehicles, burning of agricultural materials, wildfire, and industrial processes that can enter air sac in the lungs causing various diseases related to the respiratory system and lung diseases if exposed in large quantity and in long period of time. It will accumulate in lung tissues and will degrade the functioning of lungs causing bronchitis and asthma.

4) Temperature inversion is the natural phenomenon that takes place in winter when night is longer than usual with calm wind and clear sky. When the cold layer is kept under the warmer layer, the calm wind will not combine the two layers of atmosphere. Clear sky and longer nights will greatly reduce land temperature. Humidity kept in the atmospheric layers becomes fog.

5) Urban heat Island is the phenomenon that temperature in Bangkok is significantly higher than surrounding temperature. The main cause of urban heat island is the change of land surface from urban development using materials that cause accumulated heat, as well as heat released using energy in various buildings. When the

center of urban population changes, the change of land surface increases accordingly. It is the cause of the average general increase of temperature.

1.6 Research Hypothesis

Factors of locations and activities in each district group impact the characteristics of generation, spread, and intensity of particulate matter (PM_{10} and $PM_{2.5}$) of each area in Bangkok.

1.7 Expected Benefits from the Research

1) BMA can formulate policies and plans to control air pollution in Bangkok under its responsibilities for more efficient and effective operation.

2) Other agencies relevant to BMA can develop the study findings in the formulation of policies and plans to reduce the problems of air pollution.

3) Bangkok residents reduce risks from impact of air pollution and create image of Bangkok as Smart City.

1.8 Methodology

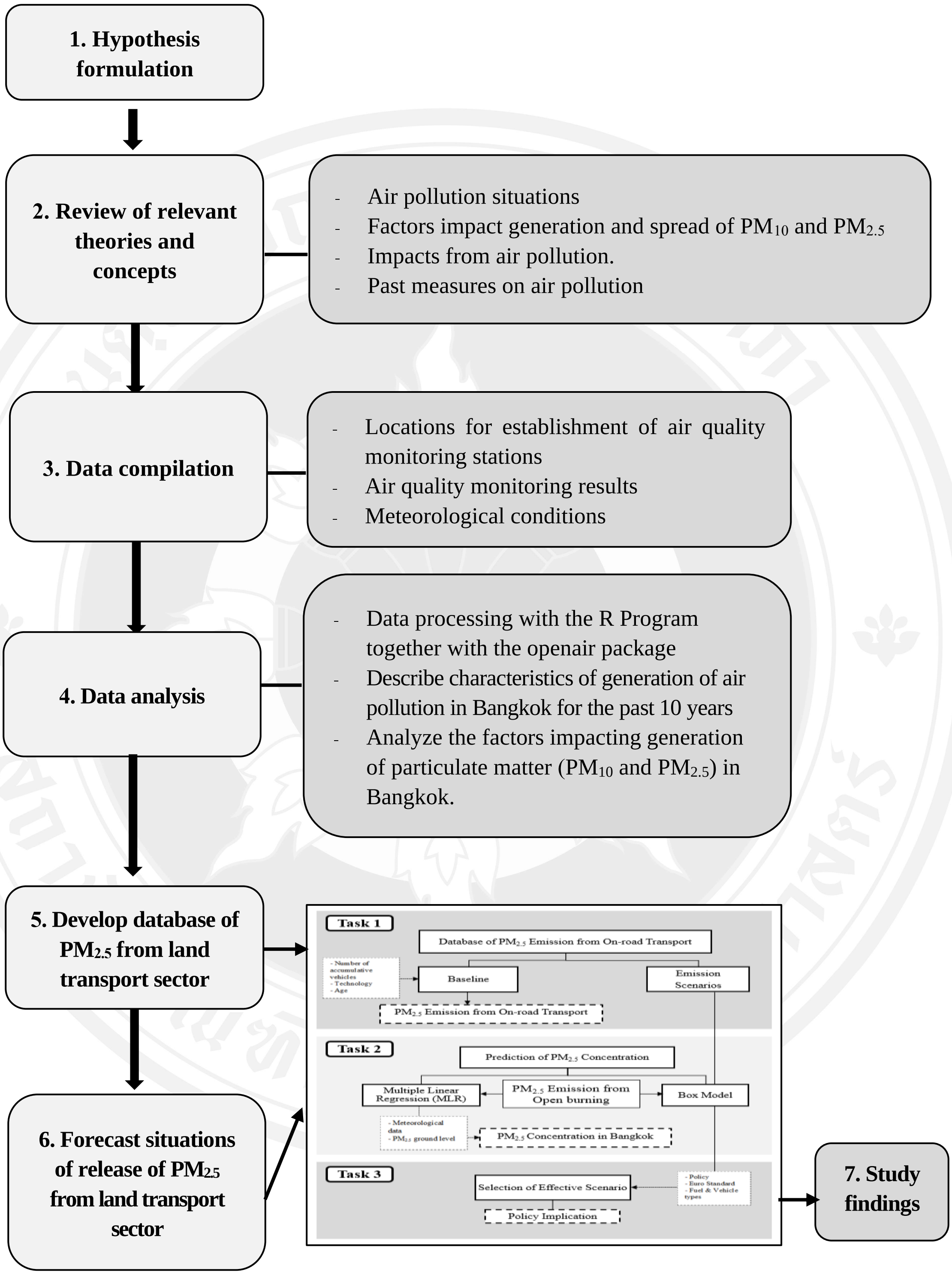


Figure 1.1 Research Conceptual Framework

CHAPTER 2

RELEVANT CONCEPTS, THEORIES, AND RESEARCH WORKS

2.1 General Information of Bangkok

2.1.1 Boundary

Bangkok is connected by land with Samut Sakhon, Nakhon Pathom, Nonthaburi, Pathum Thani, Chachoengsao, and Samut Prakan. It is connected by sea via inner Gulf of Thailand with Phetchaburi, Samut Sakhon, Samut Prakan, and Chon Buri with the following details:

In the north, it borders Nonthaburi and Pathum Thani.

In the east, it borders Chachoengsao.

In the south, it borders Samut Prakan and the Gulf of Thailand (The part of the Gulf of Thailand which was the former area of Thon Buri is currently Bang Khun Thian which borders the Gulf of Thailand with Samut Sakhon, Phetchaburi, Chon Buri, and Samut Prakan, divided according to the Act to determine the boundary of provinces in inner Gulf of Thailand 1959).

In the west, it borders Samut Sakhon and Nakhon Pathom.

2.1.2 Geography

The area of Bangkok is 1,568.7 square kilometers. The 372 km. long Chao Phraya River flows through it. As a result, Bangkok Metropolitan Region forms part of Thailand’s lower central plains which are abundant land suitable for cultivation. Most areas in Bangkok are alluvial plains situated in the river delta due to alluvium with 1.50-

2 meters above mean sea level with the slope from the north to the Gulf of Thailand in the south. Specifically, the lower Chao Phraya River does not exceed 1.50 meters above sea level, causing frequent floods during the monsoon season.

2.1.3 Climate

Bangkok is situated in the tropical zone with the type of tropical savanna climate (Aw) according to the global climate classification by Waldimir Koppen. The average temperature in the month with the lowest temperature is higher than 18 degrees Celsius. Hydro-Informatics Institute of Ministry of Higher Education has collected data on rainfall in Thailand in each province from 2018 to 2022. From the data, it was found that the amount of rainfall in the first 7 months of the year 2022 was rainfall. Accumulated at 73,894 millimeters, which is higher than the average with a volume of 58,377 millimeters and the highest value compared to four years ago. The climate in Bangkok is influenced by the southwest monsoon (Mid-May to October) and the northeast monsoon (November to mid-February). There is a passing monsoon trough between May and September which causes heavier rainfall than usual. But during June-July, this monsoon trough will move up north causing less rainfall. In November, when the northern hemisphere moves away from the sun, high-pressure area from China will move down. The northeast monsoon blowing dryness and chill will render the weather cool and dry with bright sky, no cloud, and little rainfall. Until the latter half of February, the northeast monsoon will drop. It changes to summer when the weather is getting hotter. The wind current during this period will blow from the south or the southeast called “Trade winds”.

2.1.4 Administrative Areas

Bangkok is divided into 50 administrative districts as shown in Figure 2.1

1) Inner areas consist of Phra Kakhon, Pom Prap Sattru Phai, Samphanthawong, Pathum Wan, Bang Rak, Watthana, Yan Nawa, Sathon, Bang Kho Laem, Dusit, Bang Sue, Phaya Thai, Ratchathewi, Huai Khwang, Khlong Toei, Chatuchak, Thon Buri, Khlong San, Bangkok Noi, Bangkok Yai, and Din Daeng, in total 21 districts.

2) Middle areas consist of Phra Khanong, Prawet, Bang Khen, Bang Kapi, Lat Phrao, Bueng Kum, Bang Phlat, Phasi Charoen, Chom Thong, Rat Burana, Suan Luang, Bang Na, Thung Khru, Bang Khae, Wang Thonglang, Khan Na Yao, Saphan Sung, and Sai Mai, in total 18 districts.

3) Outer areas consist of Min Buri, Don Mueng, Nong Chok, Lat Krabang, Taling Chan, Nong Khaem, Bang Khun Thian, Lak Si, Khlong Sam Wa, Bang Bon, and Thawi Watthana, in total 11 districts.

The 50 administrative districts are divided into 6 district groups for efficient urbanization as follows:

1) North Thon Buri consists of Thon Buri, Chom Thong, Bangkok Yai, Khlong San, Bangkok Noi, Bang Phlat, Thawi Watthana, and Taling Chan (8 districts).

2) Central Bangkok consists of Samphanthawong, Dusit, Phra Nakhon, Pom Prap Sattru Phai, Phaya Thai, Ratchathewi, Din Daeng, Wang Thonglang, and Huai Khwang (9 districts).

3) South Thon Buri consists of Phasi Charoen, Bang khae, Nong Khaem, Rat Burana, Thung Khru, Bang Khun Thian, and Bang Bon (7 districts).

4) East Bangkok consists of Bueng Kum, Bang Kapi, Khan Na Yao, Saphan Sung, Nong Chok, Lat Krabang, Min Suri, Khlong Sam Wa, and Prawet (9 districts).

5) South Bangkok consists of Khlong Toei, Bang Kho Laem, Pathum Wan, Bang Rak, Sathon, Yan Nawa, Watthana, Bang Na, Phra Khanong, and Suan Luang (10 districts).

6) North Bangkok consists of Lat Phrao, Lak Si, Chatuchak, Bang Sue, Sai Mai, Bang Khen, and Don Mueng (7 districts).

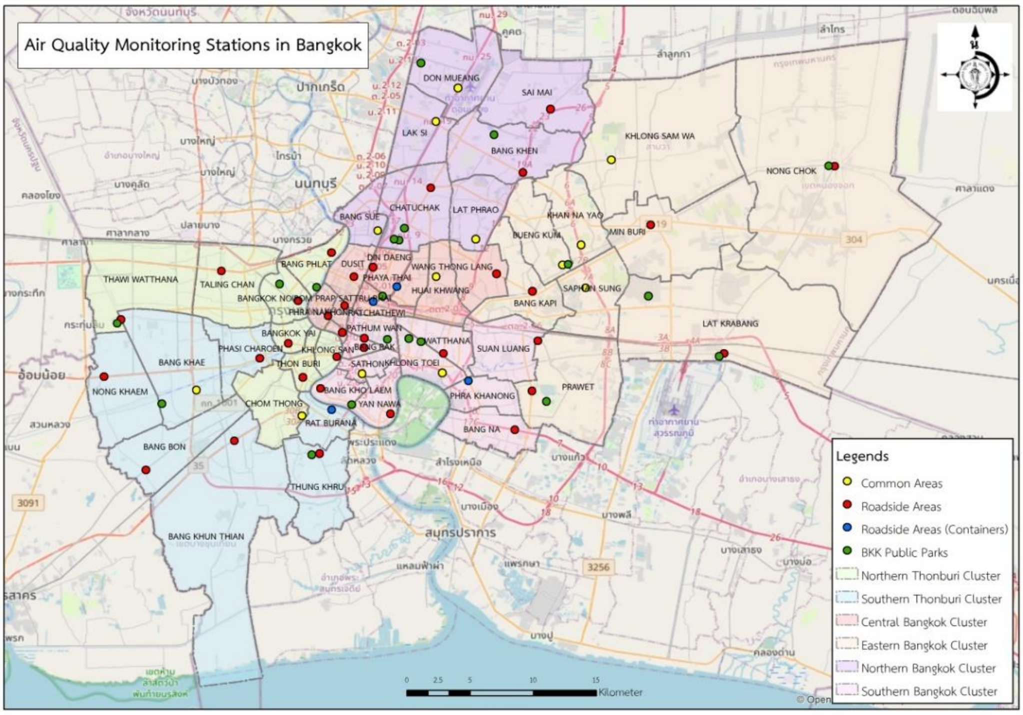


Figure 2.1 Map Showing the Division of Bangkok’s Administrative Districts into Six District Groups

2.1.5 Population

1) Number of populations

As per the end of 2018, the population of Bangkok was 5,676,648, divided into 2,679,453 males and 2,997,195 females. The density of population per km. was 3618.61. The increased rate of population was -0.10. The number of households totaled 2,959,524. The average size of households of persons per household was 1.92 or approximately 2 persons/household. In terms of the population in each district, it revealed that the district with the highest population was Sai Mai with the population of 204,532 and the district with the lowest population was Samphanthawong with the population of 23,855.

2) Distribution of population

Based on the information of civil registration in 2018 in terms of distribution of population, the mostly populated district in Bangkok was Sai Mai with the population of 204,532 or 3.60% of the total population of Bangkok, followed by Khlong Sam Wa and Bang Khae with the population of 198,019 and 193,315 or 3.49% and 3.41% respectively. The districts with the lowest population in Bangkok included Samphanthawong with a population of 23,655 or 0.42%, followed by Pom Prap Sattru Phai and Bang Rak with the population of 45,701 and 48,207 or 0.81% and 0.85% respectively.

3) Density of population

Bangkok has the density of population of 3,619 per square kilometer. The first five districts with the highest density of population included Pom Prap Sattru Phai, Samphanthawong, Din Daeng, Thon Buri, and Khlong San with the density of population of 23,667 16,706 14,455 12,601, and 11,927 per square km. respectively. Based on the data, the districts with high density were mostly situated in inner Bangkok with high urban growth up till the present. In many areas, there was population saturation. So, the population tended to decrease, and the distribution of population expanded to residential areas, including suburban and agricultural areas both in the east and the west.

The first 5 districts with the lowest density of population included Nong Chok, Lat Krabang, Bang Khun Thian, Thawi Watthana, and Khlong Sam Wa with the density of population of 732, 1,418, 1,524, 1,561, and 1,789 per square km.

respectively. The districts were situated in suburban areas with land mostly used for agriculture and empty space.

4) Change of population

Compared with the population in the previous year (in 2017), the population in Bangkok decreased 5,767 or the change rate of population decreased 0.10%. The districts with the increased rate of the change of population were mostly situated in suburban and agricultural areas on the east side, as well as residential areas. The top 5 districts with the most increased rate of changes included Khlong Sam Wa, Prawet, Nong Chok, Lat Krabang, and Sai Mai with the increased change of population of 2.11%, 1.50%, 1.38%, 0.96%, and 0.96% respectively. As for suburban residential areas and agricultural areas in the west, there was a slight increase in population. In terms of the change of population, it revealed that most districts with the increased population were those with low density of population compared to the competency to accommodate the population in the areas. Most were the areas with increased construction of residential buildings. For the areas with already high population density, the increased number was due to increased construction of condominiums along the mass rail transit system. The top 5 districts with a decreased rate of change included Samphanthawong, Pom Prap Sattru Phai, Phra Nakhon, Thon Buri, and Pathum Wan with the decreased rate of change of population of 2.05%, 1.89%, 1.66%, 1.58%, and 1.50% respectively.

5) Births

In 2018, in Bangkok, the number of births totaled 84,477, divided into 43,356 males and 41,121 females. The crude birth rate equaled 14.87 meaning in Bangkok the number of births was approximately 15 per 1,000 mid-year population (mid-year population in 2018 in Bangkok was 5,679,532). The districts with the highest births were mostly situated in inner and middle Bangkok. The top 5 districts with the highest births included Ratchathewi, Bangkok Noi, Phathum Wan, Khan Na Yao, and

Sai Mai with 10,529, 7,902, 6,721, 5,691, and 4,901 births respectively. It was found that Ratchathewi had the most overnight hospital beds, indicating the major factors of the number of births in each area which depended on the number and size of hospitals with beds in the area.

6) Deaths

In 2018, in Bangkok, the deaths totaled 43,371, divided into 24,252 males and 19,119 females. The crude death rate was 7.78, meaning in Bangkok there were approximately 8 per 1,000 mid-year population. The districts with the highest deaths were situated mostly in central business districts, commercial districts, and residential areas. The top 5 districts with the highest deaths included Ratchathewi, Bangkok Noi, Sai Mai, Pathum Wan, and Khan Na Yao with 4,590, 3,164, 2,143, 1,994, and 1,592 deaths respectively.

7) Migration

In 2018, in Bangkok, the gross migration of population totaled 699,574, divided into 320,472 for in-migration or 56.43% of the in-migration rate and 379,102 for out-migration or 66.75% of the out-migration rate. Based on the statistics, it was found that in Bangkok there was more out-migration than in-migration. The net migration or the balance between in-migration and out-migration in Bangkok was -58,630 persons or -10.32 of net migration. It means /that in Bangkok, in terms of the out-migration of the population, the population for the net migration was approximately 10 per 1,000 mid - year population. The areas with high migration were located mostly in residential areas. In terms of the number of in-migration, it was found that the top 5 districts with the highest in-migration included Sai Mai, Khlong Sam Wa, Don Mueng, Bang Khen, and Prawet with the population of 15,583, 14,765, 14,315, 13, 396, and 11,633 respectively. In terms of out-migration, it was found that the top 5 districts with the highest out-migration included Sai Mai, Ratchathewi, Bangkok Noi, Don Mueng, and Bang Khen with populations of 17,464, 14,121, 13,804, 13,368, and 12,206 respectively. The district with the highest in-migration was Khlong Sam Wa and the district with the highest out-migration was Ratchathewi.

8) Latent population

In terms of the annual survey of latent population conducted by National Statistical Office with additional questions on the survey of population's migration, the survey defined "latent population" in 2 characteristics namely the population who made day trip for work or study in the provinces that were not of their domicile called "Commuter population" and those who resided regularly but did not move their house registration or without their names in the house registration where they lived called "Non-registered population".

According to the number of latent populations in Bangkok Metropolitan Region as appeared in the report of the survey of latent population in Thailand in 2018 by National Statistical Office, it was found that Bangkok had the highest number of latent populations of 2,165,821, divided into mostly non-registered population of 205,300, commuter population for work of 101,000, and commuter population for study of 11,200.

In terms of the population density according to the house registration combined with latent population, it was found that Bangkok had the highest density of latent population reaching 1,380 persons per square km. In the past, the population density of those only in the house registrations in Bangkok accounted for 3,619 persons per square km. As a result, Bangkok had a population density reaching 4,999 persons per square km.

9) Foreign workers

At present, it is generally recognized that foreign workers especially those from neighboring countries such as Myanmar, Laos, and Cambodia constitute important low-skilled labor force for some markets in Thailand. The statistics of Foreign Workers Administration Office, Department of Employment, Ministry of

Labour showed the number of foreigners permitted to work in Bangkok Metropolitan Region since the relaxation of registration of foreign workers in 2006. That year, the number of foreign workers totaled 353,173 with 178,415 foreign workers in Bangkok. The tendency was stable continuously up to 2009 when Thailand signed the Memorandum of Understanding (MOU) on employment of workers with Myanmar, resulting in the double increase of foreign workers into Thailand from 2008. Similarly, in Bangkok Metropolitan Region the foreign workers increased from 364,503 in 2009 to 726,107 in 2011 whereby the foreign workers in Thailand increased to 1,950,650, with 468,647 foreign workers in Bangkok. Later in 2012, the Myanmar government opened the country and received foreign direct investment. International ban was lifted and the labor markets in Myanmar rapidly required more labor. Over half of Myanmar labor force migrated back to Myanmar. As a result, in 2012, in Thailand, the number of foreign workers decreased substantially. In Bangkok, the foreign workers decreased from 468,647 to 125,514. After the situation became stable, the number of foreign workers started to rise continuously until 2018 when foreign workers in Bangkok accounted for 588,795.

2.1.6 Land use and Buildings

The survey results of the existing land use of Bangkok at present total 1,568.7 square kms. The study of the aerial photographs to inspect the urbanized area of Bangkok revealed that in 2014 Bangkok had almost all urbanized areas or approximately 1,320 square kms. The survey of existing land use revealed that in Bangkok, there were 3 types of land use. Among the adjacent areas, 34.67% of the total areas was the land use for residential areas or 544 square kms. 27.64% of the land use was for agriculture or 434 square kms., and 10.13% was for the use of empty space or 159 square kms. The rest was various land uses such as commercial purposes, industrial purposes, government buildings, etc. The survey results of the land use were considered in terms of characteristics and types of land use in various areas in Bangkok could be summarized as follows:

1) Central Business District (CBD) was mostly for residential purposes, commercial purposes, government institutions, academic institutions. The land use of residential purposes was the most land use in all districts with the highest rates in Watthana, Sathon, Bang Kho Laem, and Yan Nawa. As for the land use of commercial purposes which was prominent in terms of land use of central business district, the highest rate of land use for commercial purposes was in Samphanthawong, Bang Rak, and Pom Prap Sattru Phai.

2) In inner Bangkok, most land use was for government institutions. Over half of the land for government institutions in Bangkok was highly dispersed in Dusit, Ratchathewi, and Phaya Thai. The land use of academic institutions was mostly dispersed in Chatuchak and Dusit.

3) East Bangkok was the area to accommodate the expansion due to development of inner areas. Therefore, the rate of land use for commercial purposes was high in Bang na and Suan Luang due to the communication network and the connecting points of communication and transport system. The land used for industrial purposes was in Bang Na and Lat Krabang. Moreover, the land use of large warehouses was in Phra Khanong.

4) In upper Bangkok, most land use was for agricultural purposes. The rate of land use for agricultural purposes was the highest of Bangkok's agricultural areas. The agricultural areas with the highest rate of land use were in Nong Chok and Khlong Sam Wa. The land use for government institutions was highly dispersed in the northern areas in Don Mueng and Bang Khen with buildings of military activities, airports, as well as central government agencies and state enterprises.

5) In Thon Buri, most land use was for residential areas and there was concentration of land use for industrial purposes in Bang Bon, Rat Burana, and Nong Khaem. Rapid urban expansion from centers to suburbs generated a large amount of empty space waiting for development or not exploited in Bangkok and Thon Buri.

2.1.7 Trend of Changes of Land use and Buildings

1) Residential land

The land use of residential purposes in Bangkok increased from 239,086 rai in 2000 to 339,958 rai in 2014. The areas with a lot of houses were inner and upper Bangkok as well as Thon Buri such as Chatuchak, Bang Kapi, Bang Khen, Sai Mai, and Bang Khun Thian. At the same time, the land use for residential areas in inner areas changed into large buildings with high density of land use. In terms of the change of residential buildings, the statistics of the number of houses in Bangkok increased from 2.29 million houses in 2009 to 2.67 million houses in 2014 or the average increase of 76,000 houses a year. The areas with the most increased number of houses included inner Bangkok, upper Bangkok, east Bangkok, as well as Thon Buri with the increase of 94,329 houses. In terms of the changes of the increased number of houses between 2009-2014, the districts with the highest increase included Huai Khwang, Bang Khun Thian, Chatuchak, Khlong Sam Wa, and Lat Krabang. The areas with the least changes and even decreased number of houses included Samphanthawong and Bang Kho Laem. As the areas had high economic value, there were changes in land use from residential areas to economic activities.

2) Industrial land

According to the survey in 2000, the use of industrial land accounted for 17,092 rai or 1.47% of the land. The dispersion of industrial areas was mostly in east Bangkok, especially Lat Krabang with the location of Lat Krabang Industrial Estate. As for the increased changes, it was found that between 1986-1995, the industrial land increased from 14,759 rai to 18,371 rai or an increase of approximately 24.47%. The changes of industrial areas were in line with the government's policy focusing on the dispersion of naiant manufacturing plants and factories outside Bangkok, distribution of workforce to regional areas, and maintenance of good environment of Bangkok. Due to the policy, the industrial areas in inner city were clearly decreased especially in the west whereas the adjacent areas had the same number as the old areas. The suburbs in the west experienced a high rate of expansion with an increase from 2,231 rai in 1995 to 3,229 rai. In comparing the accumulated statistics of the number of factories in Bangkok between 2014 and 2018, it was found that there was a tendency to decrease 21.75%. In 2014, group 2 and group 3 factories which were large factories with a large amount of horsepower of machines and workforce totaled 18,006 factories. In 2018, there were 14,090 factories under group 2 and the group 3 factories (Business Industry Information Center, Department of Industrial Works, 2018).

3) Agricultural land

The agricultural space in Bangkok had gradually decreased. The survey of land use in 2010 specified that Bangkok had 243,776 rai for agricultural purposes. Afterwards in 2017 the agricultural land decreased to 233,389 rai. The areas in the east and west had similar rates of changes. Agricultural practice in Bangkok was different depending on each area. In the east namely Nong Chok, Khlong Sam Wa, Lat Krabang, Sai Mai, and Saphan Sung, the areas were used for rice farming and crop farming. In the west, Thawi Watthana, Taling Chan, Nong Khaem, Thung Khru, the areas were used for vegetable plots, ornamental plants, fruit orchards, and aquaculture with the area for fishponds and shrimp ponds in Bang Khun Thian. The change of land use for agriculture would be in line with the tendency of urbanization and agricultural land would have inverse relationship with the economic situations and land value in each area. This was in accordance with the study of Woralak Promsombat (2011) which studied the urbanization according to the theory of urbanization. The area study was conducted on Khok Faet subdistrict, Krathum Rai subdistrict, and Nong Chok subdistrict, Nong Chok district, Bangkok. The data obtained from the classification of land use by interpretation of aerial photographs in 2006 and in 2010 was superimposed to compare the change rate of land use each year. The study results showed that most of the land use was for agricultural purposes. But at present, the agricultural areas decreased while the residential areas increased due to the development of numerous increased facilities. It could then be summarized that community dispersion was continuously changed and developed. It was the urbanization theory in the form of multiple-nuclei theory. The urbanization came from many nuclei not any one nucleus. This is because, at present, there are areas for industrial and commercial purposes, government buildings and academic buildings, as well as public utilities and public facilities. As a result, many residential nuclei popped up with community dispersion to various areas providing convenience for each person's needs.

4) Empty space

Based on the study and interpretation of satellite photographs in the past, in 2006, in Bangkok, the empty space totaled 166,098,921.04 square m. (166.10 square km.) or 11 % of the total areas of Bangkok. But in 2015, there were 120,511,643.05 square m. (120.51 square km.) or 7.7% of the total areas of Bangkok. It meant that empty space decreased 45,587,277.99 square m. (45.59 square km.). It was also found that in each district group, planning of empty space decreased due to various factors such as economic and social growth leading to residential buildings, housing estates, condominiums, commercial buildings, establishments, department stores, gas stations, football fields, driving golf range, as well as the growth of warehouses and various establishments. In some areas, there were more areas for agriculture thus decreasing empty space in Bangkok. But in some districts, such as Lat Krabang, Thung Khru, Pathum Wan, Pom Prap Sattru Phai, empty space increased due to factors such as demolition of buildings or the areas which were formerly used for agriculture but were left unused, etc.

The comparison between 2006 and 2015 revealed that the district with the mostly decreased empty space was Phasi Charoen with the decreased empty space of 77.35% of the total empty space and the district with the least decreased empty space was Ratchathewi with the empty space decrease of 4.54% of the total empty space (Report of comparison of empty space in Bangkok between 2006 and 2015 Department of City Planning revealed that available space in Bangkok, 2015).

2.1.8 Communication and Transport

The current communication and transport system in Bangkok depends mainly on land, especially communication and transport by road as the system is accessible to communities more conveniently than other systems. As for 2022, it was found that there were over 11.61 million registered cars or over 370,000 cars more than in 2021. This was partly due to the marketing of the car business with fierce competition and motivation for car purchase of high-income potential customers. Therefore, sales were promoted, and conditions were determined to motivate easier decisions for purchase. This was partly due to the need for convenience and comfort, traveling safety, and popularity in passenger cars for those with increased income or in better economy. Therefore, the number of cars is not in relation to the existing number of roads or the potential of roads able to accommodate traffic (Transport Statistics Sub-division, Planning Division, Land Transport Department, 2016). Table 2.1 represents the traveling of Bangkok residents over 16 million trips a day with various traveling modes (Mass Rapid Transit Authority of Thailand, 2016). excluding traveling by water. It was expected that in 2021, Bangkok residents would travel 26.2 million trips a day (Nutwara Ngamlamom & Chamlong Phoboon, 2012). Based on the above information, it could be seen that people mostly favored passenger cars, followed by buses. Traveling by rail was not very popular during this year. This was in line with (Praphan Sakdasak, 2014) who discussed the promotion of physical access and linkage of routes to road networks with provision of footpaths, bicycling with appropriate distance to replace the use of passenger cars. The improved environmental conditions would ensure access to areas in terms of traveling on foot and by bicycle. If the routes lacked physical features and facilities for convenience, which was taken into consideration in terms of the distance from community centers, it would impact the change in the traveling behavior.

Table 2.1 Types of Traveling of Bangkok Residents

Modes of Traveling	**Number (Million Trips/Day)**
Passenger cars	9.5
Buses	6
BTS	0.70
MRT	0.25
BRT	0.04

Source: Transport Statistics Sub-division, Planning Division, Land Transport Department, (2016).

2.1.9 Number of Traveling and Modes of Traveling

The results of the analysis of the number of travels in Bangkok Metropolitan Region between 2017-2042 divided by the modes of traveling could be summarized as follows:

Table 2.2 Number of Traveling in Bangkok Metropolitan Region between 2017 and 2042

Modes	**Number of Traveling (Million Trips/Day)**					
	2017	**2022**	**2027**	**2032**	**2037**	**2042**
Passenger cars and Motorcycles	22.44 (68.7%)	23.30 (66.0%)	24.43 (64.8%)	24.99 (64.5%)	25.00 (63.6%)	24.29 (60.8%)
- Cars	14.12 (43.2%)	15.60 (44.2%)	17.22 (45.7%)	18.31 (47.3%)	18.98 (48.3%)	19.11 (47.9%)
- Motorcycles	8.32 (25.5%)	7.70 (21.8%)	7.21 (19.1%)	6.68 (17.2%)	6.02 (15.3%)	5.18 (13.0%)
All public transport system	10.21 (31.3%)	11.99 (34.0%)	13.25 (35.2%)	13.77 (35.5%)	14.31 (36.4%)	15.64 (39.2%)
- Taxis	1.36 (4.2%)	1.59 (4.5%)	1.87 (5.0%)	2.02 (5.2%)	2.19 (5.6%)	2.44 (6.1%)
- Public transportation	6.60 (20.2%)	7.83 (22.2%)	8.62 (22.9%)	8.85 (22.8%)	9.09 (23.1%)	9.94 (24.9%)
- Shuttle buses	0.62 (1.9%)	0.81 (2.3%)	0.88 (2.3%)	0.96 (2.5%)	1.06 (2.7%)	1.26 (3.2%)
- Walking	1.63 (5.0%)	1.76 (5.0%)	1.88 (5.0%)	1.94 (5.0%)	1.97 (5.0%)	2.00 (5.0%)
Total	**32.65**	**35.29**	**37.69**	**38.75**	**39.31**	**39.93**

Source: The Office of Transport and Traffic Policy and Planning (2017).

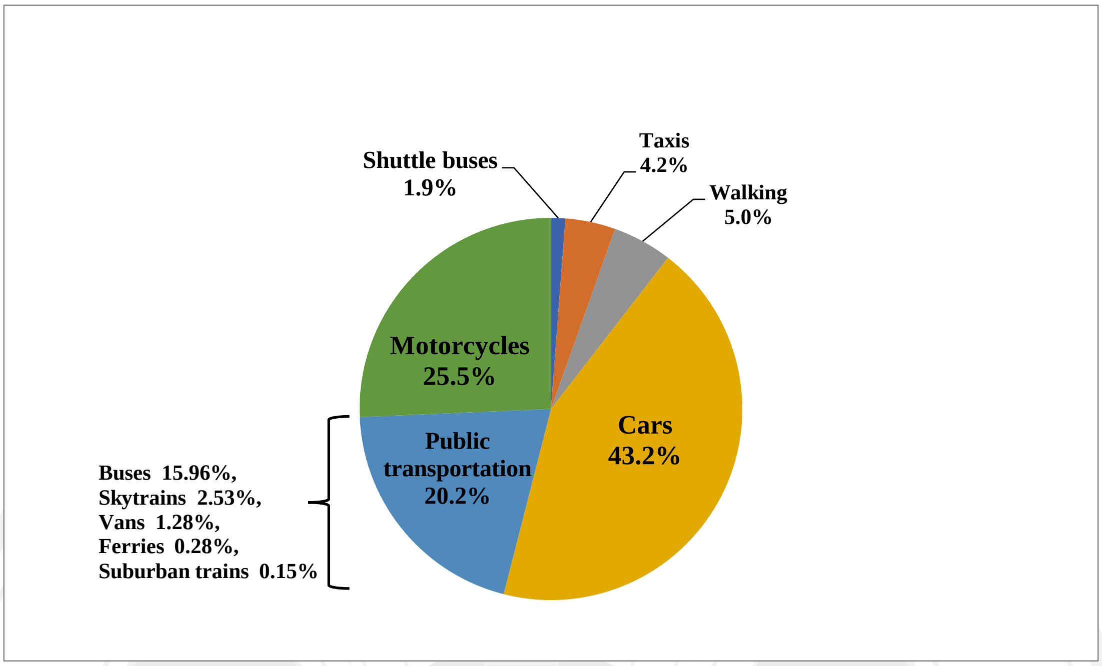


Figure 2.2 Modes of Traveling in 2017

2.1.10 Forecast of Traffic Situations Divided by Areas

The Extended Bangkok Urban Model (eBUM) is a strategic model developed by the Thailand Transport Institute (TTI) as a base model for analyzing and forecasting transportation conditions and traffic patterns resulting from changes in the transportation network. It is also used to test traffic management measures in the Bangkok Metropolitan Area and its surrounding suburbs.

eBUM serves as a tool to simulate and evaluate the impacts of various transportation strategies and policies on the urban transportation system. By inputting data such as population, land use, road network, public transportation routes, and travel demand patterns, the model can provide insights into the potential outcomes of different scenarios and help inform decision-making processes.

The eBUM model incorporates a range of factors, including travel demand, traffic flow, mode choice, and network performance. It enables analysts and policymakers to assess the effectiveness of different transportation interventions, such as infrastructure improvements, public transport enhancements, or traffic management measures, in mitigating congestion and improving overall mobility in the Bangkok Metropolitan Area and its surrounding regions.

Using the eBUM model, transportation planners and policymakers can make informed decisions based on projected outcomes and evaluate the potential benefits and drawbacks of different strategies before implementing them in the real world. This approach allows for evidence-based planning and helps optimize the allocation of resources for transportation infrastructure and services in the Bangkok Metropolitan Area and its environs. This can be divided into three zones as shown in figure 2.3

1) Inner areas consisted of areas within Ratchadaphisek Ringroad

2) Middle areas consisted of Bangkok and adjacent areas namely parts of Pathum Thani, Samut Prakan, and Nonthaburi covering rail and skytrain routes in the future according to M-Map

3) Outer areas namely the areas not situated in middle areas such as some parts of Pathum Thani, Samut Prakan, Nonthaburi and areas of Nakhon Pathom, Samut Sakhon, Ayutthaya, and Chachoengsao

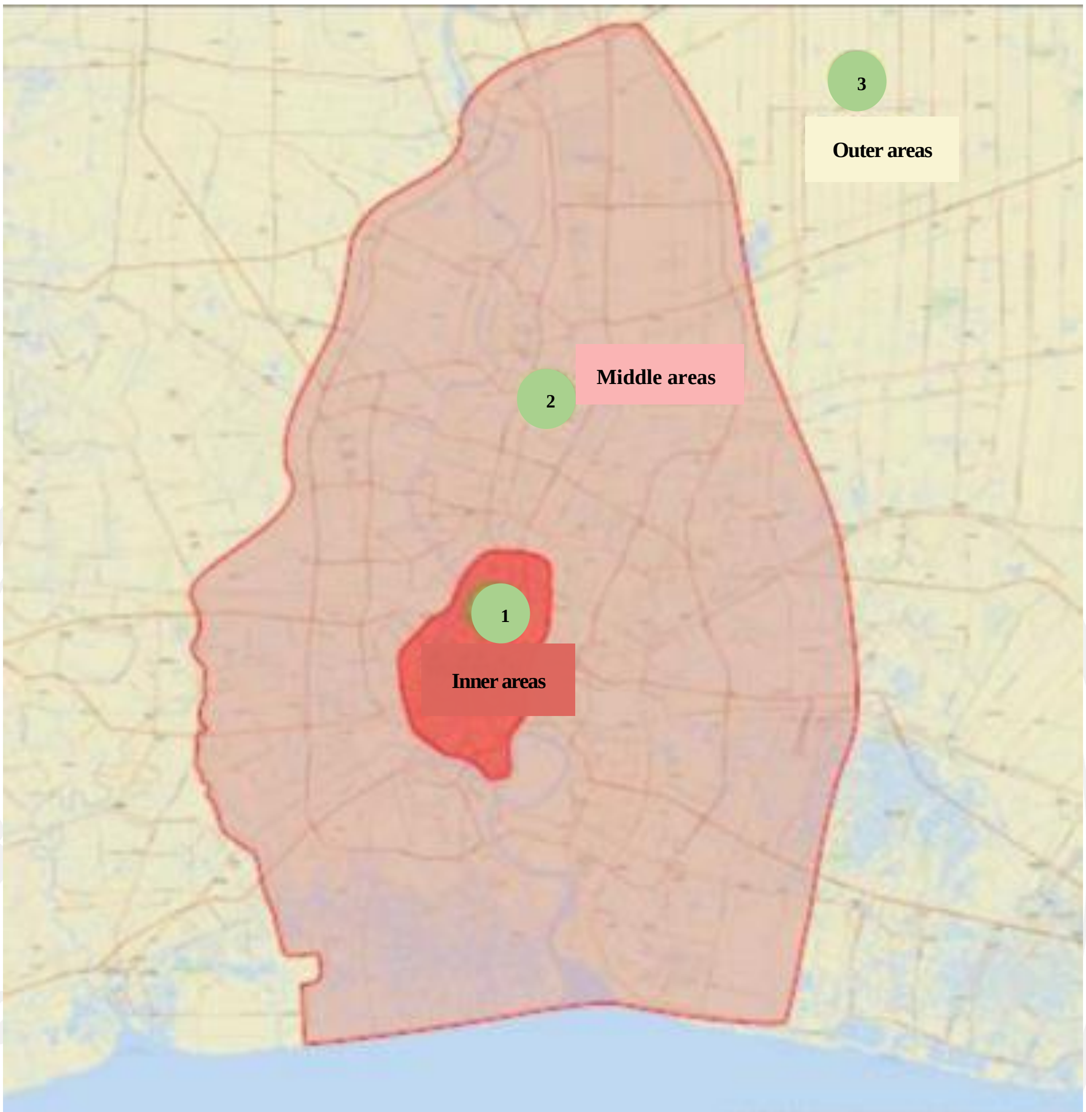


Figure 2.3 Areas of Traffic Forecast

The traffic situations during morning and evening rush hours in 2019 compared to 2018 were as follows:

1) Inner areas with slightly decreased speed due to the increased number of trips. But roads could not be increased, and rail mass transit system was under construction. The system was not open for complete network services.

2) Middle areas with slightly better speed due to the increased number of trips. There was development and construction of roads, and the service was open for rail mass transit system MRT Green line Project Bearing-Samut Prakan.

3) Outer areas with slightly decreased speed due to increased number of trips caused by urbanization. In outer areas, the development of public transportation was not covered so people mainly depended on passenger cars.

Table 2.3 Average Speed During Morning Rush Hours (Kms. Per Hour)

Areas	2017	2018	2019
1) Inner areas	10.72	10.61	10.51
2) Middle areas	18.52	18.54	18.57
Greater Bangkok (1+2)	16.36	16.35	16.34
3) Outer areas	31.99	31.95	31.91
Bangkok Metropolitan Region (1+2+3)	20.63	20.63	20.63

Source: The Office of Transport and Traffic Policy and Planning (2017).

Table 2.4 Average Speed During Evening Rush Hours (Kms. Per Hour)

Areas	2017	2018	2019
1) Inner areas	14.21	13.93	13.64
2) Middle areas	20.77	20.73	20.70
Greater Bangkok (1+2)	19.23	19.12	19.01
3) Outer areas	33.66	33.63	33.60
Bangkok Metropolitan Region (1+2+3)	23.56	23.47	23.38

Source: The Office of Transport and Traffic Policy and Planning (2017).

The average traffic conditions during daytime in 2019 compared to 2018 revealed that the speed slightly increased due to the development of infrastructures and the service was open for the MRT Green Line Bearing-Samut Prakan in December 2017.

Table 2.5 The Average Speed During Daytime (Kms. Per Hour)

Area	2017	2018	2019
Bangkok Metropolitan Region (1+2+3)	33.20	33.26	33.33

Source: The Office of Transport and Traffic Policy and Planning (2017).

2.2 Air Pollution

Air pollution means the conditions of the air with contaminants in sufficient quantity and duration to harm the health of humans, animals, plants, and various materials. The contaminants can be natural or man-made substances or compounds or in the form of gas, liquid drops, or solid particles. The major air pollutants include Particulate Matter, lead (Pb), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxide (NO_x), and ozone (O_3).

2.2.1 Air Pollution System

1) Emission Sources are the sources that generate air pollution and emit it to the atmosphere. The types and volume of air pollutants emitted to the atmosphere depend on the types of the sources of air pollutants and the methods to control the emission of the air pollutants.

2) Atmosphere is part of the system that supports air pollutants emitted from various sources and acts as a medium to disperse the emitted air pollutants. Meteorological factors include air temperature, speed, and direction of wind, as well as topography such as mountains, valleys, and residential buildings as the determinants of the characteristics of the dispersion of pollutants into the air.

3) Receptors constitute part of the system that is in contact with air pollutants causing damage or danger. Those affected may be living creatures such as humans, plants, and animals, or non-living objects such as clothes, buildings, houses, materials, or constructions. The degree of damage or impact will depend on the concentration of air pollutants and the duration of contact.

Based on the composition of the mentioned system of air pollutants, the volume and types of pollutants emitted from sources (emissions), conditions of meteorology, and topography will determine the types, volume, and density of pollutants contaminated in the air in the distant. At the same time, air quality will determine the characteristics and seriousness of the air pollution effects.

2.2.2 Sources of Air Pollution

1) Natural sources are the sources that cause air pollutants according to natural procedures without relevant man-made actions such as volcanic eruption, wildfire, sea, and ocean which are sources of salt spray, etc.

2) Man-made sources are the sources from human activities with emission of air pollutants divided into 2 types as follows:

(1) Mobile sources such as cars, motorboats, planes, etc.

(2) Stationary sources mean immovable sources such as industrial plants of which air pollutants are derived from the use of fuel and the various manufacturing processes.

(3) Non-stationary sources such as biomass.

2.2.3 Types of Air Pollutants

1) Primary Air Pollutants are air pollutants directly generated and emitted from sources such as SO_2, CO, NO_2, ash, and black smoke derived from combustion of fuel in vehicles and incinerators in industrial plants, etc.

2) Secondary Air Pollutants are air pollutants not generated or emitted from any source but take place in the atmosphere in general through chemical reaction between primary air pollutants and other compounds in the atmosphere such as O_3 is derived from photochemical oxidation between nitrogen oxide (NO_x) and other hydrocarbon compounds and inorganic air pollutants such as hydrogen sulfide and lead dust, etc.

In Thailand, there was notification on the volume of pollutants permitted for emission into the atmosphere to control 7 types of main pollutants, composing mainly of primary air pollutants namely CO, NO_2, SO_2, total suspended particulate (TSP), PB, particulate matter, and O_3 which are secondary air pollutants. Moreover, there are Hazardous Air Pollutants (HAPs) or Toxic Air Pollutants (Air Toxic) which are carcinogens and with long-term impact on health through destruction of immunity of nervous system and abnormality in reproductive and endocrine systems, etc. In the US, 189 types of hazardous air pollutants are identified with major sources being chemical industrial plants, pesticides, combustion, etc. At present, in the US, the standard of HAPs has not been established from sources as many as possible. As for Thailand, the standard of HAPs in the atmosphere has not been established but there is a policy formulated to control the HAPs from sources by using the measures to control the emission from sources such as pollution prevention or clean technology, etc.

2.2.4 Major Air Pollutants

1) Particulate Matter (PM)

PM is the particle suspended in the atmosphere which can be both solid particles and liquid droplets (U.S. Environmental Protection Agency: US EPA, 2010). The main source of PM can be created by incomplete burning; thus, PM can be made several sources such as open-burning, industry activity, power plant, automobile, etc. Moreover, fine particulate matters can be ranged of 1 µm and 2.5 µm (World Health Organization: WHO, 2000, p. 39). The to the small size of PM, the surface of PM is very large, thus hundreds of chemicals such as SO_2 and NO_2 can be contained on PM. Furthermore, PM can be transferred by wind/or aerosol which takes PM to many locations. Thus, PM can deposit and sink on buildings, utility, and human eyes. Not only enter the human eyes but PM can enter the breathing system which can cause several negative impacts to human health. According to Mühlfeld et al. (2008) defined size of fine PM by 3 types which are PM_{10}, $PM_{2.5}$, and $PM_{0.1}$ (indicated in Figure 2.4). Due to easy movement and specific properties of PM, PM is the significant harmful pollutant in the atmosphere.

The definition covers solid particles and liquid drops suspended in the air. Some of the particles are big and black soot. But some are so small they are invisible to the naked eye. In general, the PM suspended in the air has the size of not exceeding 100 microns. The PM impacts the health of humans, animals, and plants damaging residential buildings, causing troubles to people, obscuring vision, and obstructing transport. Many countries therefore have devised the standards of the PM in the atmosphere. In US, the United States Environmental Protection Agency (US EPA) has devised the standards of the total suspended particulate and

PM_{10}. Based on the studies, the small sized particulate matter would be more harmful to the health than the total suspended particulate as it could gain access to the inner respiratory system and impact health more than the TSP. Therefore, US

EPA abolished the standards of the TSP and devised the standards of the PM into 2 types namely PM_{10} and $PM_{2.5}$.

PM_{10} according to the definition of US EPA means Coarse Particle with the radius of 2.5-10 microns generated from traffic on unpaved roads according to the transport of particle from stone crushing activities.

$PM_{2.5}$ according to the definition of US EPA means Fine Particles with the radius smaller than 2.5 microns. Fine particles are generated from exhaust fumes, power plants, industrial plants, and smoke from cooking using firewood. Moreover, SO_2, NO_x, and VOC can interact with other substances in the air causing fine particles.

Small particulate matter will seriously impact health. When inhaling, it will enter the lower respiratory system. In the US, those exposed to PM_{10}, at a certain level, will get asthma. $PM_{2.5}$ in the atmosphere will relate to the increased rate of patients with heart and lung diseases and premature deaths, especially elderly patients, patients with heart disease, asthma, and children with higher rate of risk than normal people.

In Thailand, the definition of PM is the TSP which is large sized particulate with the radius of 100 microns downwards. As for PM_{10}, it means PM with a radius of 10 microns downwards which is the PM that poses the number one problem of pollution in Bangkok. In 1998, the World Bank provided funding for the study of the impact of PM on the health of Bangkok residents. It was revealed that the PM in Bangkok had a serious impact on health and hygiene at a level like the study of other cities worldwide. The level of small PM might be the reason for 4,000-5,500 premature deaths among Bangkok residents a year. Moreover, it was also revealed that hospitalization was related to the amount of small PM. The economic assessment showed that the reduced amount of PM_{10} could reduce 1 0 cubic meters in the atmosphere and could reduce health impact valued 35,000-88,000 million baht per year.

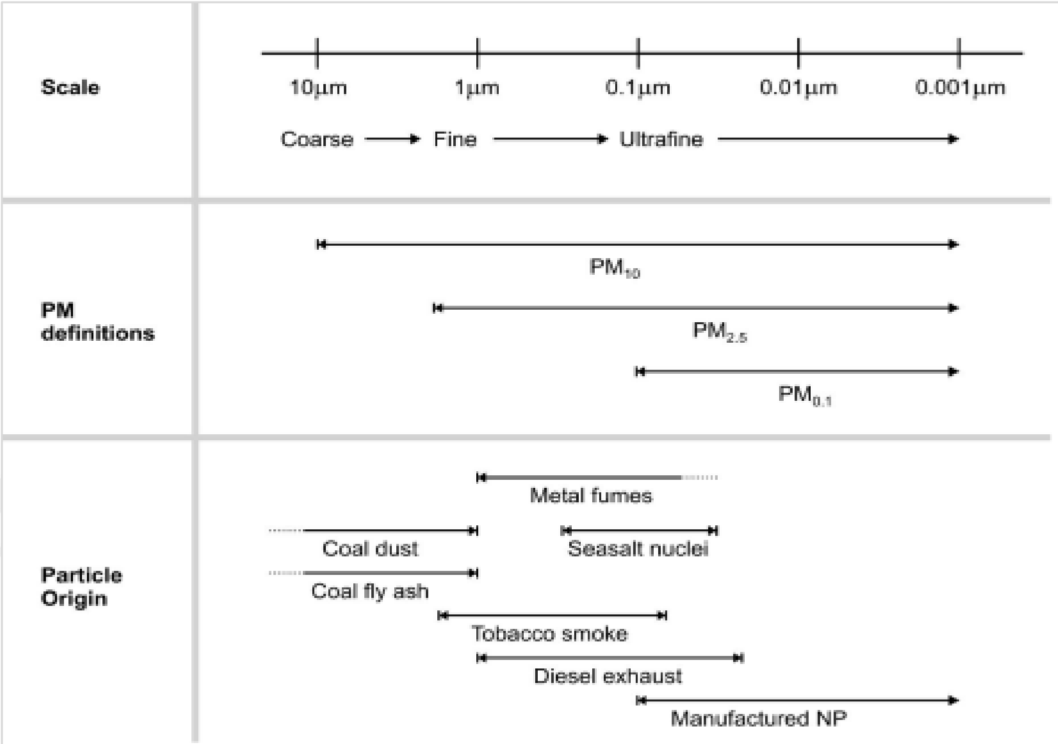


Figure 2.4 Classification of PM

Source: Mühlfeld et al. (2008).

2) Carbon monoxide (CO)

CO has no color, flavor, or smell. It is slightly lighter than the general air. When inhaling, it will combine with Hemoglobin in red blood with 200-250 times more than oxygen. It will result in carboxyhemoglobin (COHb) which reduces the ability of blood to become the oxygen conductor from the lungs to various tissues. In general, the main component causing the large or small amount of carboxyhemoglobin depends on the concentration of CO in the air that people breathe in and the duration of the condition. Human reaction mainly depends on the percentage of carboxyhemoglobin and individual susceptibility.

3) Nitrogen dioxide (NO_2)

NO_2 consists of nitrus oxide (N_2O), nitric oxide (NO), dinitrogen trioxide (N_2O_3), nitrogen dioxide (NO_2), dinitrogen tetroxide (N_2O_4), and dinitrogen pentoxide (N_2O_5). Generally, the types of gas that generate air pollutants include NO_2 and nitric oxide (NO) which are inert gases with anesthetic properties and without color or smell. In nature, generally, they are found in the amount which is smaller than 0.5 ppm. It is also slightly soluble. As for NO_2, it is brown gas. If in sufficient large volume, it is visible. Both types of gas can exist in nature such as lightning, volcanic eruption, or microorganic mechanism. Moreover, they are caused by human activities such as industries namely nitric acid or sulfur acid manufacturing industries, explosive manufacturing factories, and engine combustion, etc.

NO will react with O_3 in the atmosphere and cause NO_2 and oxygen. On the contrary, with sunlight, the Nitrogen oxide (NO_x) will cause reverse reaction.

$$NO + O_3 \longrightarrow NO_2 + O_2$$

Generally, NO_2 is not harmful to human health. But when NO_2 is mixed with water in the air, it will become Nitric acid (HNO_3) with corrosive property. NO_x, NO, and NO_2 come from combustion at high temperatures. The main substances of this group of gas are the cause of air pollution. NO_2 can react in fine mist to become HNO_3 that can corrode metals. Moreover, it can react with photochemistry reducing the visibility in the atmosphere. NO_2 is more hazardous than NO.

4) Sulfur dioxide (SO_2)

Sulfur oxide (SO_x) consists of SO_2 and SO_3. It is generally referred to as SO_x. SO_2 has no color. It is nonflammable and has a sharp smell that irritates the nose. It is highly soluble and is changed into sulfuric acid (H_2SO_4). Generally, in nature, it is found in small quality in the atmosphere between 0.02-0.1 ppm. But if found in large quantities, it is generated mostly from combustion using fuel or material with sulfur as composition. The reaction generates SO_2.

$$S + O_2 \longrightarrow SO_2$$

If SO_2 interacts with O_2 in the atmosphere, it will generate SO_3. If the atmosphere has the catalysts such as manganese, iron, or metallic oxide, it will accelerate the reaction.

$$SO_2 + 1/2O_2 \xrightarrow{\text{catalyst}} SO_3$$

If there is vapor or high humidity in the atmosphere, SO_2 will be formed into acid rain having impact on eco-system, forests, water sources, living creatures, and causing corrosion of buildings.

$$2SO_2 + 2H_2O + O_2 \longrightarrow H_2SO_4$$
$$SO_3 + H_2O \longrightarrow H_2SO_4$$

SO_x in the atmosphere are mostly found in the form of SO_2 which has no color. It is nonflammable and nonexplosive. It can have flavor if found in large quantity. With time, SO_2 will be changed into SO_x, H_2SO_4, and sulfate salt through the catalytic reaction or photochemical reaction in the air. SO_2 generally is derived from the combustion of sulfur in the fuel from petroleum and coal. It is toxic gas that is mainly generated from industrial plants and diesel engines.

5) Ozone (O_3)

O_3 is a type of photochemical oxidant from the photochemical oxidation between hydrocarbon and NO_x with sunlight as catalyst. Other photochemical include aldehyde, ketone, and peroxyacetyl Nitrate (PAN) causing the condition called photochemical smog. It is white fog widely spread in the air. In general, O_3 will cause irritation of the eyes and the respiratory system, reducing the function of the lungs.

6) Lead (Pb)

Pb in the air, especially in cities comes from benzene-run vehicles as benzene consists of tetraethyl Lead or tetramethyl Lead which is mixed to increase octane to the benzene to prevent engine knocking. Lead will be emitted through the exhaust pipe in the form of solid matter. Lead is a heavy metal with high toxicity, especially in children. It is seriously harmful to people's health. For example, it will destroy bone marrow and red blood cells, causing anemia, and can be transmitted from mother to fetus through the placenta.

2.2.5 Standards of Air Quality in the Atmosphere in Thailand

The standard of air quality in the atmosphere aims to upgrade the air quality as required. It is shown in the form of the average concentration of each type of pollutant permitted in the atmosphere during the determined period. It is determined using the information and scientific research findings which identified the damage and danger of each pollutant when in contact with those pollutants at various concentration levels and the durations of contact as the foundation and other possible factors namely technological and economic factors, etc. Therefore, the standards of the air quality in the atmosphere must be regularly reviewed and improved to be appropriate for circumstances according to the Notification of the National Environmental Board No. 10 (1995) and No. 12 (1995).

Table 2.6 Standards of Air Quality in the Atmosphere in Thailand

Pollutants	Average of 1 Hour Mg/M^3 (Ppm)	Average of 8 Hours Mg/M^3 (Ppm)	Average of 24 Hours Mg/M^3 (Ppm)	Average of 1 Month Mg/M^3 (Ppm)	Average of 1 Year Mg/M^3 (Ppm)	Methods of Measurement
CO	30	9	-	-	-	Non-Dispersive Infrared Detection
NO_2	0.17	-	-	-	-	Chemiluminescence
SO_2	0.3	-	0.12	-	0.04	UV fluorescence system
TSP	-	-	0.33	-	0.10	Gravimetric-Hi Volume
PM_{10}	-	-	0.12	-	0.05	Gravimetric-Hi Volume
$PM_{2.5}$	-	-	0.05	-	0.025	Gravimetric-Hi Volume
O_3	0.10	-	-	-	-	Ultraviolet Absorption Photometry
PB	-	-	-	1.5	-	Atomic Absorption spectrometer

Note: Remarks: 1 . Standard of short-term average (1,8, and 24 hours) determined to prevent Acute effect on health and hygiene

2. Standard of long-term average (1 month and 1 year) determined to prevent Chronic effect on health and hygiene.

Source: Pollution Control Department (2005).

2.2.6 Overview of Fine Particulate Matter ($PM_{2.5}$)

2.2.6.1 $PM_{2.5}$

According to the previous section, $PM_{2.5}$ or fine PM size is over than WHO global air quality guidelines which can cause negative impacts on human body. Therefore, this section would educate the definition, source, and situation of $PM_{2.5}$.

1) $PM_{2.5}$ and Its Impact on Human Health

According to Figure 2.1, $PM_{2.5}$ is the PM which has the size less than 2.5 µm or equal to 2.5 µm. Therefore, the surface of $PM_{2.5}$ is very large, which can absorb several pollutants on their surface. U.S. Environmental Protection Agency: US EPA (2003) reported that the size of PM has the direct impact on human health problem. Due to the small size of PM, especially $PM_{2.5}$, they can go deeply into the heart and lungs. It can also enter to blood system and distribute to human body (Falcon-Rodriguez, Osornio-Vargas, Sada-Ovalle, & Segura-Medina, 2016). For instance, when fine PM enters blood vessel through a respiratory system, it will affect heart rate irritation, plasma viscosity, and blood pressure changes. Furthermore, myocardial infarction can be occurred when the concentration of PM rises (Li, Li, Wang, & Zhou, 2016). However, it not only affected long-term exposure, but also affects short-term endangers. In case of short-term exposure, PM has an impact on morbidity incidents in all age groups, particularly sensitive groups such as children, older and pregnant to cardiovascular and respiratory diseases caused by inhalation of fine particles. Figure 2.5 presents the pathway of fine PM which can affect organism system.

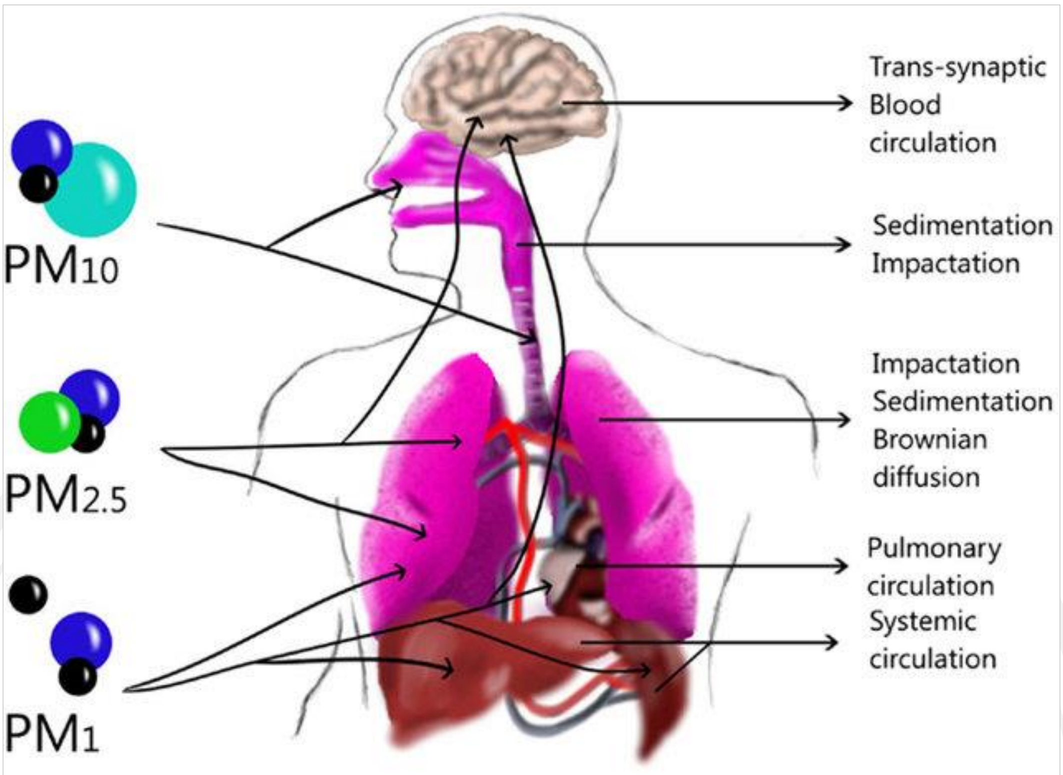


Figure 2.5 Pathway of PM

Source: Falcon-Rodriguez et al. (2016).

In brief, due to $PM_{2.5}$ can enter to blood stream and able to distribute to human organism, it leads to premature death, chronic heart, and lung disease, including asthma, respiratory symptoms, and lung function. Therefore, the air quality standard is created to control the negative effect from PM (Table 2.7).

Table 2.7 Air Quality Standard Including National Ambient Air Quality Standards (NAAQS) and WHO Guidelines

Size of Particulate Matter (PM)	**Average**	**NAAQS 2023**	**WHO Guidelines 2023**
Total Particulate matter	24 hr	330 µg/m^3	-
(<100 µm)	1 year	100 µg/m^3	-
PM_{10} (<10 µm)	24 hr	120 µg/m^3	100 µg/m^3
	1 year	50 µg/m^3	50 µg/m^3
$PM_{2.5}$ (<2.5 µm)	24 hr	37.5 µg/m^3	15 µg/m^3
	1 year	15 µg/m^3	5 µg/m^3

Source: Muro, Van, and Narita (2019); Pollution Control Department: PCD (2023); World Health Organization: WHO (2023).

The NAAQS of Thailand have been implemented for controlling major air pollutants. Initially, the standards were established for CO, NO_2, SO_2, PB, PM_{10} and TSP. After that the regulation has been expanded to control volatile organic compounds (VOCs) and fine particles which is $PM_{2.5}$ since 2007 and 2010, respectively.

1) Emission Source of $PM_{2.5}$

There are two main sources of $PM_{2.5}$ emission in most regions which are transportation and biomass burning. However, PM from man-made activities occur primarily from four source categories which are fuel combustion, industrial processes, and non-industrial fugitive sources (e.g., dust from paved and unpaved roads, wind erosion, and so on) and transportation. Moreover, biomass open burning is also a major source of PM, especially in the rural and sub-urban areas (Kim Oanh, 2012).

Specifically, the emissions caused by the transport sector have adverse effects on ambient air quality, climate and on human health (Yan et al., 2014:5709). Air pollutants from mobile sources can be classified as primary air pollutants and secondary air pollutants. Pollutants that are emitted directly into the atmosphere are termed as primary air pollutants and pollutants that result from chemical reactions between pollutants in the atmosphere are coined as secondary air pollutants.

2) Situation of $PM_{2.5}$ in Bangkok, Thailand

According to Pollution Control Department (PCD), annual report in 2017, the proportion of agricultural residue burning, and household cooking was 40-45 while 30-35% came from transportation. Moreover, the proportion of industrial activities was 10-15%. However, construction and road dust are the main cause of coarse PM_{10}. Bangkok is the capital and the economic center of Thailand. It has more than 10 million people living here due to the migration of employment. Thus, the number of vehicles has led to an increase significantly (DLT, 2019). For this situation, the $PM_{2.5}$ concentration in Bangkok have high level, especially on roadside areas such as Kanchanaphisek Road, Bang Khun Tian District, Bang Na District, Din Dang District, and Phraya Thai District (Pollution Control Department, 2015).

PCD (2019), mentioned that the 24-hour average value of PM_{10} in Bangkok, Thailand during 2008 to 2018 was about 42 microgram per cubic meter which is lower than the WHO Global air quality previous guidelines (50 microgram per cubic meter), while the 24-hour average value of $PM_{2.5}$ presented with the opposite value. The 24-hour average value of $PM_{2.5}$ in Bangkok and vicinity was about 30 microgram per cubic meter which was more than the WHO global air quality previous guidelines (25 microgram per cubic meter). Figure 2.6 presented the annual average of concentration of $PM_{2.5}$ during 2011 to 2018.

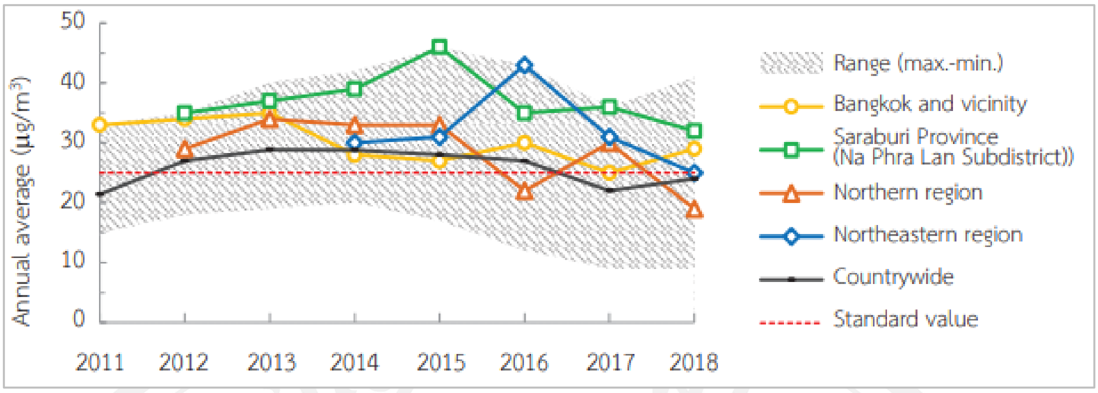


Figure 2.6 Annual Average of Concentration of $PM_{2.5}$ during 2011 to 2018

Source: Pollution Control Department (2017).

2.2.7 Policy Regarding $PM_{2.5}$ in Bangkok.

In Thailand, the policy of air quality management is generally adopted based on the international standards such as WHO guideline, Environmental Protection Agency, and EURO standards. The Royal Government of Thailand had issued an official statement concerning air quality in Bangkok and its vicinities, followed by a city-wide action plan to mitigate the $PM_{2.5}$ situation.

2.2.7.1 Policy Status Associating $PM_{2.5}$ in Thailand

In Thailand, the basic national regulation of environmental quality standards is under the Enhancement and Conservation of National Environmental Quality Act established in 1992. This law is enforced by the PCD which is the primary national agency of environmental regulation under the Ministry of Natural Resources and Environment (Muro et al., 2019). The initial regulation for controlling air quality in Thailand is NAAQs established since 1995 (As seen in Section 2.1.2).

Additionally, the emission standards have been established to control emission from mobile sources and their origin control of emission sources for mobile devices by PCD. Since 1998, the responsible regulatory agencies have adopted the European emission standards, with emission control from the sources being managed by various organization and ministries of Thailand. For example, the Ministry of Industry was responsible for controlling emissions of industries and refineries. While the Ministry of Natural Resources and Environment is responsible for controlling the emissions from power plants and the significant factors affecting air pollutant concentration such as forest fire, biomass open burning. Specifically, the mobile source emission control has established the standard for new light-duty vehicles (e.g., passenger cars, taxis and so on) in Thailand. They have been obligated to correspond with the Euro 4 emissions standards since 2012. These guidelines on mobile sources are accompanied to public campaigns for the use of public transportation and of transportation based on alternative fuels such as electricity and natural gas (Muro et al., 2019).

2.2.7.2 Current Measures and Policies for $PM_{2.5}$ Agenda in Bangkok and Metropolitan Region

The current measures and policies are under the "Solving the $PM_{2.5}$ pollution problem" for driving the national agenda for $PM_{2.5}$ situation in Thailand, including Bangkok and metropolitan region. It focuses on the prevention and solution in terms of spatial pollution management, particularly in the provinces where dust crises have. For Bangkok and its vicinities, this agenda covers the consideration of main pollution sources such as vehicles, open burning, industrial sectors, construction, and haze transboundary. Table 2.8 presents the measures of $PM_{2.5}$ to Control and reduce pollution from vehicles by PCD.

Table 2.8 The Measures of $PM_{2.5}$ to Control and Reduce Pollution from Vehicles

No.	Description
2.2.1	Use incentive measures to promote pollution to bring fuel to the source. There is no more than 10 ppm sulfur for sale / before the law comes into effect.
2.2.2	Complete the improvement of fuel quality with sulfur content up to 10 ppm by 2023. And the use of fuel with sulfur content not more than 10 ppm from 1 January 2024 onwards.
2.2.3	Increase convenient and safe transportation options for people such as local roads, bicycles, and pedestrian walkways.
2.2.4	Expedite the connection of public transport systems, both primary and secondary systems, to be efficient Pollution-free and convenient for users.
2.2.5	Control the use of used cars in foreign countries (Personal use) into Thailand, which must comply with the air pollution standards for new production vehicles that Thailand is enforcing at the import time.
2.2.6	Control import of old used engines (both cars and boats) must comply with the air pollution standards for new production vehicles that Thailand is enforcing at the time of import and must not be older than 5 years.
2.2.7	Do not import all types of used engines.
2.2.8	Increase strictness, standards, and methods for measuring the emission from cars pollution, reduce the age of cars that must be checked for annual vehicles, develop a car inspection system to have a link to the condition examination results for more efficiency.
2.2.9	Use incentive measures to promote the use of electric vehicles.
2.2.10	Buy and replace old government vehicles with electric cars.
2.2.11	Demand Side Management to increase transportation capability access to services of people using the service.
2.2.12	Specify areas and measures to limit the number of cars entering the city center.

No.	Description
2.2.13	Study of suitability in limiting the useful life of the car, including the car wreck management system that expires.
2.2.14	Enforce air pollution standards from new Euro 5 cars by 2021 and Euro 6 by 2022.
2.2.15	Change all BMTA buses into BMTA with low pollution (Electric train / NGV/ Euro VI standard).
2.2.16	Promote and support the use of Electric cars and civil service use, private public transport services.
2.2.17	Update and edit annual taxation for used cars.
2.2.18	Control the dust from Loading and unloading goods at the port and from boat to ship.
2.2.19	Consider moving the Khlong Toei Port out of the Bangkok area.
2.2.20	Control air pollution from non-road related engines such as machinery (Diesel) used in construction and agriculture, ground equipment in airports, or trains etc.

Source: Pollution Control Department (2019).

2.2.7.3 European Emission Standards

The European Emission Standards are the guidelines of vehicle emission for fuel gases. These standards are specified in a series of “European Union directives staging the progressive introduction of increasingly stringent standards”. According to Ben et al. (2014) revealed that “the aims of these standards need to rapidly adapt new engine concepts, design and related control strategies which implies using multiple technologies that raise the number of actuators to control”. Figure 2.4 illustrates the timeline of Euro standard registration from Euro 1 to Euro 6 of PM and NO_x reduction efficiency. For example, it can be seen in Figure 2.7, Euro VI required a reduction in PM to 0.01g/kWh, and reductions in NO to 0.4g/kWh.

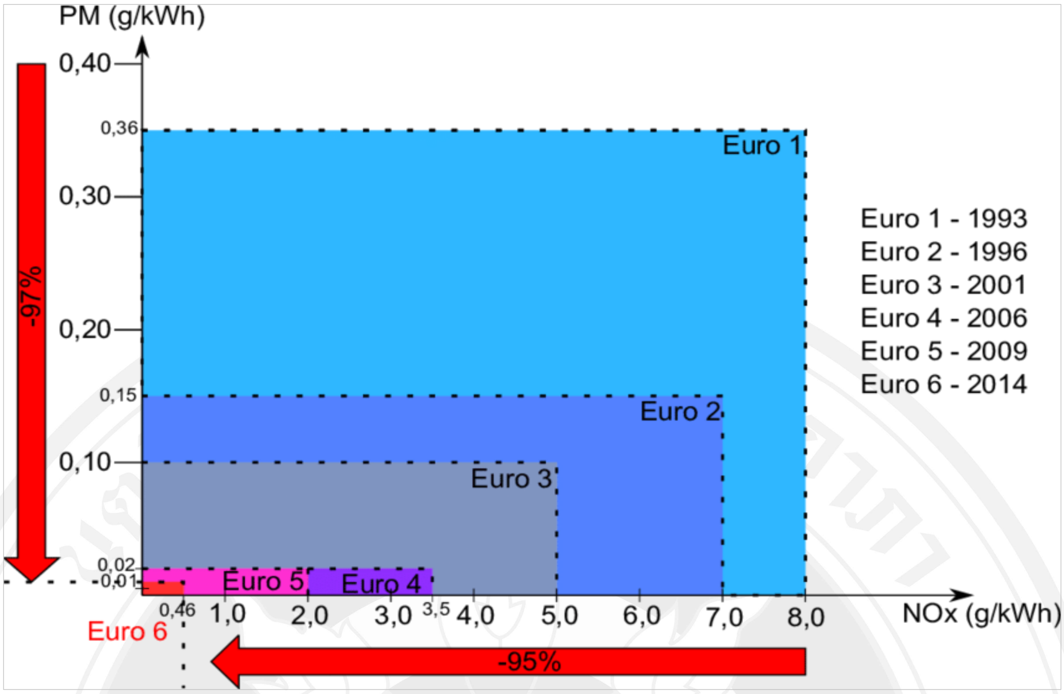


Figure 2.7 Euro Emission Standards (Euro 1 to 6)

Source: Ben et al. (2014).

For automotive manufacturing, guidelines are gradually more stringent in terms of fuel consumption and pollutant emissions reduction than previously. Moreover, new vehicles must comply with these rules to be sold.

2.2.8 Number of Vehicles

The traffic problems mainly derive from the increased number of vehicles. According to the statistics of the accumulated registered vehicles in Bangkok in 2021, it revealed that the number of accumulated registered vehicles was as high as 11,244,732 units (Land Transport Department, 2021). The first 3 types of accumulated registered vehicles included Sedan not more than 7 passengers, Motorcycle, and Van & pickup respectively.

Table 2.9 Number of Accumulated Registered Vehicles as Per December 31, 2021

Types of Vehicles	**Bangkok**
Grand total	11,244,732
A. Total Vehicle under Motor Vehicle Act	11,051,186
Vehicle 1 Sedan (Not more than 7 passengers)	5,100,317
Vehicle 2 Microbus & Passenger Van	222,959
Vehicle 3 Van & Pick Up	1,459,893
Vehicle 4 Motorcycle	770
Vehicle 5 Interprovincial Taxi	-
Vehicle 6 Urban Taxi (Not more than 7 passengers)	81,461
- Ordinary people	24,773
- Juristic persons	56,137
- Not specified	551
Vehicle 7 Fixed Route Taxi	1,851
Vehicle 8 Motorcycle Taxi (Tuk Tuk)	9,183
Vehicle 9 Hotel Taxi	483
Vehicle 10 Tour Taxi	1,510
Vehicle 11 Car for Hire	39
Vehicle 12 Motorcycle	3,971,771
Vehicle 13 Tractor	109,618
Vehicle 14 Road Roller	4,245
Vehicle 15 Farm Vehicle	7
Vehicle 16 Automobile Trailer	5,225
Vehicle 17 Public Motorcycle	81,854

Source: Land Transport Department (2021).

2.2.9 Vehicle Emission Inventory

Emissions Inventory (EI) is the database of the amount of air pollutants emitted into the atmosphere in a specific period. Air pollution emission inventories are the basis to identify significant sources of air pollutants and to target regulatory actions and policy (U.S. Environmental Protection Agency: US EPA, 2006). Moreover, the aims of EI are for trends analysis, regional and local scale air quality modeling, regulatory impact assessments and human health impact modeling.

In general, an EI of pollutant sources should categorize into two main categories which are point sources and area sources. Mobile sources are a subcategory within the area source (U.S. Environmental Protection Agency: US EPA, 2014). Shrestha et al. (2013) revealed that the "On-road transportation includes all types of light duty vehicles (automobiles and light trucks), heavy duty vehicles, (buses and large trucks), and on-road motorcycles, including mopeds, scooters, and three-wheelers". In this study, the EI of on-road transport, which is defined as one of the mobile sources, was conducted. The basics of an EI from mobile sources are developed as follows.

$$EI = NV \times EF \times VKT \qquad \text{(Eq. 2.1)}$$

Where;

NV = Number of vehicles

EF = Emission Factor (g/km)

VKT = Vehicle kilometers travelled (km)

The above equation is the detailed method for accounting the total emission of transportation. Normally, the calculation of total emission is to consider the activity data for each vehicle category and appropriate emission factors. Specifically, the emission factors vary based on input data such as driving conditions, climatic conditions, etc.

2.2.10 $PM_{2.5}$ Air Quality Monitoring Station in Bangkok

In Thailand, the PCD is mainly responsible to monitor the major pollutant in the country. Generally, PCD has monitored and collected $PM_{2.5}$ level in the unit of microgram per cubic meter of air (μg/m^3) and provided $PM_{2.5}$ concentration online for public awareness. The major pollutants which are monitored consist of CO, NO_2, SO_2, and ground-level O_3 and particulate matters (TSP, PM_{10} and $PM_{2.5}$). Additionally, each station monitors the local meteorological parameters such as wind speed, relative humidity, and temperature (PCD, 2018).

Currently, the ambient air quality monitoring networks are more than 60 continuous fixed ambient air quality monitoring stations within the country. In 2018, PCD reported that the PCD ground-based monitoring stations in Bangkok have totally 12 continuous automatic monitoring stations. Moreover, there are mobile stations spreading to monitor in the further areas in Bangkok.

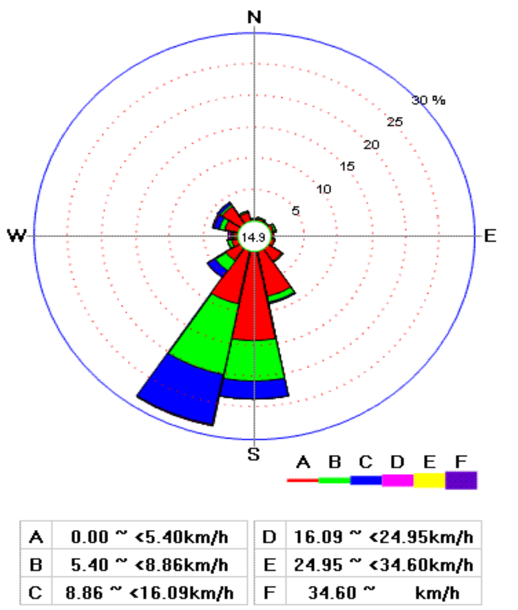
2.2.11 Meteorological Parameter

Meteorological parameters play a key role in ambient air quality. They can affect both terms of direct and indirect impacts. These factors influence pollutant emission, transportation, dispersion, deposition, and air pollutant removal. Many researchers reported that the relationship between meteorological parameters and pollutant concentration has good association significantly (Luo et al., 2019).

2.2.11.1 Wind Speed and Wind Direction

For wind speed, a basic instrument used to measure wind speed is the anemometer. Normally, wind speed is measured at the monitoring station by using a sonic anemometer which is generated based on wavelength. The steps of measurement are that ultrasonic wave releases from a conductor. Then, the wind blocked the ultrasonic movement. This equipment can determine both wind speed and wind direction (Peña et al., 2019). Moreover, wind speed profile is a major parameter to project the air pollutant levels. Generally, the high wind speed affects the high volume of air pollutant dispersion. The wind speed is low because of the influence of homogeneous high pressure. In real situations, the wind speed does not change much in rural areas because of none of the friction at the surface. While the wind speed in urban areas is quite low because the high buildings have huge friction disrupts (Jayaro, Dore, Baumbach, Matthews, & Oliver, 1991).

Wind direction is a report of the direction of wind originates. Due to Coriolis force, the directions of wind in the northern and southern hemisphere are different. Generally, the wind turns to the right in NH and turns to the left in SH. In Thailand, wind rose is one or the tools that widely used to investigate the wind speed and direction in term of the bar scale in the circle and show the percentage of wind (Chen & Yang, 2008). Figure 2.8 is an example of wind rose in Bangkok reported by Thai Meteorological Department on August 21st, 2019.



37.BANGNA Agrometeorlogical Station

Date: 2019-08-20

%	A	B	C	D	E	F	TOTAL
N	0.1	0.2	0.0	0.0	0.0	0.0	0.3
NNE	0.4	0.2	0.0	0.0	0.0	0.0	0.6
NE	0.3	0.1	0.0	0.0	0.0	0.0	0.4
ENE	0.7	0.3	0.0	0.0	0.0	0.0	0.9
E	0.6	0.0	0.0	0.0	0.0	0.0	0.6
ESE	0.8	0.1	0.0	0.0	0.0	0.0	0.9
SE	2.6	0.4	0.0	0.0	0.0	0.0	2.9
SSE	7.5	1.0	0.3	0.0	0.0	0.0	8.8
S	14.4	6.4	2.8	0.0	0.0	0.0	23.7
SSW	8.8	11.4	8.2	0.1	0.0	0.0	28.5
SW	2.5	2.0	1.3	0.0	0.0	0.0	5.8
WSW	0.9	0.5	0.0	0.0	0.0	0.0	1.4
W	0.6	0.2	0.2	0.3	0.0	0.0	1.2
WNW	1.9	0.9	0.9	0.1	0.0	0.0	3.7
NW	3.1	0.5	0.4	0.0	0.0	0.0	4.0
NNW	1.3	0.2	0.0	0.0	0.0	0.0	1.5
CALM				14.9			
TOTAL	46.3	24.2	14.1	0.5	0.0	0.0	100.0

Figure 2.8 Wind Rose Charts at Bang Na station on August 20th, 2019

Source: Thai Meteorological Depart (2019).

2.2.11.2 Temperature and Mixing Height

Temperature is one of the factors affecting the pollutant levels in the atmosphere. Especially, the temperature and sunlight are significantly related to the chemical reaction in particularly photochemical smog situation. When the temperature roses, the pollutant concentration will also high, especially O_3 and PM (Kalisa, Fadlallah, Amani, Nahayo, & Habiyaremye, 2018, p. 111). Moreover, the temperature can affect air pollutant dispersion and transportation. For example, air pollutant concentration at ground level during daytime normally has high temperature. Thus, it causes high turbulence in the air that leads to a good dispersion of the air.

As mentioned above, the temperature decreases with height. Mixing height is defined as the height above the surface in which an air pollutant can be dispersed. During nighttime, there is a clear sky, or it is called temperature inversion, thus, the mixing height turns to zero and has high concentration due to the stable condition, especially in the urban area during nighttime. The relationship between temperature and height can be expressed as a temperature profile as shown in Figure 2.9.

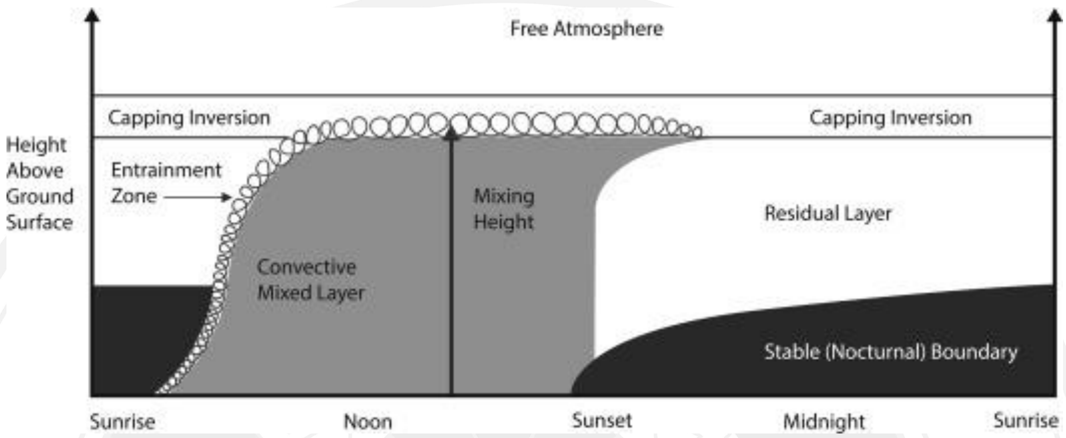


Figure 2.9 A Representative Diurnal Pattern of Mixing in the Planetary Boundary Layer (PBL) during Fair Weather over Land at Midlatitude

Source: Hemond and Fechner (2023).

In general, the vertical temperature profile of the atmosphere is used to classify and distribute the temperature of each altitude. However, the different layers have different compositions of the air pollutants. If the upper layer is warmer than the lower layer, an inversion will occur. Then, the lower layer is a mixing height (or mixing depth) since the pollutants are mixing in this layer.

2.2.11.3 Pressure

Pressure is a considerable indicator which is applied to identify the hydrodynamic properties of air pollutant mass. For example, the strong inversion layer above the atmospheric boundary layer induced by the low-pressure system (Kim Oanh, 2012). Moreover, the pressure of a given amount of the air is directly relational to the temperature at a given volume. The higher the temperature, the higher pressure also goes up, and vice versa.

2.2.11.4 Humidity

Generally, humidity in the atmosphere is demonstrated as a proportion of saturated water vapor water at a given temperature. It is also called relative humidity (RH). The humidity of each location is different due to its topography. For instance, the RH is high if the water bodies are close to the location. Moreover, other parameters, particularly wind speed, wind direction, and temperature associate with RH. For example, the proportion of humidity is high during rainy season because of the high evaporation rate and high precipitation.

Achilleos et al. (2017, p. 189) revealed that the relationship between RH and PM level had significant correlation. The results show that low RH (RH <70%) can increase pollutant concentration. On the other hand, the mid RH to extreme humidity (RH = 70-100%) has a negative correlation to the PM concentration. Hence, it can be indicated that the higher RH, the higher particles can be removed.

2.2.12 MODIS Satellite for Fire Hotspots Detection

A hotspot is defined as a high intensity pixel on the infrared satellite image demonstrating a source of heat of burning vegetation. A pixel of each hotspot represents one square kilometer on the ground. Additionally, a hotspot may represent one fire or is being one of several hotspots representing a larger fire. The source of accessing the hotspot from NASA is the Fire Information for Resource Management System (FIRMS). It distributes "Near Real-Time (NRT) fire/thermal anomaly data within 3 hours of satellite observation from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra and Aqua satellites".

MODIS Collection 6 has been accessible since April 2021. This collection processing does not include any change to the science algorithm. Thus, the update is from changes and enhancements to the calibration approach used in the generation of the Terra and Aqua MODIS Level 1B products. One of the improvements of product collection 6 is to reduce incidence of false alarms caused by small forest clearings and improve detection of small fires. In addition, Level 2 Fire Products: MOD14 (Terra) and MYD14 (Aqua) are basically used in scientific research.

However, the relationship between open burning or forest fire situation and hotspot is widely conducted on the air quality research. According to Chuersuwan, Nimrat, Lekphet, and Kerdkumrai (2008) mentioned that automobile/ or on-road and biomass burning/ or open burning were the majority source of both $PM_{2.5}$ and PM_{10} which was created the air pollution issue in Bangkok province. Much research suggested that controlling the emission at source was the best method to manage the pollution situation. Therefore, source identification was the important section for air pollution control. On-road emission could be measured by air monitoring station and was explained in sector 2.3 and 2.4, while the biomass burning could not determine by air monitoring station. Due to the verities source and period of open burning, spatial information was introduced to analyze and determine the value of PM from open burning. Due to the several of spatial information thus the representation point especially “Hotspot” was introduced to represent the open burning in spatial information. Therefore, the popular source of spatial data for biomass burning was received from satellite information.

2.2.13 Cross- boundary Transboundary Aerosols

It is the PM that blows from one country to another. For example, in the case of the cross-boundary PM from Cambodia to Thailand, the PM will cause direct impact. The PM that moves in at a high level will drop and mix with local PM. As for the central plains which are in the form of a basin, the PM moving at low speed will be attracted by the earth’s gravity to fall to the earth. Moreover, the PM will cause indirect impact. The PM will bar the sun rendering the atmosphere and the earth surface to have lower temperature than normal. As a result, the atmosphere near the earth surface has lower level, causing the PM near the earth surface to have higher concentration. This phenomenon took place between January-February 2019. Afterwards, the wind current blew from the Gulf of Thailand up north decreasing the amount of PM in Bangkok Metropolitan Region. At the same time, there was decreased burning in Cambodia. Based on the above information, the PM was very dense at the beginning of 2019 which derived from the PM from the burning of biomass in Cambodia and was blown by the wind at the higher level to Bangkok Metropolitan Region. It would add to the local PM from traffic and industrial plants. As a result, the amount of PM would be higher than normal, negatively impacting the health of the residents in the areas (Serm Janjai).

2.2.14 Urban Heat Island

The urban heat island started when Luke Howard observed the change in temperature in suburban London in 1820. He found that the town center would have higher temperatures than suburbs. Temperature was measured to inspect and make comparison. It was revealed that at nighttime, the urban temperature would be warmer than the suburbs 3.7 degrees Celsius. This phenomenon was later called "urban heat island".

The urban heat island is when the air around a lot of buildings has higher temperature than the surrounding forest areas, raising the urban temperature. It is the temperature that humans can feel the differences in the temperature. Sauer and Schroth (1995) described the 4 aspects impacting the urban temperature as follows:

1) Development and change of urban environment: Development here means buildings in urban areas. At present, Bangkok has a lot of buildings. These buildings consist of materials that are different than the surface in the rural areas such as the use of concrete, asphalt, and stones, etc. These materials have the quality to absorb and maintain heat whereas materials made from natural plants are found in suburbs. Moreover, it reflects heat to other nearby surfaces at night, making urban temperatures higher than in the surrounding areas.

2) Movement of wind in the city: Urban areas consist of diverse surface materials with different levels, as well as more complexities than in rural areas. These factors will affect the movement of wind, slowing down the wind speed that blows past the city. It means that it reduces heat dispersion in the city. It is different from rural areas with lower, more horizontal buildings and with less complexities. These features of the rural areas will not obstruct the flow of wind, making better heat dispersion. The movement of wind is yet another factor that makes urban areas have higher temperatures than suburban areas.

3) Rate of water's evaporation in urban areas is lower than rural areas: Water's evaporation results in coldness, reducing the amount of heat. The reason that the rate of water's evaporation in urban areas is lower than suburban areas is because the urban surface is hardscape, with the ability to drain rapidly but with the disability to store water on the surface, contrarily to rural areas with the use of vegetation to cover the ground. When the urban areas have hardscape, it cannot store water, rendering the water that is evaporated into vapor to help ventilate heat in the atmosphere is less than in rural areas. Vegetation and soil in the rural areas help slow down the flow of water and increase the flow rate.

4) Heat derived from human activities: Due to higher heat in urban areas, humans must use more energy for air conditioners, impacting the increased heat in the atmosphere. This is because the use of air conditioners is to ventilate air from inside the building to outside. It also impacts humans' quality of life and may destroy human health and other living creatures.

The above 4 factors generate the phenomenon called Urban heat island. Simply put, the temperature in any area is higher than the surrounding temperature. It derives from the factors of development and change in environment in urban areas, features of the movement of the wind, the rate of water's evaporation, and heat from human activities.

2.2.15 Impacts of Urban Heat Island

The impacts of urban heat island derive from the increase of temperature with direct and indirect impacts on humans as follows:

1) Impact on human health

The changing urban weather (microclimate) impacts humans. The biological features and the environment are influenced by the phenomenon. Due to the environmental modification in the urban areas to accommodate more convenience and comfort, it impacts human health. Weather impacts human health and hygiene. As temperature goes up, the direct impact is uncomfortable climate. Indirect impacts include destruction of human health through the eco-system, water cycle, food sources, and carriers of disease. Human beings can adapt themselves to gradual, long-term change. But short-term change may gravely have negative impact. It can be seen from the increased death rates, hospitalization, people's feeling of malaise. These symptoms are clearly the results of the influence of climate.

2) Impact on air quality

As the urban areas have dense activities, these activities may cause ensuing pollution. The pollution will be blown away if there is wind circulation. But if there is the concentration of dense pollution during calm wind and for a long period of time, heat will take place as the air cannot be conveniently ventilated.

3) Impact on the loss of energy

When the urban areas have higher temperatures, especially in summer, the demand for energy increases to ventilate heat and to reduce temperature in residential buildings. The increased energy demand with higher temperature results in continuous and daily energy consumption and the rapidly increased temperature in urban areas.

2.2.16 Atmospheric Movement

According to Boundary Layer Climate Second Edition T.R.OKE Chapter 9 the movement of atmosphere will transport various masses in the air to move with it. Different temperatures at different levels of altitude of the layers of atmosphere will impact the movement of various masses to insert or to stay in the layers of atmosphere. The main method that the substances will insert themselves in the layers of atmosphere is called "Free convection". The vertical altitude that various masses are mixed with the atmosphere is called "Mixed layer". The levels of various masses will be well inserted or mixed in the atmosphere with unstable boundary layer and with very high mixed layer which usually takes place in summer on clear days without cloud. Heat radiation which is long wavelength will render the air near the ground hot. The hot air will float upwards in turbulence and bring substances or pollutants to circulate upward as high as 2,000-3,000 meters (Mixed layer). On the contrary, the dissipation of various masses to insert themselves in the atmosphere in winter is poor due to a lot of clouds. Temperature inversion will take place and result in Stable boundary layer. This is because the atmosphere near the ground level has lower temperature than the atmosphere above, the cold air will subside instead of floating upward. The circular movement is then impossible, and the Mixed layer will reduce to only 200-300 meters. Therefore, with stable or calm air, the dissipation of pollution will be limited as well.

The temperature inversion in the atmosphere according to the definition means the hot air is superimposed on the cold air. Usually without inversion, the temperature in the atmosphere is hot below and gradually cools down at a higher level. But whenever there is air mass inserted between cold air, it is called "Atmospheric inversion" divided into the following:

1) Inversion due to cooling: With cool ground, the atmosphere next to the ground will be cooler than at the next level (Inversion by cooling). This layer may be 50-100 meters from the ground. It takes place mostly at night when the weather is

cool. With sunrise, the temperature at the ground will gradually rise and float to mix with the layer until the layer is eroded. But in some areas with cold, cloudy weather, and with close sky and calm wind, the atmospheric inversion will not disappear and may linger on for weeks before it disappears. In this case, air pollution will be kept in the area and cannot be ventilated. The above layer of hot air will act as a cover that hinders air mass below from inserting or mixing with the air mass above vertically. And if the wind current is not strong, it cannot blow the pollution horizontally as well. This was the case of the situations of $PM_{2.5}$ in Bangkok Metropolitan Region in January 2019. Apart from the activities that emitted a lot of $PM_{2.5}$ in the areas (combustion from a lot of cars in Bangkok, burning of paddy fields, and burning of garbage in the adjacent provinces), it was also due to other factors. It was winter so the temperature inversion increased $PM_{2.5}$. There was also photochemical smog or the smog that covered the whole areas of Bangkok Metropolitan Region. The ensuing sore throat, burning eyes, and burning nose were believed to be from air pollutants consisting of NO_2 and PAN (Peroxy Acetyl Nitrate).

2) Inversion due to warming: In the Middle Troposphere, the above cold air mass subsides as in Figure 2.10 (a) slowly about 1 km. a day from Figure 2.10 (b) at the altitude A. If the air mass subsides to altitude B, the below atmosphere at the altitude will have higher pressure and will force the air mass to subside from A to B and to have smaller volume, raising temperature. In the unsaturated atmosphere, when it moves downward, temperature will rise at the rate of 9.8 degrees Celsius per km. (Dry adiabatic rapes rate or Γ). If the air moves downward 1 km. a day, it means that the temperature will rise 9.8 degrees Celsius a day. So, the base has layers of hot air and results in Subsidence inversion and this layer is like the cover that hinders the air mass at the base from mixing with the air mass at the top with enormous volume.

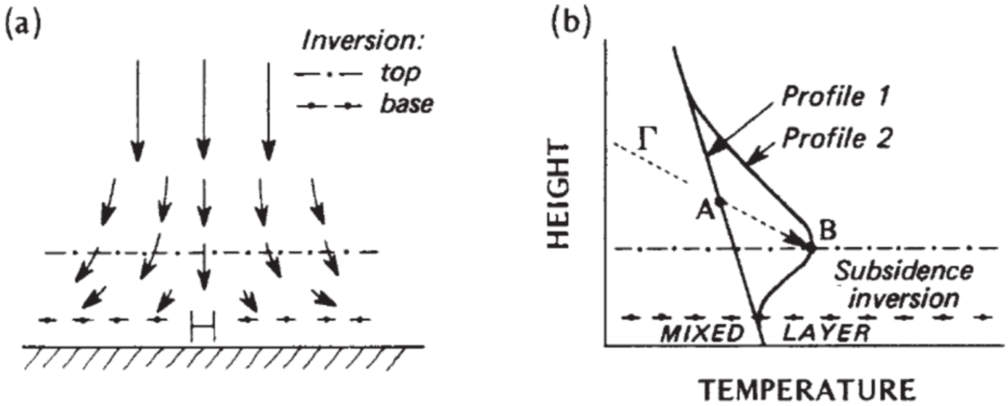


Figure 2.10 Inversion Due to Warming

The inversion due to warming can also take place in 2 situations namely the shady valley hidden by mountains and under the wind as in Figure 2.11 (c). In winter, the valley will be cooler than the areas exposed to sunlight. The atmosphere in the valley is cooler and causes hot air to move down, resulting in temperature inversion. The other situation of temperature inversion is the area below the clouds as in Figure 2.11 (d). During the day in summer, heat from the ground will raise the hot air mass to the top bringing at the same time humidity. When blowing upwards, it will be in contact with the cold air at the top so vapor will evaporate into fine mist and formed into cumulus clouds. The rising air mass will be replaced by the air mass that subsides from above to the atmosphere below which has higher pressure and will force the air mass to have smaller volume, raising temperature. Hot air mass is then found between the cold air above and below resulting in temperature inversion due to the moving down of the air mass.

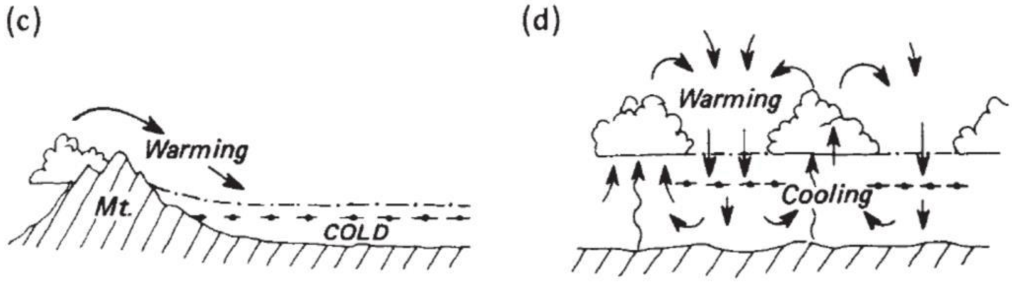


Figure 2.11 Phenomenon of Temperature Inversion in Winter in the Shady Valley (c) and Phenomenon of Temperature Inversion in Summer Below the Clouds (d)

3) Inversion due to advection: In the case when the cold air mass meets hot air and replaces the wedge-shaped hot air, the heavier cold air which is heavier will be below while the hot air will be above called "Cold front". It will cause Temperature inversion as in Figure 2.12 (a). On the contrary, in the case where the hot air mass meets the cold air, the hot air mass will be horizontally above the cold air mass called "Warm front" as in Figure 2.12 (b). Generally, the phenomenon of Inversion will not take long and does not seriously impact air pollution. But the problem arises in the case of the warm front with slow movement of warm air, there will be low slope at the average not exceeding 1: 200. The temperature inversion in terms of warm air will not be very high above the ground. The Mixed layer is relatively thin causing a poor dispersion of pollution until the warm front passes and moves away.

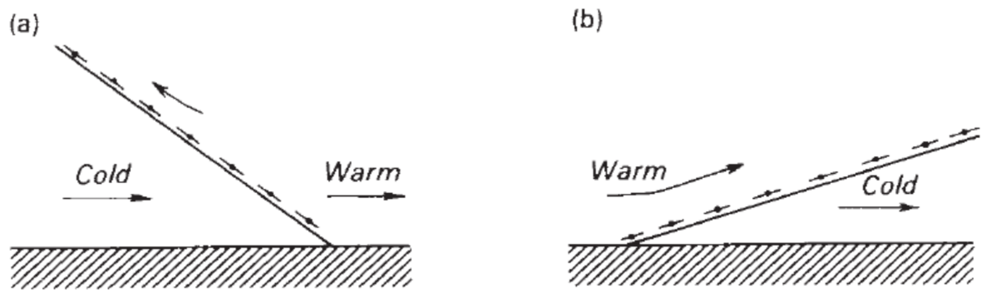


Figure 2.12 Inversion Derived from the Contacts of Horizontal Air Mass

Advection Inversion is also derived from hot air that passes cold surface such as hot air from land passes colder water surface or water surface covered with ice, etc. As in Figure 2.13 (c), the coldness of the water surface below causes Inversion. The base of the Inversion is at the ground level. From Figure 2.13 (c), θ is the Potential temperature. As the air mass moves from higher to lower position, the temperature will increase. This is because at the base the air pressure is higher, it will squeeze the volume of air mass to be smaller. When smaller, the molecules of the air will enter in contact with one another, raising the temperature. To ensure the same standard, Potential Temperature (θ) is determined. It is the level of temperature that moves from the old point to the position of the same standard with the pressure of 100 kPa. From Figure 2.13 (c), if the position of θ is more to the right, it means that in terms of land, the potential temperature is higher than the high level until it reaches a level where the value is stable. In terms of lake or sea, the potential temperature at the water level is lower than the above until it reaches a certain level where the potential temperature is stable. The space below the dash line is the space where the potential temperature is lower than the top and causes temperature inversion. The layer of the temperature inversion below is at the surface level. The top is the line that connects the dots that are changed from the curved line to the linear line of the θ line. In the case when the wind blows from the cold-water surface to the hot surface in Figure 2.13 (d) at position 1, the potential temperature at the level of water surface is colder than above and will cause Inversion. The low edge of Inversion is at the level of water surface. The high edge is at the high point of the curve of the highest potential temperature (at the farthest right) and then changes the direction to the left (reduced potential temperature). When reaching position 2, the ground level will have the highest potential temperature and gradually decreases with higher level. The changed point of the first curved line is the low edge of Inversion that is raised. As for the top edge of Inversion, it is the changed point of the curved line of the highest potential temperature (farthest right) that starts to decrease. When moving to position 3, the low edge of the Inversion is raised, and Inversion will disappear when reaching position 4.

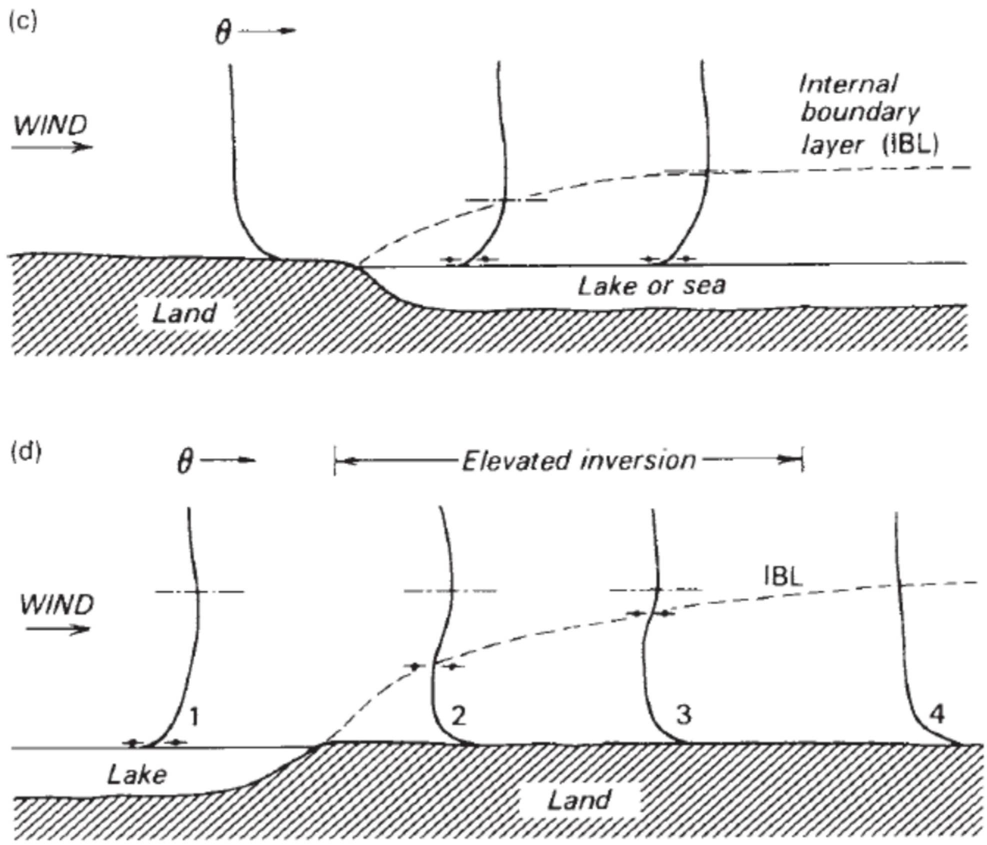


Figure 2.13 Advection Inversion Derived from Hot Air Passing Cold Surface

4) Results of wind speed from dilution or transport of air pollution in the atmosphere: Wind speed is the wind current that will dilute or transport pollution. If the eddy is smaller than the mass of pollution, it will dilute the pollution. If the eddy is bigger than the pollution, it will transport it away. The dilution of the pollution is in the wind direction or the eddy in the horizontal or vertical direction. From Figure 2.14 (a), if the pollution is emitted from the funnel for 1 puff per second and the wind speed equals 2 meters/second, the group of emitted pollution (replaced by opaque black circle) will be 2 meters apart. If the wind speed increases to 6 meters/second, the group of pollution will be 6 meters apart. We will see that the group of pollution becomes bigger. Due to the high wind speed, the eddy will increase and dilute more of the group of pollution and spread it even more as in Figure 2.14 (b). The strong wind current will cause the pollution to blow far from the sources and to be highly diluted in the atmosphere, reducing the concentration of the pollutants.

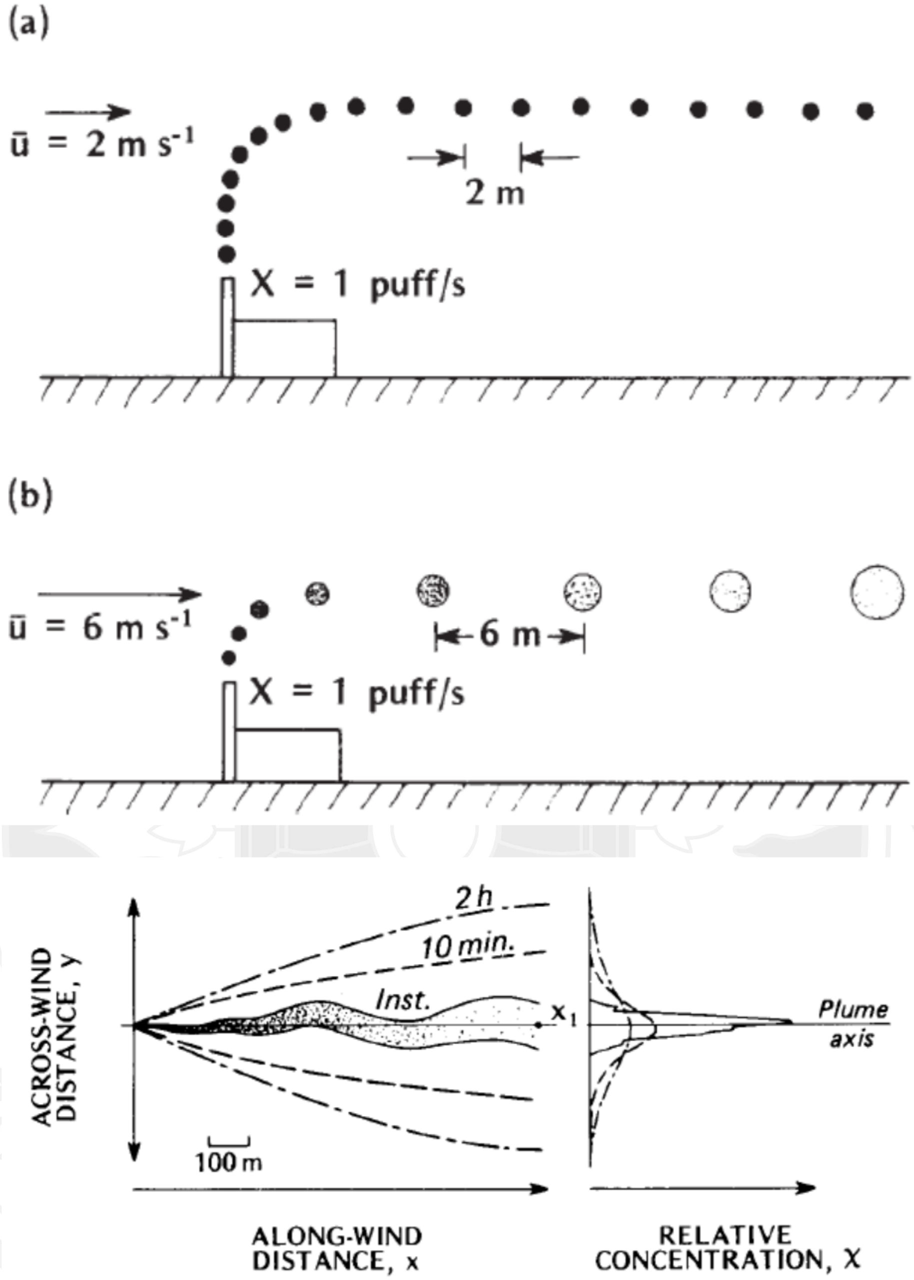


Figure 2.14 Results of Wind Speed in the Dilution and Transport of Air Pollution

5) Local winds such as land breeze, sea breeze, valley breeze, foothill wind, rural wind and city wind had very low impact on the dilution and transport of pollution due to the following:

(1) Low wind speed at the average not exceeding 7 meters/second

(2) During the day, the wind will blow in one direction. At night, it will blow back in the same direction such as land breeze, sea breeze. In the day, the sea breeze will blow from the sea to the land. At nighttime, the land breeze will blow from the land to the sea. So, pollution cannot be blown far away.

(3) Blowing wind in the closed system is the wind current that is blown in a circle. The test is conducted by releasing a balloon at a coast at 09.00 a.m. The wind will blow the balloon from the shore to the land for the distance of 4 kms. Afterwards, at 09.45 a.m., the cold air is in contact with the hot air resulting in the cold front moving to the land. The cold front will raise the hot air to the level of 800 meters to 1,000 meters. It causes the Counter flow which blows back to the water as farthest as 2 kms. Then, it is blown back to the land as before at 11.00 a.m. Afterwards, the balloon will be blown into the land at the distance of 6 kms at 11.15 a.m. when it is very sunny. The hot air on the ground will cause the air to elevate and lift the balloon (Line 3 in Figure 2.15 d). The balloon will then be blown into the land as far as 13 kms. and then disappear (passing Line 4 in Figure 2.15 d).

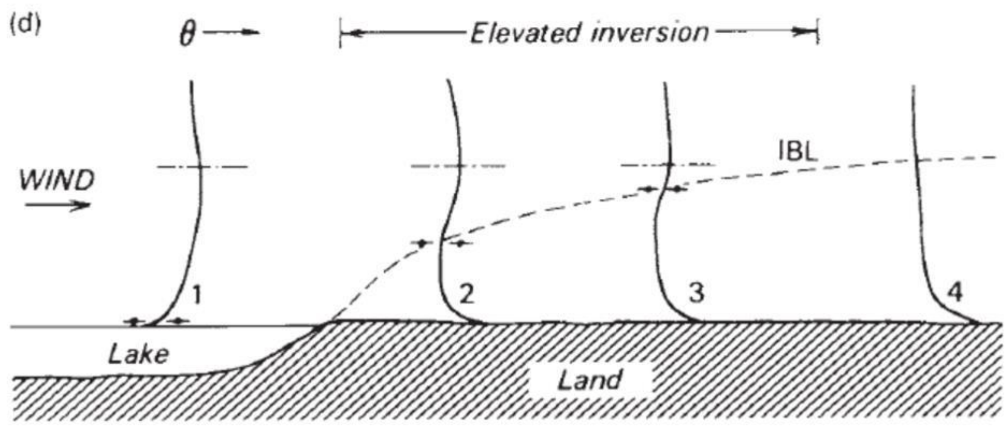


Figure 2.15 Testing of the Release of Balloon from the Shore Towards the Land

2.2.17 Measures to Manage the Problems of $PM_{2.5}$ in Bangkok Metropolitan Region

1) Standards of air quality in the atmosphere were determined to prevent the impact on people's health (abroad there may be special standards to protect the environment, plants, and animals). The study must be conducted on epidemiology to prove the evidence of health impact from each type of air pollutants both in short-term and long-term, including the situations of air quality and other local environments and consideration of impact from standard determination both in economic and social aspects.

The standard of air quality in the atmosphere in Thailand was first published in the Royal Gazette in 1981 and continually improved based on the academic knowledge on the impact of air pollution on health and hygiene from formerly the only standard of TSP to the added standards of PM_{10} in 2004 and $PM_{2.5}$ in 2010. There was health evidence that the inhaled small PM could reach the lower respiratory tract and alveoli, enabling the $PM_{2.5}$ to have more serious impact than large PM.

The standards of air quality in the atmosphere in Thailand with the old format used in 1981 were different from the international standards continually developed. One reason that made standards different (Table 2.6) was the standard of PM in the atmosphere that consisted of short-term (24 hours) and long- term (1 year) standards. The differences of the short-term standards in Thailand were determined at the highest value at the PM level that must not exceed even one day in a year. Wongpun Limpaseni (2017b) recommended the adjustment of the standards of PM_{10} and $PM_{2.5}$ in Thailand as 95^{th} percentile (allowance of the number of days that could exceed the standard 5% in 365 days or equal to 18 days in a year) and to ensure that the standard had the same stringency the standard must decrease to 35 micrograms per cubic meter which was comparable to the US standard (Table 2.10). The new standard had the same stringency. The use of the percentile standard instead of the current highest value would be appropriate as the highest value was highly volatile as it might be influenced by the dire meteorological conditions during a short period of time or the sources with abnormally high pollution in the area or blown from other areas that day. The results of the inspection of air quality found that the exceeding percentile standard was a warning signal to agencies that the short-term measures must be put in place to control air pollutants not to exceed the number of allowed days. World Health Organization (World Health Organization: WHO, 2011) specified that there was no proof to pinpoint the safe level of PM or the level of PM that did not have negative impact on health and hygiene. Therefore, it was the mission of the government agencies responsible for health and hygiene and control of pollution sources to seek to improve the standards of air quality for more stringency in the long run.

Table 2.10 Comparison of the Standards of $PM_{2.5}$ between Thailand and Foreign Countries

Countries	**Average of 24 Hours (Micrograms/ Cubic Meters)**	**Yearly Average (Micrograms/Cubic Meters)**
WHO (old)	25	10
WHO (new)	15	5
EU	-	25
US	35	12
Thailand (Old)	50	25
Thailand (New)	37.5	15
Recommendations for Thailand	35	25

Source: PCD (2023); WHO (2023); Wongpun Limpaseni (2017).

2) The study of the impact on health and hygiene revealed that $PM_{2.5}$, when breathing, could enter the lower respiratory tract and alveoli, resulting in acute effects on health (hourly or daily) and chronic effects (monthly or yearly). For example, respiratory illness and coronary illness such as asthma, respiratory illness, admittance in hospital, and death from respiratory illness and coronary illness, including lung cancer. $PM_{2.5}$ had a negative impact on health more clearly than larger PM. A study finding revealed the estimate that the death rate of all diseases increased 0.2-0.6% per PM_{10} with the increase of 10 micrograms per cubic meter. At the same time, the death rate only from respiratory diseases increased 6-13% per $PM_{2.5}$ with the increase of 10 micrograms per cubic meter (World Health Organization: WHO, 2013). Small PM was more dangerous than large PM because small PM had high surface space so that it could absorb highly hazardous substances. IARC-International Agency for Research on Cancer, an agency of World Health Organization (World Health Organization: WHO, 2012), classified diesel engine exhaust as carcinogenic to humans Group 1 which means that there is proof that diesel engine exhaust causes cancer in humans (IARC classified diesel engine exhaust as carcinogenic to humans (Group 1)). At the beginning of 2018, Germany allowed cities to issue the laws banning cars run on diesel. Consequently, there was the domino effect by which other cities such as Rome, Paris, Madrid, Athens, and Mexico City planned to ban cars run on diesel on the streets by 2025.

3) Pollution Control Department, with support from World Bank, in 1997 established the strategic project to control PM_{10} in Bangkok Metropolitan Region. Although it was not to control the $PM_{2.5}$. The lessons learned and the success in controlling PM_{10} should serve as a good example in planning and determining the measures to control $PM_{2.5}$ in the future. The study conducted the listing of pollution sources and revealed that the first 4 major sources of origin of PM_{10} from the most to the least included road dust, steam boiler in industrial plants, traffic, and power plants.

The study recommended the measures to control the particulate matter by prioritizing the break-even points namely:

(1) Cleaning of roads

(2) Change of types of fuel to natural gas or fuel oil with low sulfur

(3) Improvement of the standards of cars or fuel or the change of engine for function of cars with superior standards

(4) Change of fuel for power plants

The measures had the positive NPV (net present value) and high value for the past 5 years from hundreds of million US to tens of billion US. In other words, the benefit gained is much higher than the costs. The implementation of the measures has decreased PM_{10} gradually since 1997 up to the present. The level of PM_{10} found generally is below standard whereas the amount along the roads tend to reduce on a par with the standard.

4) Improvement of the standards of cars and the quality of Euro 3 diesel. In 2004, Department of Energy Business determined the standards and the quality of fuel by determining the features and the quality of fuel in various aspects as appropriate to the function of engine and the control of pollution emission especially PM, black smoke, and SO_2. The Notifications were issued in 1993, 1996, 1999, and 2004 which determined the amount of sulfur not to exceed 0.5%, 0.25%, 0.05%, and 0.035% by weight respectively. The reduction of sulfur in diesel caused vehicles to reduce exhaust fumes with sulfur oxide, lessening the amount of sulfate dust. Importantly, sulfate must be reduced in parallel with the Notifications to use the Euro 3 vehicle standards, causing PM_{10} to reduce 14.4 micrograms per cubic meter or 18.3% compared to 2004.

5) Improvement of the standards of cars and the quality of Euro 4 diesel. In 2013, due to the success of the improvement of the standards of cars and the quality of Euro 3 diesel in 2004, Pollution Control Department conducted the study of the guideline to improve the standards of cars and the quality of Euro 4 diesel by

considering the reduction of the amount of sulfur in benzene from 500 ppm to, and not exceeding, 50 ppm. and the reduction of the amount of sulfur in diesel from 350 ppm to, and not exceeding, 50 ppm. The study findings revealed the following:

(1) Reduce the amount of sulfur in benzene from 500 ppm to, and not exceeding, 50 ppm, resulting in the following:

(1.1) Reduce the emission of pollution from exhaust fumes such as reduce CO_2 28%, HC 38%, NO 2.6%, and benzene 7.1%

(1.2) Reduce the emission of pollution into the atmosphere such as reduce CO_2 32,650 tons a year, HC 11,892 tons a year, NO 7,188 tons a year, and benzene 1,548 tons a year.

(2) Reduce the amount of sulfur in diesel from 350 ppm to, and not exceeding, 50 ppm, resulting in the following:

(2.1) Reduce the emission of pollution from exhaust fumes such as reduce CO 31%, HC 20%, NO 3%, and PM 15%

(2.2) Reduce pollution emission into the atmosphere such as reduce CO 26,194 tons a year, HC 5,854 tons a year, NO 4,446 tons a year, and PM 1,732 tons a year.

(2.3) Reduce particle matter in the atmosphere by 4.05 micrograms per cubic meter.

(2.4) Reduce impact on health, reduce the rate of 284-810 premature deaths a year valued 22,680-56,700 million baht.

(3) Improvement of the standards of vehicles run on benzene and diesel from Euro 3 standard to Euro 4 standard as well as improvement of fuel quality to be in line with Euro 4 standard which will help reduce the rate of pollution emission of cars with Euro 4 standard from the cars with Euro 3 standard. For cars run on benzene, the emission will be reduced for HC, CO, and NO_x at 50%, 57%, and 47% respectively. For cars that run on diesel, the emission will be reduced for CO, NO_x,

$HC+NO_x$, and PM at 22%, 50%, 46%, and 50% respectively. The introduction of cars run on low pollution benzene (Euro 4) in Thailand will generate the maximum efficiency to reduce pollution but the amount of sulfur in the fuel must be reduced to, and not exceeding, 50 ppm.

CHAPTER 3

RESEARCH METHODS

3.1 Methodology

This research used sources relevant to the changes in the situation and the problems of air pollution in Bangkok. The secondary data was collected from statistical data, news, and documents to explain and summarize the situations of air pollution in Bangkok, other data sources, including international news, statistics, documents, and academic journals relevant to the air pollution data in Bangkok. Then, the analysis was conducted on the overview and the changes in situations and problems of air pollution in Bangkok which currently constitute a major environmental problem. The study was conducted using data and research methods to answer the objectives of the study on the factors impacting the formation and dispersion of PM_{10} and $PM_{2.5}$ in Bangkok, develop the database of $PM_{2.5}$, as well as the forecast of the situations of $PM_{2.5}$ from the land transport sector in Bangkok leading to the efficient formulation of management policy to control, prevent, and undertake surveillance of air quality.

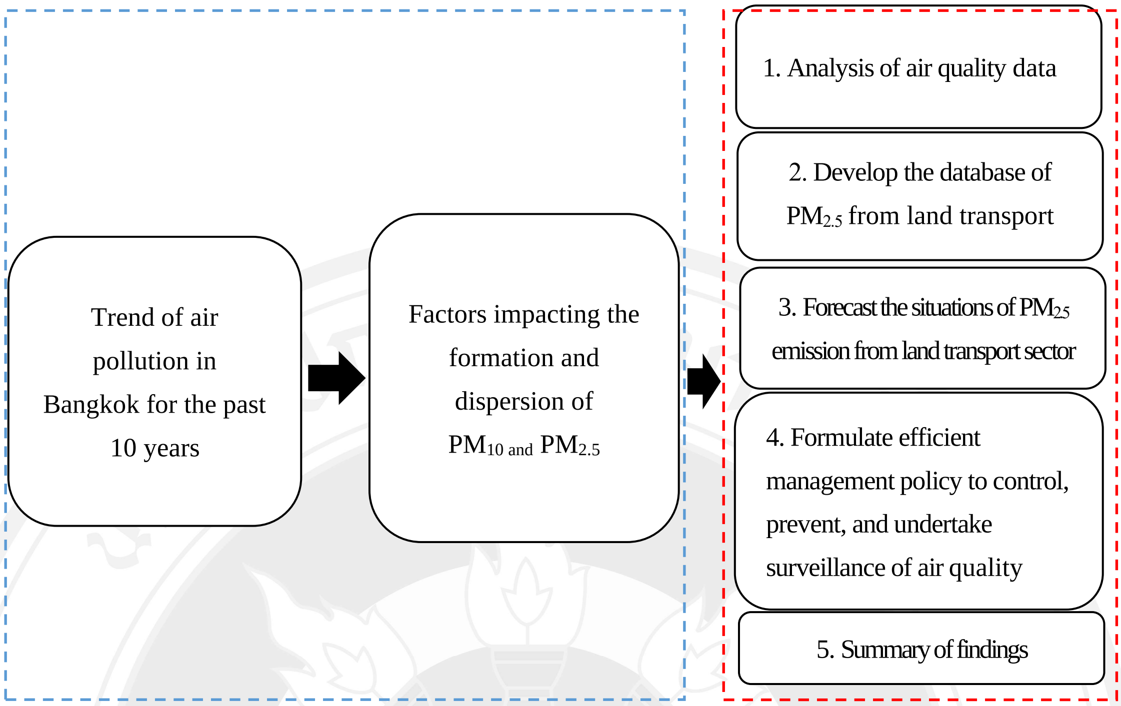


Figure 3.1 Conceptual Framework of the Study

3.2 Research Processes

This research aimed to study the characteristics of the generation of air pollution in Bangkok for the past 10 years and conduct the analysis of factors impacting air pollution in Bangkok using the Quantitative Research which used the data of the results of the measurement of air quality from air quality monitoring stations of Pollution Control Department and Bangkok Metropolitan Administration. Then, the analysis was conducted on the overview and the changes of situations and problems of air pollution in Bangkok, as well as factors impacting the formation and dispersion of PM_{10} and $PM_{2.5}$ in Bangkok, the development of the database of $PM_{2.5}$, as well as forecast of the situations of $PM_{2.5}$ from the land transport sector in Bangkok. The study processes would use the data and the tools currently with the highest efficiency as possible because many parts of the data and the tools in the study processes have some limitations such as limited duration of data, continuity, and completeness of statistical data each year. Therefore, some parts of the data in the study and the tools used in the research would be screened and applied as most appropriately to the study to ensure reliable data under the conditions and the limitations that occurred.

3.3 Study Area and Data Collection

3.3.1 Study Area

The study area of this study is Bangkok, Thailand (Latitude 13.7563° N and longitude 100.5018° E). Bangkok locates in the central of Thailand. The weather of the area is influenced by two monsoons which are northeast monsoon and southeast monsoon that generate the different seasons. Figure 3.2 represents the map of Bangkok, Thailand.

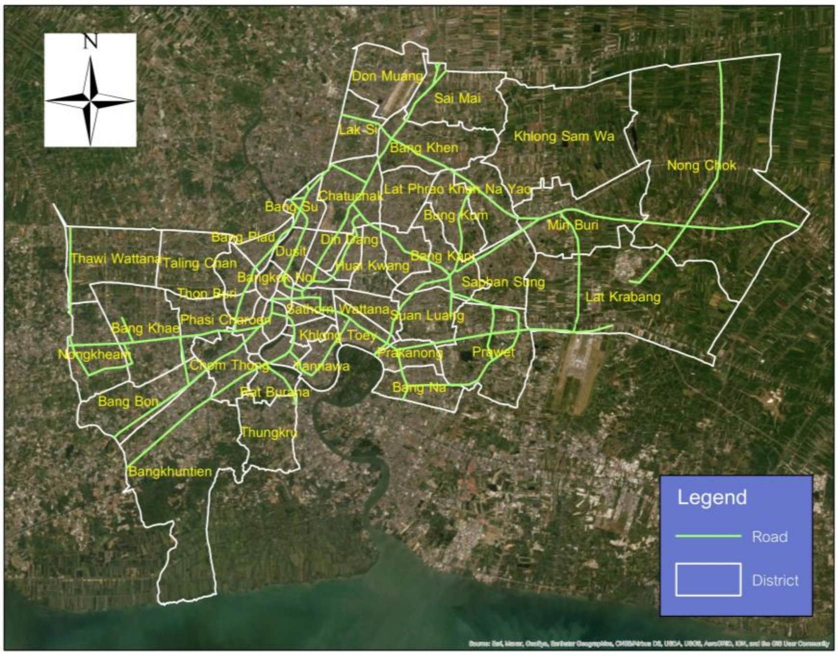


Figure 3.2 The Map of Bangkok, Thailand

3.3.2 Data Collection

The overall annual data collection and preparation of this study is illustrated in Table 3.1.

Table 3.1 Data Collection of this Study

No.	Data	Period	Source
1	Number of cumulative vehicles	2010 - 2019	Department of Land Transport (DLT)
2	$PM_{2.5}$ ground-based monitoring station	2007 - 2020	Pollution Control Department (PCD) and Environmental Office and Bangkok Metropolitan Administration, (BMA)
3	Meteorological parameters	2017 - 2020	Thai Meteorological Department (TMD)
4	MODIS Collection 6.1 Active Fire Product	2017 - 2020	Fire Information for Resource Management System (FIRMS)
5	Crop production and Annual yield of rice	2017 - 2020	Office of Agriculture Economics, Thailand

The data collection was separated into two main parts which were to develop and predict the $PM_{2.5}$ air quality emission and concentration. The details of each data collection are as follows.

1) Number of cumulative vehicles: The numbers of cumulative vehicles were collected from the DLT. In this study, the data of each vehicle type was categorized based on the engine and fuel type of vehicles. The vehicle types of this study consist of personal cars, taxi, motorcycles, vans, public pick-up transport, buses,

trucks, pick-ups, and tuk-tuk. The details of each vehicle type and fuel type classification are presented in Appendix A.

2) $PM_{2.5}$ ground-based monitoring station: The 12 $PM_{2.5}$ ground-based air quality monitoring stations in this study were collected annually from PCD and Environmental Office and 24 air quality monitoring stations of BMA of both ambient and roadside stations during 200 7 to 2020. These data were used to develop the predictive air quality model in Bangkok. The background Information of $PM_{2.5}$ monitoring stations used in this study is illustrated in Table 3.2-3.3

Table 3.2 $PM_{2.5}$ Ground-based Monitoring Stations from PCD used in this Study

Station Name (PCD)	**Type of Station**	**Latitude**	**Longitude**
Highway NO.3902 km.13 +600	Roadside	13.6365	100.4143
Chulalongkorn Hospital	Roadside	13.7300	100.5364
Chokchai Police Station	Roadside	13.7954	100.5929
Department of Land Transport	Roadside	13.72264	100.5293
Thai Meteorological Department	Ambient	13.6661	100.6057
National Housing Authority Klong Chan	Ambient	13.7795	100.6457
National Housing Hua Kwang	Ambient	13.7755	100.5692
Thonburi Power Sub-Station	Roadside	13.7276	100.4866
National Housing Authority Dindaeng	Roadside	13.7626	100.5504
The Government Public Relations Department	Ambient	13.7830	100.5410
Bodindecha Sing Singhaseni School	Ambient	13.7696	100.6146
Ministry of Science and Technology	Roadside	13.7641	100.5286

Table 3.3 $PM_{2.5}$ Ground-based Monitoring Stations from BMA used in this Study

Station Name (BMA)	**Type of Station**	**Latitude**	**Longitude**
At the corner of Royal Jubilee Gate (Odeon Circle)	Roadside	13.7368	100.5122
In front of Esso gas station, Soi Lat Phrao 95	Roadside	13.7789	100.6222
Next to police booth at the yard in front of Bang Rak Lovely Plaza	Roadside	13.7284	100.5269
Area of police booth at Thanon Tok Intersection	Roadside	13.6930	100.5024
Within Bang Khen District Office	Roadside	13.8508	100.6412
Next to police booth opposite Bang Kapi District Office	Roadside	13.7664	100.6476
Within Bang Phlat District Office	Roadside	13.7936	100.5055
Rama 2 Rd.	Roadside	13.6599	100.4359
Rama 6 Rd.	Roadside	13.7836	100.5345
Rama 4 Rd. (MRT Samyan)	Roadside	13.7331	100.5283
Yan Nawa - Rama 3 Rd.	Roadside	13.6792	100.5469
Phahonyothin Rd.	Roadside	13.8399	100.5756
Lat Krabang Rd.	Roadside	13.7221	100.7841
Ratchdaphisak - Tha phra Rd.	Roadside	13.7052	100.4847
Charoen Nakhon Rd.	Roadside	13.7197	100.5088
Railroad Rd. (In front of Police station)	Roadside	13.7596	100.4811
Petchkasem Rd.	Roadside	13.7187	100.4539
Samsaen Rd. (District office)	Roadside	13.7489	100.5026
Ratchathewi District Office	Roadside	13.7592	100.5349
Bueng Kum District Office	Ambient	13.7852	100.6692
Bang Sue District Office	Ambient	13.8096	100.5379

Station Name (BMA)	Type of Station	Latitude	Longitude
Within Khlong Toei District Office	Ambient	13.7084	100.5837
Within Lak Si District Office	Ambient	13.8873	100.5792
Intersection in front of Sathon District Office at Soi Saint Louis	Ambient	13.7080	100.5261

3) Meteorological parameters: The annual meteorological parameters were collected from TMD during 2017 to 2020. These were used to incorporate into the multiple linear regressions to predict the $PM_{2.5}$ concentration in Bangkok. The meteorological data were collected from all available meteorological stations in Bangkok consist of 4 stations (i.e., Bangkok metropolitan, Klong-Toei pier, Bang Na, and Don Mueng Airport). Moreover, the parameters were applied in model prediction consisted of wind speed, temperature, pressure, and relative humidity. While the mixing height was used to predict the $PM_{2.5}$ concentration in Box model.

4) MODIS Collection 6.1 Active Fire Product: The hotspot data were used to incorporate the $PM_{2.5}$ model prediction (Model II) in Task 2 to develop the multiple linear regressions for $PM_{2.5}$ episode in Bangkok.

3.4 Data Analysis

As the air quality data was in generally in the form of secondary data, whether the concentration of air pollutants or meteorological data, the researcher chose to use the R software jointly with the Openair package for the data processing and the analysis in accordance with the objectives and the scope of the study. The processes included the following:

3.4.1 Collect the Air Quality Data from Air Quality Monitoring Stations in Bangkok

1) Air quality data from Air Quality and Noise Management Division, PCD between 2007-2016 of six stations namely Ministry of Science and Technology (MST) on Rama 6 Road, Department of Land Transport (DLT) on Phaholyothin Road, King Chulalongkorn Memorial Hospital (CUH) on Rama 4 Road, MEA Substation Thonburi (TBP) on Intharaphithak Road, Chokchai Metropolitan Police Station (CCP) on Lat Phrao Road, and National Housing Authority Dindaeng (DDC) on Din Daeng Road.

2) Air quality data from Air Quality and Noise Management Division, BMA between April 2018 – April 2020 from 24 stations

3) Parameters of the study included SO_2, NO_2, O_3, CO, PM_{10} and $PM_{2.5}$, wind speed, and wind direction

3.4.2 Analysis and Assessment of the Trend of Air Pollution with the Selected Functions as follows

PollutionRose Function is the variable of the wind Rose which is useful to consider the concentration of the pollutants jointly with wind direction. Moreover, it can also be used to show the wind direction that covers the overall concentration of pollutants through the order of statistic = "prop.mean" (proportion contribution to the mean) to ensure the wind direction with the most relevant to the overall concentration of the pollutants.

3.4.3 Development of PM2.5 Air Quality Database from On-road Transport Sector in Bangkok

In this section, the database of $PM_{2.5}$ emission from on-road transport in Bangkok during 2011 to 2019 was established based on the reference method of

Emission Inventory (EI) from “Atmospheric Brown Clouds Emission Inventory Manual” developed by Asian Institute of Technology (AIT) (Shrestha et al., 2013). Thus, the results represent the estimation of annual $PM_{2.5}$ emission from the On-Road Transport Sector. The total emission of $PM_{2.5}$ each year was used the formula from the study of Kim Oanh (2017) as shown in equation 3.1 and 3.2 for running and start-up emission, respectively.

3.4.3.1 Running Emission

The running emission is defined as the emission of $PM_{2.5}$ emitted when the engines of vehicles are running on the road.

$$\mathbf{E_{i,run} = EF_i \times VKT \times Nv} \qquad \text{(Eq.3.1)}$$

Where;

$E_{i,run}$ = Emission amount of pollutant i (ton/yr)

EF_i = Running Emission Factor of pollutant i (g/km)

VKT = Vehicle Kilometer Travelled (km/yr) per vehicle in the considered type

Nv = Number of in-use vehicles of the considered vehicle type

In this section, the Emission Factor (EF) of $PM_{2.5}$ running emission of each vehicle type is illustrated in Appendix A (Table A1). The Vehicle Kilometer Travelled (VKT) of each vehicle is applied by conducting the literature review of Asian Institute of Technology (AIT) survey in 2018 (Table A2). Lastly, the number of in-use vehicle of each type (Nv) is calculated using accumulative number of registered vehicles taken from the DLT during 2011 to 2019 with consideration of the in-use rate of each vehicle “Developing Integrated Emission Strategies for Existing Land Transport DIESEL Program” of PCD (Table A3).

3.4.3.2 Start-up Emission

The start-up emission is defined as $PM_{2.5}$ emission from the vehicles when their engines are started.

$$\mathbf{E_{i,start} = EF_i \times Mv \times Nv} \qquad \text{(Eq. 3.2)}$$

Where;

$E_{i,start}$ = Emission amount of pollutant i (ton/yr)

EFi = Start-up Emission Factor of pollutant i (g/start)

Mv = Number of start-ups per vehicle in the considered type

Nv = Number of in-use vehicles in the considered type

The EF of start-up emission is also presented in Appendix A (Table A1). In addition, the Number of start-ups per vehicle (Mv) of each vehicle type are conducted from the literature review as shown in Table A2.

3.4.4 Prediction of $PM_{2.5}$ Emission and Concentration in Bangkok

In this task, the prediction of $PM_{2.5}$ concentration in Bangkok during 2017 to 2020 based on the data availability of $PM_{2.5}$ ground-based monitoring station in Bangkok region were divided into two sections. The first one is to generate a regression model to predict the $PM_{2.5}$ concentration using Multiple Linear Regression (MLR). In this case, the models consist of Model I (baseline concentration from on-road transport), and Model II ($PM_{2.5}$ episode). Additionally, the second part is to see the overall annual $PM_{2.5}$ emission and concentration using Box model.

3.4.4.1 Database of $PM_{2.5}$ Emission from Open Burning

Firstly, the hotspot data from MODIS collection 6.1 during 2017 to 2020 were used to identify the $PM_{2.5}$ emission episode. According to Kim Oanh (2012), the $PM_{2.5}$ episode in Bangkok and metropolitan regions is mainly influenced by transportation and open burning, especially dry season. Therefore, the hotspot data was used to indicate the $PM_{2.5}$ episode in Bangkok with the criteria that if the number of hotspots in the day is higher than 30% of the maximum number of hotspots in the interested year, those days will be defined as an episode (Kim Oanh, 2012, p. 14).

Additionally, the hotspot data were used to calculate the databased $PM_{2.5}$ emission from open burning source. The emission estimation method referred to the ABC-EIM (Shrestha et al., 2013, pp. 77-78). The following equations (Eq. 3.3 and Eq. 3.4) were used to determine the emission of $PM_{2.5}$ over Bangkok and Metropolitan Regions (BMR) surrounding Bangkok about 50 Km. including Nonthaburi, Pathum Thani, Samut Sakorn, Samut Prakan, Nakorn Prathom, and Chachoengsao provinces (As seen in Figure 3.3).

$$\mathbf{Em_{i,j} = \sum_j M_j \times EF_{i,j}} \qquad \text{(Eq. 3.3)}$$

Where;

i,j = Pollutant *i* and crop type *j*

$Em_{i,j}$ = Emission of pollutant *i* from crop type *j*

M_j = Amount of burned biomass from crop type *j* (kg/yr)

$EF_{i,j}$ = Emission factor of pollutant *i* from crop type *j* (g/kg of dry matter)

However, the main agricultural residues in BMR normally come from rice. Thus, the amount of burned biomass in this study was rice crop residues. The calculation of the Amount of burned biomass from rice (M_j) can be calculated based on the Equation 3.4.

$$\boldsymbol{M_j = Y_j \times S_j \times D_j \times B_j \times A_j \times n_j} \qquad \text{(Eq. 3.4)}$$

Where;

Y_j = Annual yield (kg/ha)

S_j = Crop-specific residue to production ratio (fraction)

D_j = Dry matter-to-crop residue ratio (fraction)

B_j = Fraction of dry matter residue in field

A_j = Area of burned biomass from Hotspot (ha/yr)

n_j = Crop-specific burn efficiency ratio (fraction oxidized during combustion)

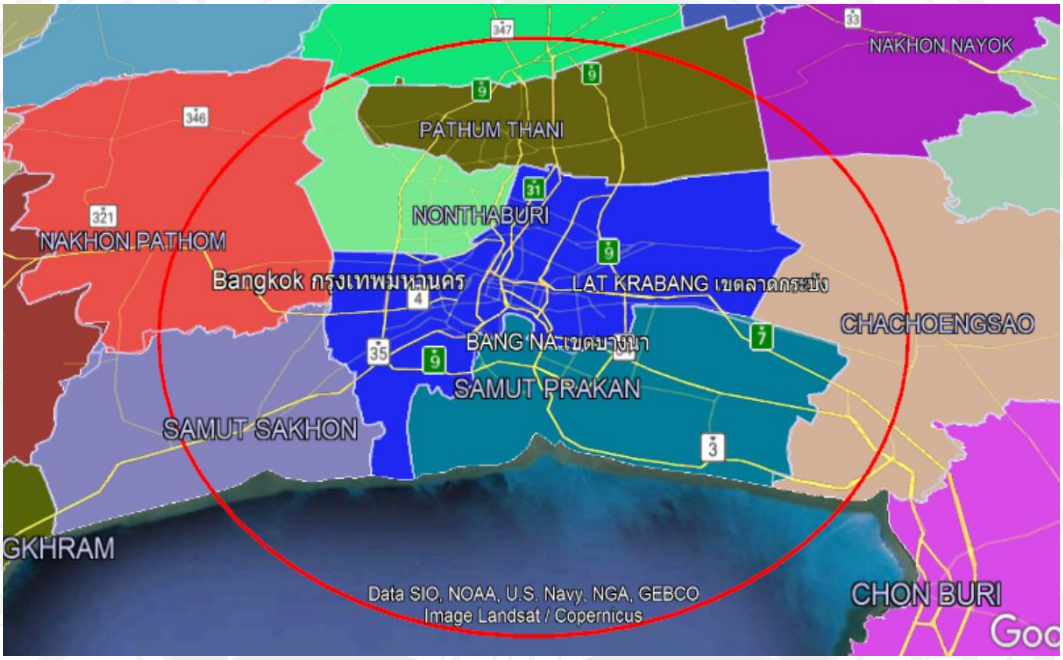


Figure 3.3 Bangkok and Metropolitan Region Surrounding 50 km.

3.4.4.2 Prediction of $PM_{2.5}$ Emission and Concentration in Bangkok using Multiple Linear Regression (MLR

In this study, the independent variables which accounted to the regression was used the criteria of statistical analysis of F-entry ≤ 0.1 and removal ≥ 0.15 (Leelasakultum, 2009). The summary of the data used in this section is illustrated in Table 3.4.

Table 3.4 The Summary of Data used for $PM_{2.5}$ Prediction Model

Data	Period	Purpose
• $PM_{2.5}$ ground-based monitoring data • Meteorological data • Hotspot data • $PM_{2.5}$ emission	2017 – 2019 2020	Model development Model validation

(Model I) $PM_{2.5}$ Concentration from on-road Transport Sector The main task of this task is to develop the $PM_{2.5}$ concentration model to estimate the baseline concentration in on-road transport sector in Bangkok. The model incorporated the relationship among $PM_{2.5}$ emission from on-road transportation sector in the previous section, $PM_{2.5}$ levels from ground-based monitoring station and meteorological data which has strong correlation factors with $PM_{2.5}$. Therefore, the multiple linear regressions are selected to make correlation analysis between $PM_{2.5}$ concentrations and other observation components to represent the model prediction of $PM_{2.5}$ levels in Bangkok. The multiple linear regressions in this study can be expressed as follows:

$$\mathbf{PM_{2.5,con}} = \boldsymbol{\alpha} + \mathbf{Q} + [\boldsymbol{\beta_1} \times \boldsymbol{met_1}] + \cdots + [\boldsymbol{\beta_n} \times \boldsymbol{met_n}] \quad \text{(Eq. 3.5)}$$

Where;

$PM_{2.5,con}$ = Amount of Annual $PM_{2.5}$ concentration from ground-based monitoring station (μg/m^3)

Q = Amount of $PM_{2.5}$ emission from on-road transport sector (ton/year)

α , β = Regression coefficients

Met = Meteorological parameters (e.g., Temp, RH, and WS etc.)

Specifically, the days, which were defined as an episode (see section 3.4.1), were excluded from the regression to identify $PM_{2.5}$ concentration from on-road transport sector individually.

(Model II) $PM_{2.5}$ Concentration Episode In this case, the $PM_{2.5}$ concentration episode was defined as the overall $PM_{2.5}$ ambient air concentration in Bangkok. It was determined by using the MLR which is associated with the main source of $PM_{2.5}$ emission (i.e., on-road transport and open burning). Thus, this model incorporated the dependent variable ($PM_{2.5}$ ground-based monitoring data) and independent variables (i.e., meteorological parameters, $PM_{2.5}$ emission, and hotspot). The multiple linear regressions in this study can be expressed as follows:

$$\mathbf{PM_{2.5,con}} = \boldsymbol{\alpha} + \boldsymbol{Q_{all}} + [\,\boldsymbol{\beta_0} \times \mathbf{Hotspot}] + [\,\boldsymbol{\beta_1} \times \boldsymbol{met_1}] + \cdots + [\,\boldsymbol{\beta_n} \times \boldsymbol{met_n}] \quad \text{(Eq. 3.6)}$$

Where;

$PM_{2.5,con}$ = Amount of Annual $PM_{2.5}$ concentration from ground-based monitoring station ($\mu g/m^3$)

Q_{all} = Amount of $PM_{2.5}$ emission episode (ton/year)

α , β = Regression coefficients

Hotspot = Number of Hotspot in 50 km surrounding Bangkok

Met = Meteorological parameters (e.g., Temp, RH, and WS etc.)

3.4.4.3 Validation of $PM_{2.5}$ Concentration Model Prediction

Model validation refers to the process of verifying that the model accomplishes its intended purpose. This study used the data of all variables in 2020 to validate the performance of the model. Then, statistical analysis is normally used to evaluate the performance of model prediction. Thus, the statistical parameter in this study is correlation of determination (R^2). Thus, the $PM_{2.5}$ concentration retrieved from the model was correlated to the $PM_{2.5}$ concentration from ground-based monitoring station. Moreover, the proportion of the variation in the dependent variable ($PM_{2.5}$, con) which is predictable from the independent variables (Q and met). The coefficient of determination normally ranges from 0 to 1. If the R^2 of the model results close to 1, it will be acceptable that the model performs well.

Additionally, the statistical analyses of observation data and estimation data (Modeled) were Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE). The calculation of each statistic is presented in Table 3.5.

Table 3.5 The Statistical Analyses used in This Study

Statistics	**Equation**
Root Mean Square Error (RMSE)	$MAE = \frac{1}{N}\Sigma_1^N\lvert Cm{-}C0\rvert$
Mean Absolute Error (MAE)	$RMSE = \sqrt{\frac{1}{N}\Sigma_1^N(\mathrm{Cm}-\mathrm{C0})^2}$
Mean Absolute Percentage Error (MAPE)	$MAPE = \frac{1}{N}\Sigma_1^N\left\lvert\frac{\mathrm{Cm}-\mathrm{C0}}{\mathrm{C0}}\right\rvert \times 100$

Note: Remarks: C_o = observation, C_m = model

3.4.4.4 Estimation of $PM_{2.5}$ Concentration in Bangkok using Box Model

To verify the emission and concentration of $PM_{2.5}$ in Bangkok, box model, which is one of simple urban air quality models, is applied to calculate ground-level concentrations of $PM_{2.5}$ emitted from the on-road activity into the atmosphere. In this case, it assumes that $PM_{2.5}$ emitted to the ambient air are uniformly mixed in a volume and fails to account for spatial information (Reed, 2005). However, it is still useful for general estimations of average pollution levels. Thus, Bangkok is defined as a box. The model generally used is as follows.

$$\mathbf{C} = \mathbf{C_0} + \frac{\mathbf{qL}}{\mathbf{\mu H}} \qquad \text{(Eq. 3.7)}$$

Where;

C = The concentration of the air pollutant in the entire town ($\mu g/m^3$)

C_0 = The background concentration of the air pollutant ($\mu g/m^3$)

q = The emission rate of the air pollutant ($g/s \cdot m^2$)

L = Length (m)

H = Height or Mixing Height (m)

μ = Velocity of the air (m/s)

3.5 Implication of Policy to Reduce $PM_{2.5}$ Concentration Contributed On-road Transportation.

The implication of policy in this study is mainly based on “the vehicle emission standards in Thailand” developed by Thai Industrial Standards Institute (TISI) and PCD. In general, these Thai emission standards are basically referred to European emission standards. Moreover, the possible measurement aspects were applied to implicate the policy scenarios which corresponded to mitigate the $PM_{2.5}$ levels in on-road transportation.

Table 3.6 Policy Implication Based on Different Scenarios in this Study

Scenario	Description
S_0	Normal $PM_{2.5}$ concentration scenario (Base case).
S_1	Promote 50% of Euro IV to ranked first of vehicle types that emit the highest $PM_{2.5}$ emission.
S_2	Promote 50% of Euro IV to ranked second of vehicle types that emit the highest $PM_{2.5}$ emission.
S_3	Remove vehicle types which use Pre-Euro engines.
S_4	Promote 20% Euro V to light-duty vehicles, especially personal cars.
S_5	Incorporate among all scenarios.

Specifically, the promotion of Euro IV and Euro V in this study is a removal of the Pre-Euro diesel vehicles as the purpose of the TIS standards needs to eliminate the vehicle age more than 7 years. This section was done by substituting and upgrading mainly in Euro IV, and Euro V, respectively. However, this study assumed that the driving activities were homogeneous as a characteristic of base case.

Finally, the best performance policy scenario was selected to represent as an effective policy implication for controlling $PM_{2.5}$ emission for on-road transport sector. Then, this result was accounted to the $PM_{2.5}$ model estimation to predict the $PM_{2.5}$ levels in Bangkok after applying the selected policy implication in the next ten year.

CHAPTER 4

STUDY RESULTS

4.1 Characteristics of Air Pollution in Bangkok for the Past Ten Years

4.1.1 Trend of Air Pollution in Bangkok

The analysis of Air Quality data from Air Quality station the results of the measuring of air quality from air quality measuring stations along road curbs in Bangkok for the past 10 years revealed that, in most air quality measuring stations, SO_2 and NO_2 tended to decrease. CO, O_3, and PM_{10} tended to be different according to stations as shown in Table 4.1 and Figure 4.1. Limiting the usage of smoke-emitting diesel cars that fail to meet the standards could decrease the amount of PM_{10} along road curbs. In 2004, Department of Energy Business formulated the policy to improve Euro 3 vehicle emission and diesel quality standards, by determining the characteristics and the quality of fuel in various dimensions appropriate to the functioning of engine to control the emission of pollution especially dust, black smoke, and SO_2. Therefore, the reduction of sulfur in diesel would reduce car exhaust containing SO_2 and reduce formation of sulfate dust. Importantly, the reduction of sulfur must be undertaken in parallel and following by Euro 4 vehicle emission standards which would also help reduce the amount of $PM_{1.0}$. From Table 4.1, in some stations, there was increased trend concentration of CO and PM_{10} such as Stations DLT, CCP, and MST due to the characteristics of such stations with regular traffic congestion, as well as the orientation of the buildings in the areas which obstructed the movement of horizontal air (Advection).

Table 4.1 Results of Air Quality from Air Quality Measuring Stations Along Road Curbs in Bangkok between 2007-2016

Stations	**Parameters**				
	CO	**NO_2**	**O_3**	**PM_{10}**	**SO_2**
1. TPB	Decrease	Decrease	**Increase**	Decrease	Decrease
2. CCP	**Increase**	Decrease	Decrease	Decrease	Decrease
3. DDC	Decrease	Decrease	**Increase**	Decrease	Decrease
4. MST	**Increase**	-	-	Decrease	-
5. DLT	Decrease	Decrease	**Increase**	**Increase**	Decrease
6. CUH	No change	-	-	No change	-

Note: - No measuring

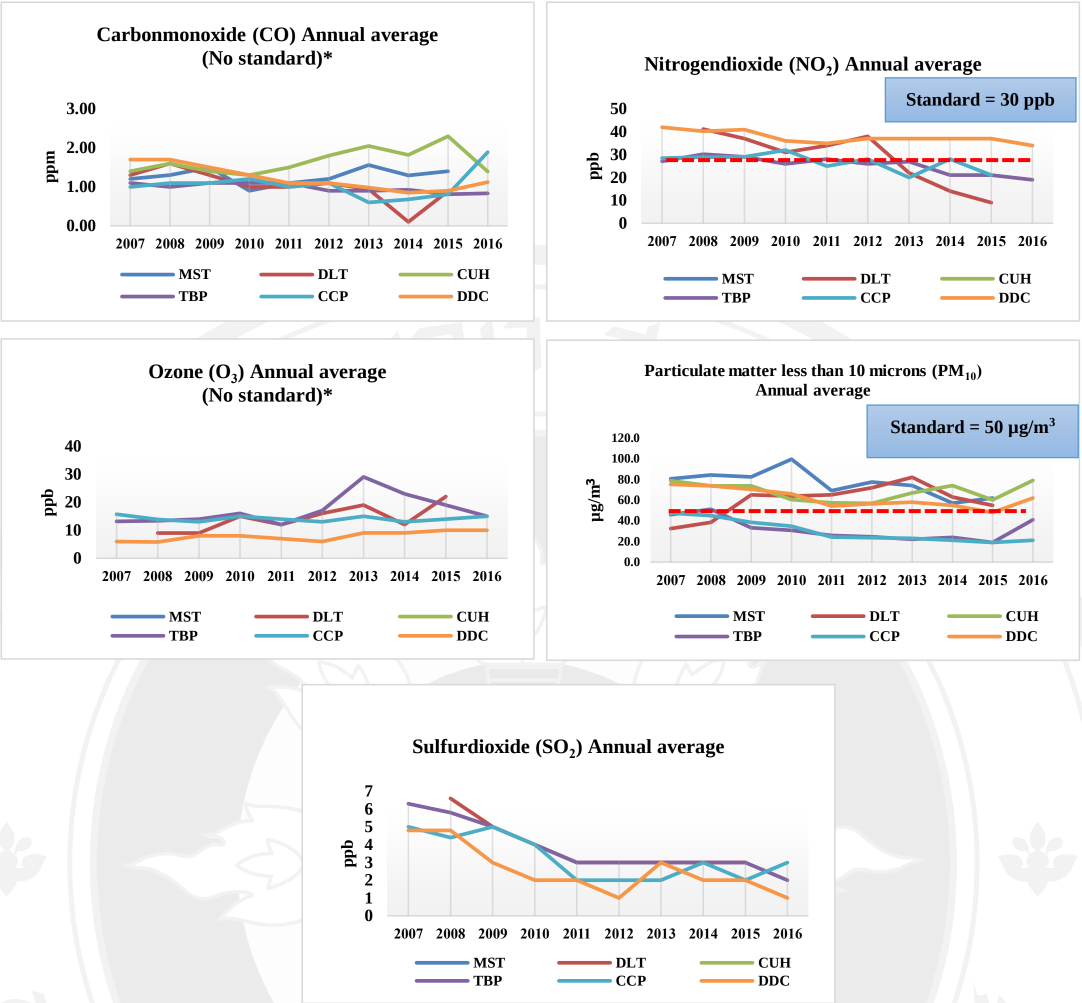


Figure 4.1 Average Annual Concentrations from Measuring Stations Along Road Curbs in Bangkok Divided by Monitored Parameters between 2007-2016

4.1.2 Correlation

The correlation between various parameters as shown in Figure 4.2 revealed that the primary pollutants tended to have positive relation such as NO_2 with CO, NO_2 with SO_2, and CO with PM_{10} etc., as the primary pollutants were usually from the same sources. As O_3 was the secondary pollutant, positive correlation with other parameters could not be observed, consistent with the study of Thanikan Lapapipatt (2006) which was conducted to find the present and past amount of concentration of O_3 at the ground level from human activities in Bangkok and to find the relation between O_3 and meteorological factors such as pressure, amount of rainfall, relative humidity, and sun radiation. Information was compiled for 5 years between 1999-2005 from the total of

11 air quality measuring stations from various parts in Bangkok, divided into 3 types of stations namely 3 stations along road curbs, 5 stations in urban areas, and 3 stations in suburban areas. It was found that the occurrence of O_3 was in high relation with sun radiation.

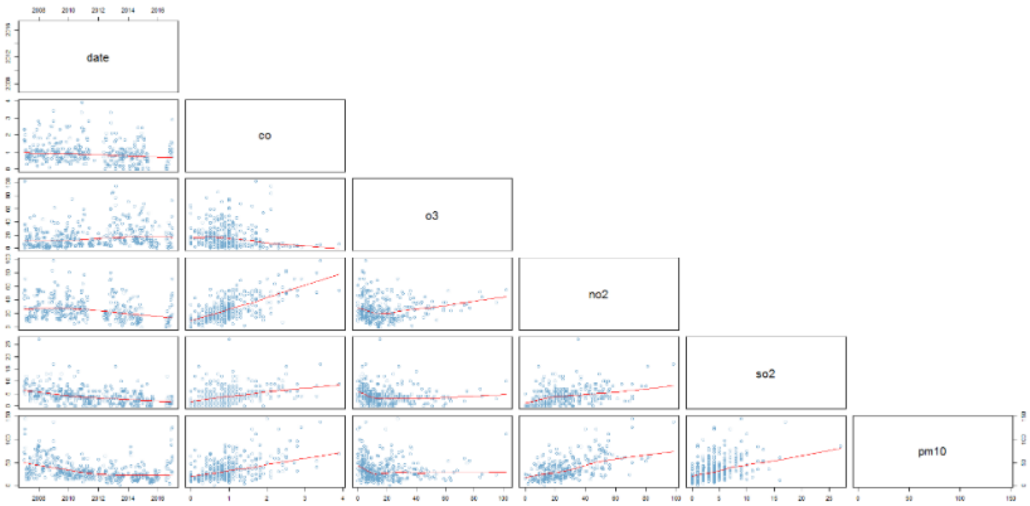


Figure 4.2 Relation between Various Parameters from Data Random Sampling of 500 Hours from TPB

4.1.3 Air Pollution Changes According to Different Time from Data

1) Seasonal change. The analysis of air quality data air pollution changes road curbs in Bangkok for the past 10 years, as shown in Figure 4.3, revealed that SO_2, NO_2, and CO had high concentration in the winter of each year, especially PM_{10} as we found the air pollution episode with higher concentration exceeding the standards many times, notably in winter every year, between November-February. Due to the dry weather in winter, relative humidity would decrease, resulting in longer resident time hanging of dust in the air. Moreover, calm weather and inverse atmospheric inversion near the ground would cause air pollutants to accumulate in a large amount. In rainy seasons, between May-September, all types of air pollutants tend to be lower than the air quality standard as rainfall would increase relative humidity in the air and cleanse pollutants in the atmosphere as well.

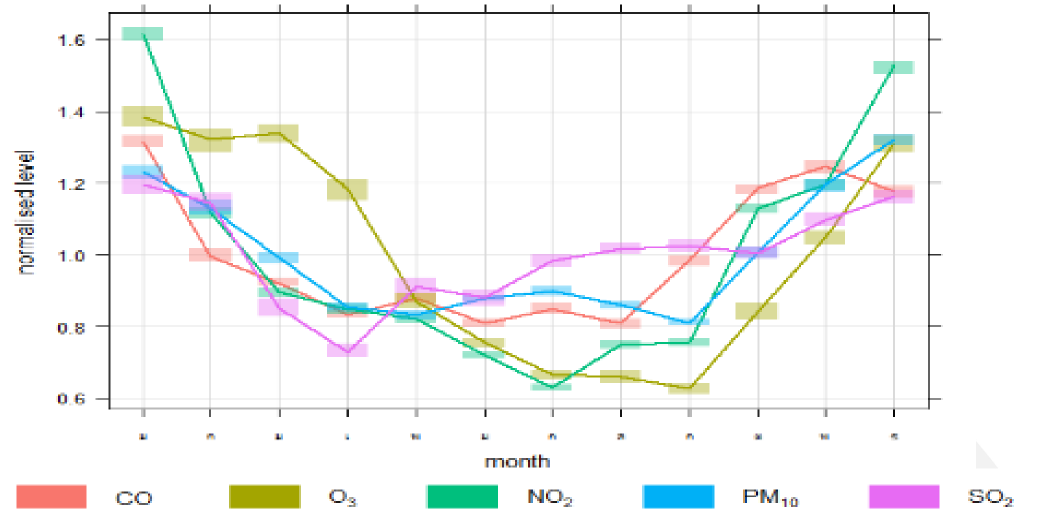


Figure 4.3 Results of Monthly Air Quality Measuring from TPB between 2007-2016

2) Diurnal change. Diurnal validation in air pollution is shown in Figure 4.4. The pollution emission of primary pollutants such as SO_2, NO_2, CO and PM_{10} would have the highest concentration in the morning, gradually decreasing in the afternoon, and then increasing again in the evening and into the night, mainly depending on the congestion of traffic. O_3 had the highest concentration in the afternoon because of photochemical reaction.

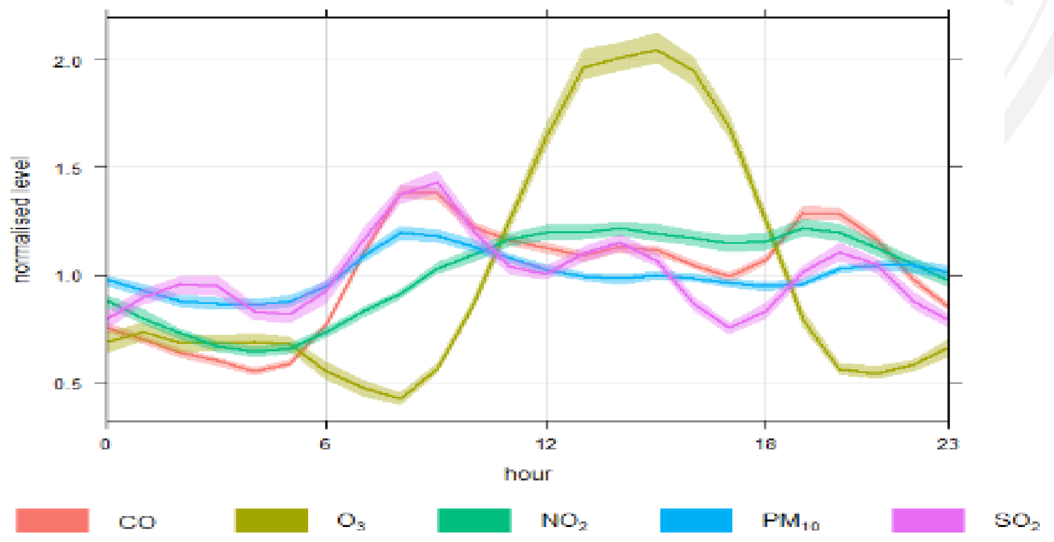


Figure 4.4 Results of Hourly Air Quality Measuring from DLT between 2007-2016

3) Weekend-Weekday change. From Figure 4.5, in each day the concentration of each type of pollutant was different: SO_2, NO_2, CO and PM_{10} were the lowest on Sundays (weekly holidays) and highest during weekday depending on the pollutant. However, O_3 was clearly the highest on Sundays and the lowest on Wednesdays and Thursdays as O_3 was the secondary pollutant derived from the reaction between primary pollutants. From the study of Brechler (2000), it was found that the highest concentration of primary pollutants at mid-week and that the amount of NO_2 would increase if the amount of traffic increased. This is consistent with the study of Mäkelä, Kanner, and Laurikko (1996) that the emission of pollution from traffic would depend on the density of the amount of traffic and car speed. Especially SO_2 and NO_2 would continuously increase when car speed increased from 40 to 120 kms/hr. Pollution Control Department (2000) revealed the relation of road pollution with car speed. The speed of each type of car would impact the emission rate of CO and NO_x in the form of NO_2. The emission rate of CO was high when a car ran at low speed. In the case of NO_x in the form of NO_2, the emission rate would gradually increase in line with the increased speed. But once constant speed was reached, the emission rate would increase because of the temperature in combustion and the amount of air with nitrogen as compound during combustion.

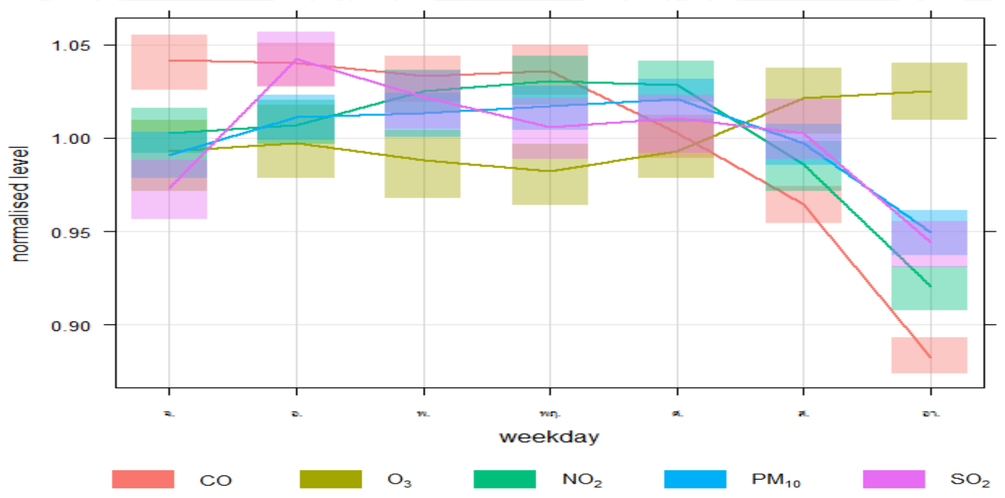


Figure 4.5 Results of Weekly Air Quality Monitoring from TPB between 2007-2016

4.1.4 Other Meteorological Factors

The comparison of the wind direction of the 6 air quality measuring stations along road curbs in Bangkok revealed that mostly wind came from the north (N) or southwest (SW) except at DDC station on Din Daeng Road where the wind came from south southwest (SSW) as shown in Figure 4.6. The study of the relation between air pollution and wind speed revealed that in calm wind, there would be fluctuations of wind causing directness movement of wind and uncertainty, further causing slow diffusion of air pollution and accumulation of air pollution. Therefore, the concentration of such conditions was high, causing seriousness and high health risks. It was not found that substances tend to increase when the wind speed subsided (Deaves & Lines, 1998). Generally, low wind speed or calm wind occurred in tropical zones at night (Sharan, Yadav, & Singh, 1995) with clear skies and stable weather. Sometimes, it can be found early in the morning. The case of calm wind in the afternoon would occur in the center of a wide space with high air pressure in winter or summer (Smith, 1992). Therefore, when air pollution was released from its sources, wind direction would influence the movement direction of air pollution and the diffused areas of air pollution. It would determine the direction of the diffusions of air pollution as wind did not move in the same direction all the time and was quite unstable. The average of wind direction was important to consider the area that might receive air pollution from sources as it determined the movement direction of plume (Bouble, Fox, Turner, & Sterm, 1994). Wind speed was therefore yet another important factor for the diffusion of the emitted air pollution from sources similarly to wind direction. Air pollution would be diluted by higher wind speed and longer distance from the source. The impact of wind speed came from horizontal air pressure and differences of temperature (differences of high air pressure, higher wind speed). Generally, wind speed would increase at be height of approximately 200-300 meters near the earth surface as about the ground friction which would decrease wind speed near the ground. The differences of pollution in each station might result from the differences in local meteorological factors. Urban topography characteristic in each area leads to differences in the amount of pollution concentration in the same city. In the case of relatively low wind speed, PM_{10} would be blown from high to low concentration (high accumulation), as well as the factors of traffics that were not equal (Table 4.2).

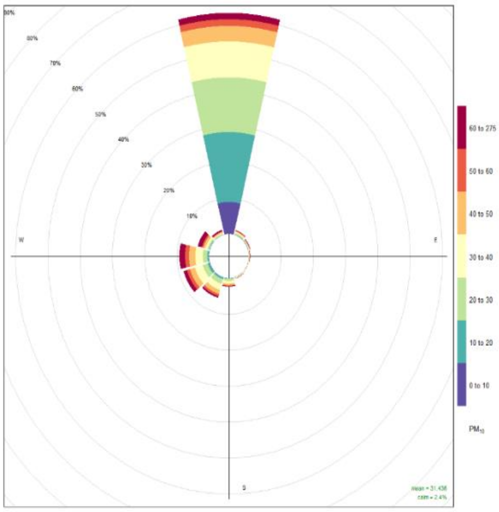


Figure 4.6 (A) Shows Wind Direction Impacting PM_{10} at CCP

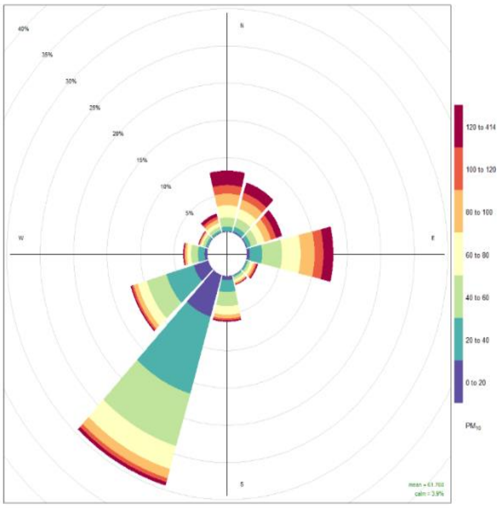


Figure 4.6 (B) Shows Wind Direction Impacting PM_{10} at DDC

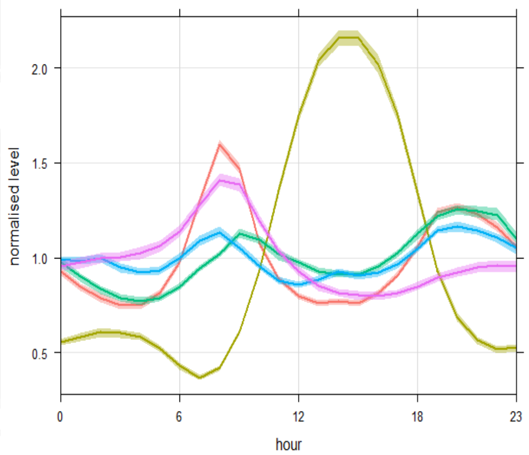


Figure 4.6 (C) Results of Hourly Air Quality Measuring from TBP

CO O_3 NO_2 PM_{10} SO_2

Figure 4.6 Shows Wind Direction Impacting and Results of Hourly Air Quality Measuring

Table 4.2 Statistics of the Amount of Traffic in Bangkok between 2008-2016 Nearby Monitoring Stations

Stations	**Roads**	**Intersections/**	**Surveyed Years**								
		Surveyed Locations	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
MST	Phaya Thai	Victory Monument	35,603	37,486	***	37,516	33,788	***	39,058	***	28,610
		Phaya Thai	41,287	39,575	36,264	37,190	38,927	***	38,790	***	36,401
		Tuek Chai	43,785	51,991	51,970	43,371	42,581	***	43,540	***	39,188
		Si Ayutthaya	47,435	42,258	37,961	41,598	***	***	39,938	***	46,132
DLT	Phahon Yothin	Ha Yaek Ladprao	***	70,834	***	***	87,076	***	***	83,957	***
		Kamphaeng Phet	71,885	70,192	75,407	68,649	67,785	70,676	62,774	60,237	***
		Saphan Khwai	34,142	34,357	34,890	33,404	34,713	33,360	31,935	***	29,471
CUH	Rama 4	Henri Dunant	52,566	52,691	***	53,660	***	***	40,809	47,384	***
		Rama 4	***	***	40,202	***	36,436	31,673	37,510	***	36,884
		Rajdamri	***	29,337	***	23,510	28,945	28,697	***	28,814	***
TPB	Intarapitak-Petchkasem	Bang Yi Ruea	42,349	***	***	39,228	***	38,760	***	30,785	***
CCP	Ladprao	Chok Chai 4	46,127	44,835	***	47,220	48,710	49,780	50,241	***	43,211
		Pawana	56,796	51,130	57,106	55,751	53,485	61,643	***	52,944	***
DDC	Asoke Din Daeng	Din Daeng intersection	83,905	77,569	76,570	76,074	78,789	72,016	***	67,082	***
		Pracha Songkhro	67,032	60,621	61,550	59,323	62,756	***	54,202	***	56,763

4.1.5 Relation between the Amount of Annual Traffic and Concentration of Pollutants

Table 4.3 and Figure 4-7 show the relation between pollution concentration and traffic. It was revealed that NO_2, SO_2 and PM_{10} have a positive relation with the amount of traffic in some monitoring stations. However, CO and O_3 were found to have different relations depending on the station. CO was a primary pollutant derived from the direct fuel combustion in cars. For O_3, negative correlation with the amount of traffic may be because it was a secondary pollutant derived from the photochemical oxidation between NO_x and HC in the atmosphere with sunlight as catalyst. SO_2, CO and PM_{10} had inconsistent correlation with the amount of traffic whereby positive, negative or no correlation were found. It must be noted that this analysis was limited due to the data of amount of traffic, which was monitored at the annual level only, and the locations of monitoring station and traffic amount which were not exactly. The researcher used data of the areas nearest to the air quality measuring stations for analysis.

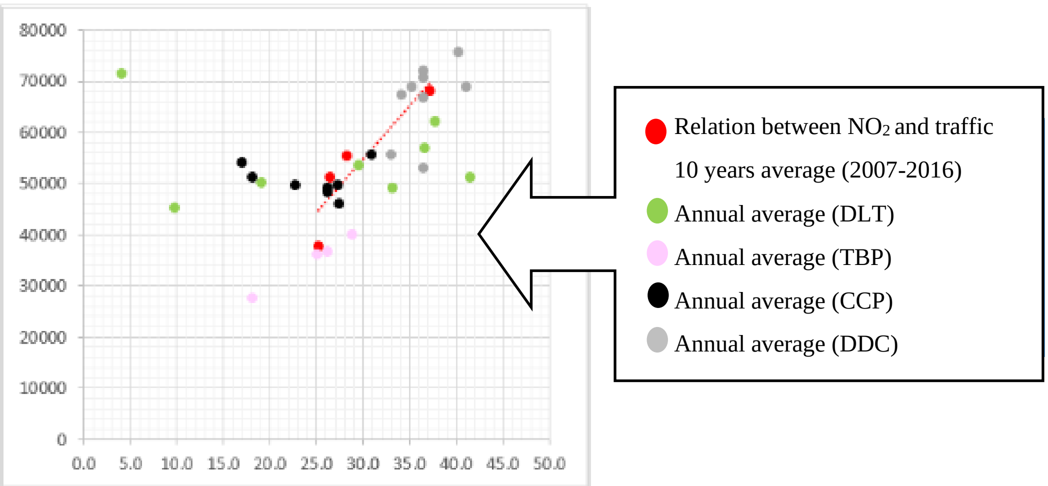


Figure 4.7 Relation between NO_2 and Traffic

Table 4.3 Relation between Concentration of Pollutants and Traffic

Relation between Concentration of Pollutants and Traffic						
	Stations	**SO_2**	**NO_2**	**CO**	**O_3**	**PM_{10}**
1	MST	-	-	NR	-	Positive
2	DLT	NR	NR	NR	Positive	NR
3	CUH	-	-	NR	-	NR
4	TPB	Positive	Positive	Positive	NR	Positive
5	CCP	NR	NR	Negative	NR	NR
6	DDC	Positive	Positive	Positive	Negative	Positive
7	All Station	NR	Positive	NR	Negative	NR

Note: NR means No Relation

- means No Data

4.2 Characteristics and Dispersion of $PM_{2.5}$

The air quality data from Air Quality and Noise Management Division, BMA were used. $PM_{2.5}$ was measured by the Beta Ray Attenuation method, in accordance with the Federal Equivalent Method (FEM), determined by US Environmental Protection Agency (US EPA). The study areas total 24 stations as shown in Figure 4.8 were divided into six district groups. The detail of each district group and the data analysis was shown in Table 4.4

1) Central Bangkok consisting of Phaya Thai District, Phra Nakhon District, Ratchathewi District, Wang Thonglang District, and Samphanthawong District

2) South Bangkok consisting of Bang Kho Laem District, Bang Rak District, Pathum Wan District, Sathon District, Yan Nawa District, and Khlong Toei District

3) North Bangkok consisting of Bang Sue District, Lak Si District, Chatuchak District, and Bang Khen District

4) East Bangkok consisting of Bang Kapi District, Bueng Khum District, and Lad Krabang District

5) North Thonburi consisting of Bang Phlat District, Khlong San District, Thonburi District, and Bangkok Noi District

6) South Thonburi consisting of Phasi Charoen District and Bang Khun Thian District

Table 4.4 Each District Group Are the Data Analysis

Group	Station	Location	Histogram of the $PM_{2.5}$	Pollution Rose
Central	1. Phaya Thai 2. Phra Nakhon 3. Ratchathewi 4. Wang Thonglang 5. Samphanthawong	Figure 4.9-4.13	Figure 4.14	Figure 4.15
South	6. Bang Kho Laem 7. Bang Rak 8. Pathum Wan 9. Sathon 10. Yan Nawa 11. Khlong Toei	Figure 4.16-4.21	Figure 4.22	Figure 4.23
North	12. Bang Sue 13. Lak Si 14. Chatuchak 15. Bang Khen	Figure 4.24-4.27	Figure 4.28	Figure 4.29
East	16. Bang Kapi 17. Bueng Khum	Figure 4.30-4.32	Figure 4.33	Figure 4.34

Group	Station	Location	Histogram of the $PM_{2.5}$	Pollution Rose
North Thonburi	18. Lad Krabang 19. Bang Phlat 20. Khlong San 21. Thonburi	Figure 4.35-4.38	Figure 4.39	Figure 4.40
South Thonburi	22. Bangkok Noi 23. Phasi Charoen 24. Bang Khun Thian	Figure 4.41-4.42	Figure 4.43	Figure 4.44

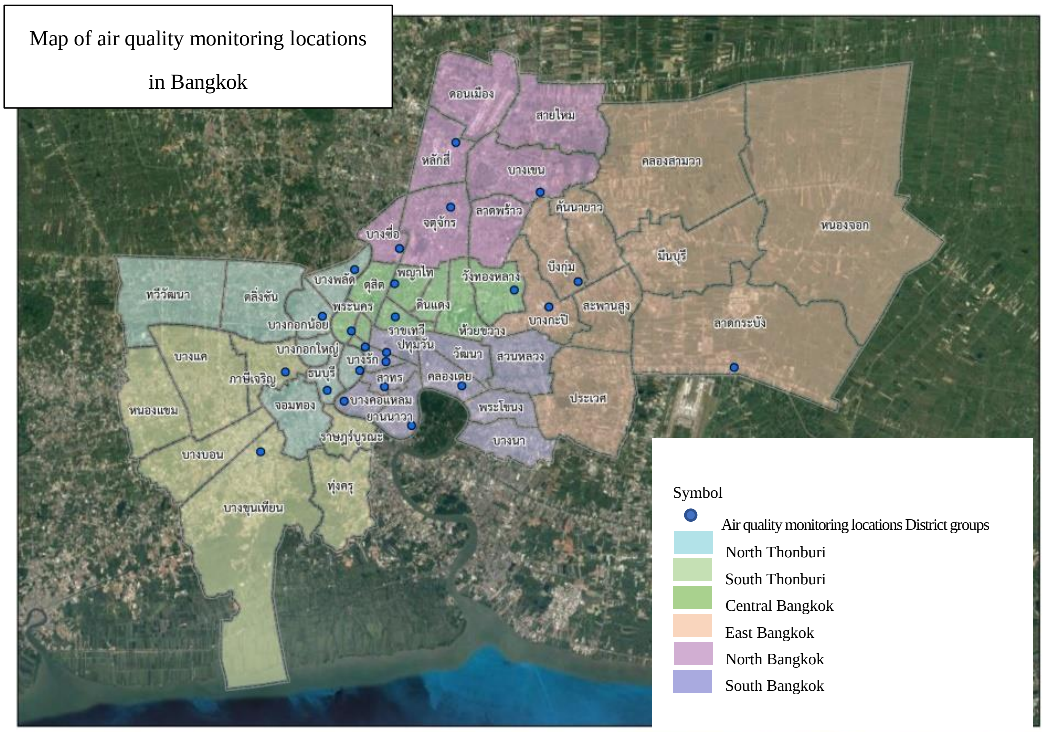


Figure 4.8 Installation Locations of 24 Air Quality Monitoring Stations in Bangkok

4.2.1 Central Bangkok

Figure 4.9 Installation Location of Air Quality Monitoring Station in Phaya Thai District

Figure 4.10 Installation Location of Air Quality Monitoring Station in Phra Nakhon District

Figure 4.11 Installation Location of Air Quality Monitoring Station in Ratchathewi District

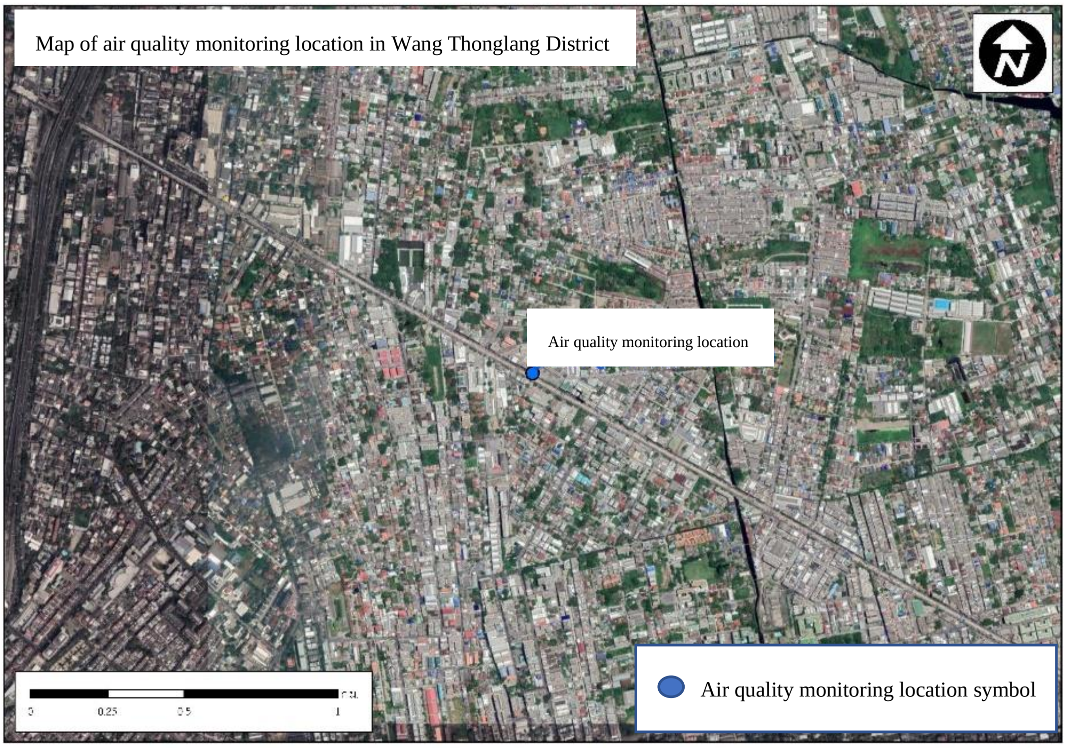


Figure 4.12 Installation Location of Air Quality Monitoring Station in Wang Thonglang District

Figure 4.13 Installation Location of Air Quality Monitoring Station in Samphanthawong Distric

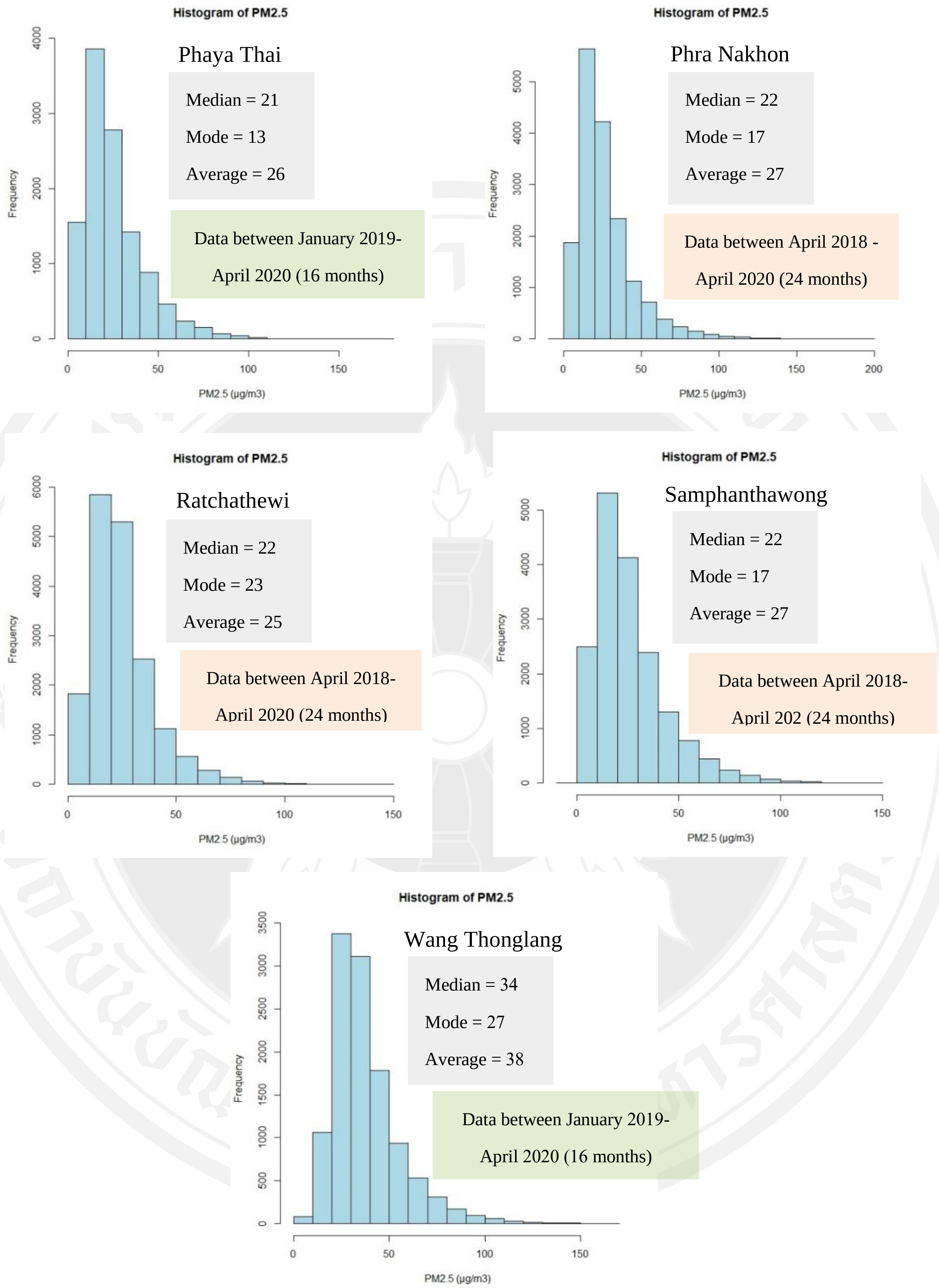


Figure 4.14 Histogram of the Concentration of $PM_{2.5}$ in Central Bangkok

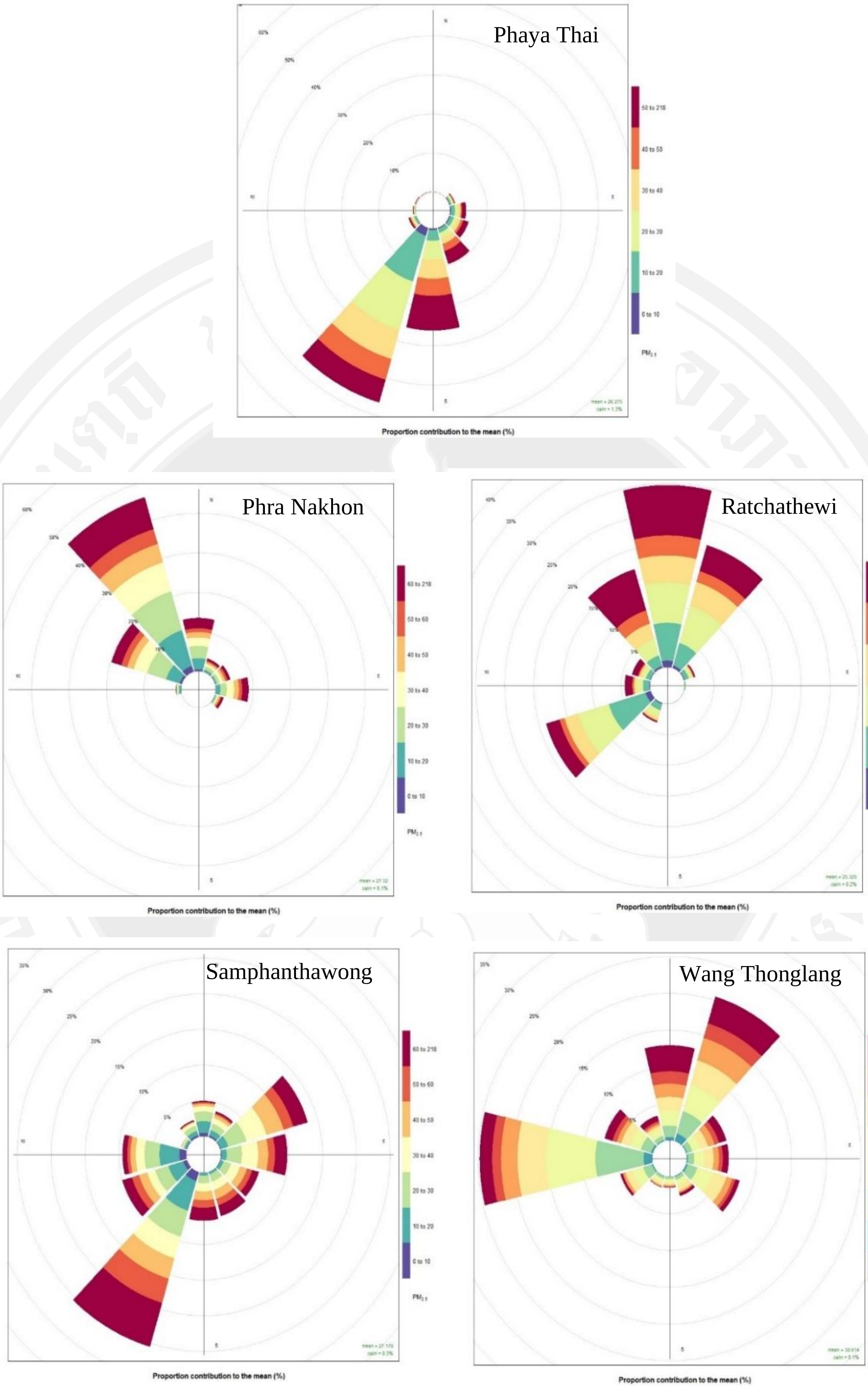


Figure 4.15 Pollution Rose of Central Bangkok

The overall average $PM_{2.5}$ levels from air quality monitoring stations in the central area of Bangkok, comprising 5 districts (Ratchathewi, Phaya Thai, Phra Nakhon, Samphanthawong, and Wang Thonglang), were found to be mostly in the range of 25-27 micrograms per cubic meter, except for Wang Thonglang, which had relatively high levels at 38 micrograms per cubic meter. This variation is due to the different durations of data used for analysis, where the stations in Ratchathewi, Phaya Thai, Phra Nakhon, and Samphanthawong had data from 16 months (excluding the rainy season), while Wang Thonglang had data from 24 months.

Regarding the location of the air quality monitoring station in Wang Thonglang, it was situated near Lardprao Road during the construction of the Yellow Line BTS (Bangkok Mass Transit System) railway, resulting in limited traffic lanes, leading to heavy and congested traffic throughout the day. Additionally, the presence of tall buildings on both sides of Lardprao Road could have hindered vertical air dispersion.

On the other hand, the station in Ratchathewi, which had the lowest average $PM_{2.5}$ levels in the central Bangkok area, was located within the Ratchathewi District Office, with the completed Yellow Line BTS railway passing through the area. Traffic flow in this region was relatively smooth due to adequate road capacity, and vertical air dispersion was enhanced as there were no tall buildings near the air quality monitoring station.

Based on these observations, it is evident that significant factors influencing $PM_{2.5}$ concentration at each air quality monitoring station depend heavily on the characteristics of the specific locations. Wind speed and direction did not appear to have a significant impact on $PM_{2.5}$ levels, as the mean and median values were similar.

4.2.2 South Bangkok

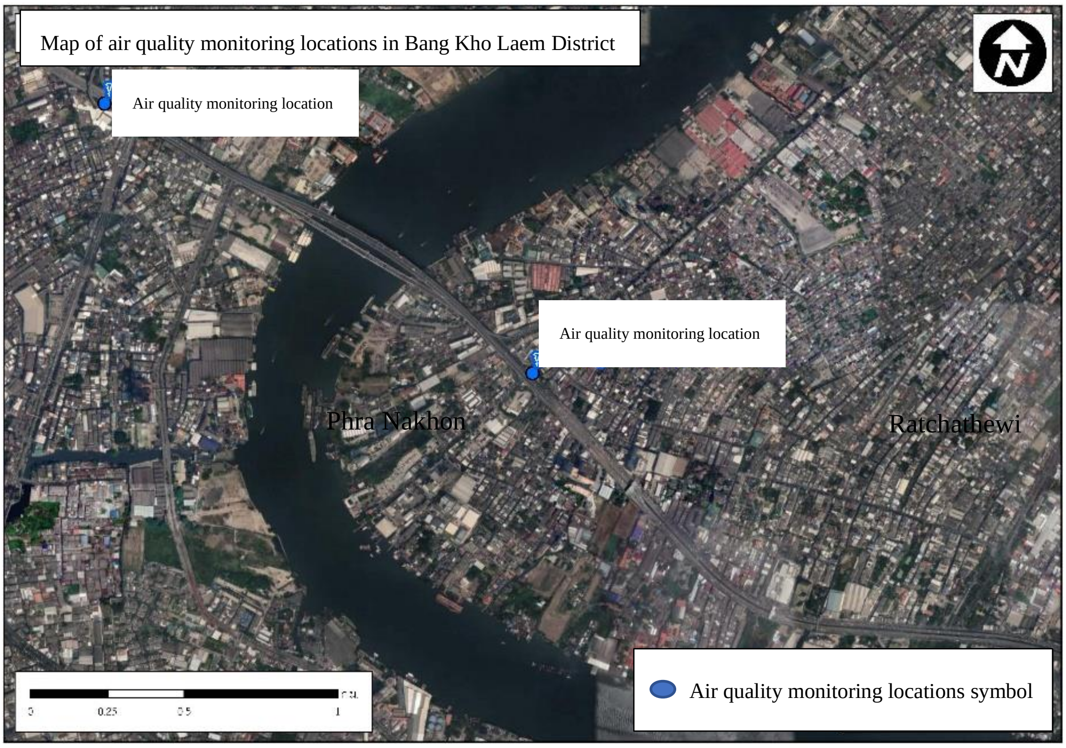


Figure 4.16 Installation Locations of Air Quality Monitoring Stations in Bang Kho Laem District

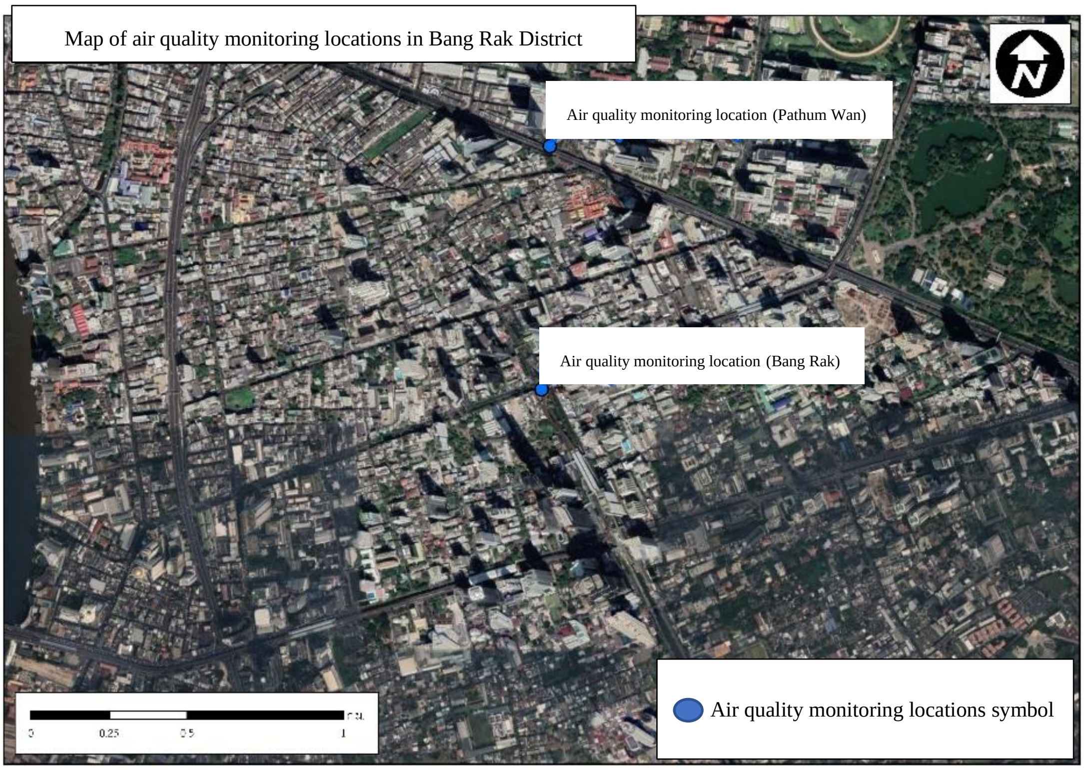


Figure 4.17 Installation Locations of Air Quality Monitoring Stations in Bang Rak District

Figure 4.18 Installation Locations of Air Quality Monitoring Stations in Pathum Wan District

Figure 4.19 Installation Location of Air Quality Monitoring Station in Sathon District

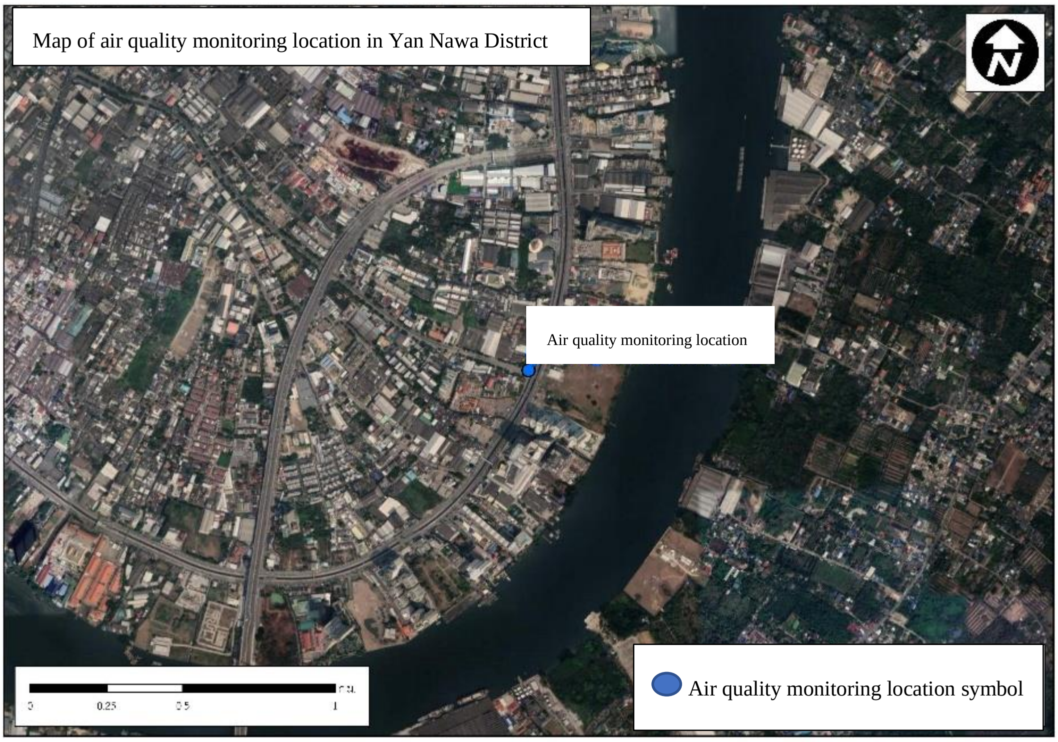


Figure 4.20 Installation Location of Air Quality Monitoring Station in Yan Nawa District

Figure 4.21 Installation Location of Air Quality Monitoring Station in Khlong Toei District

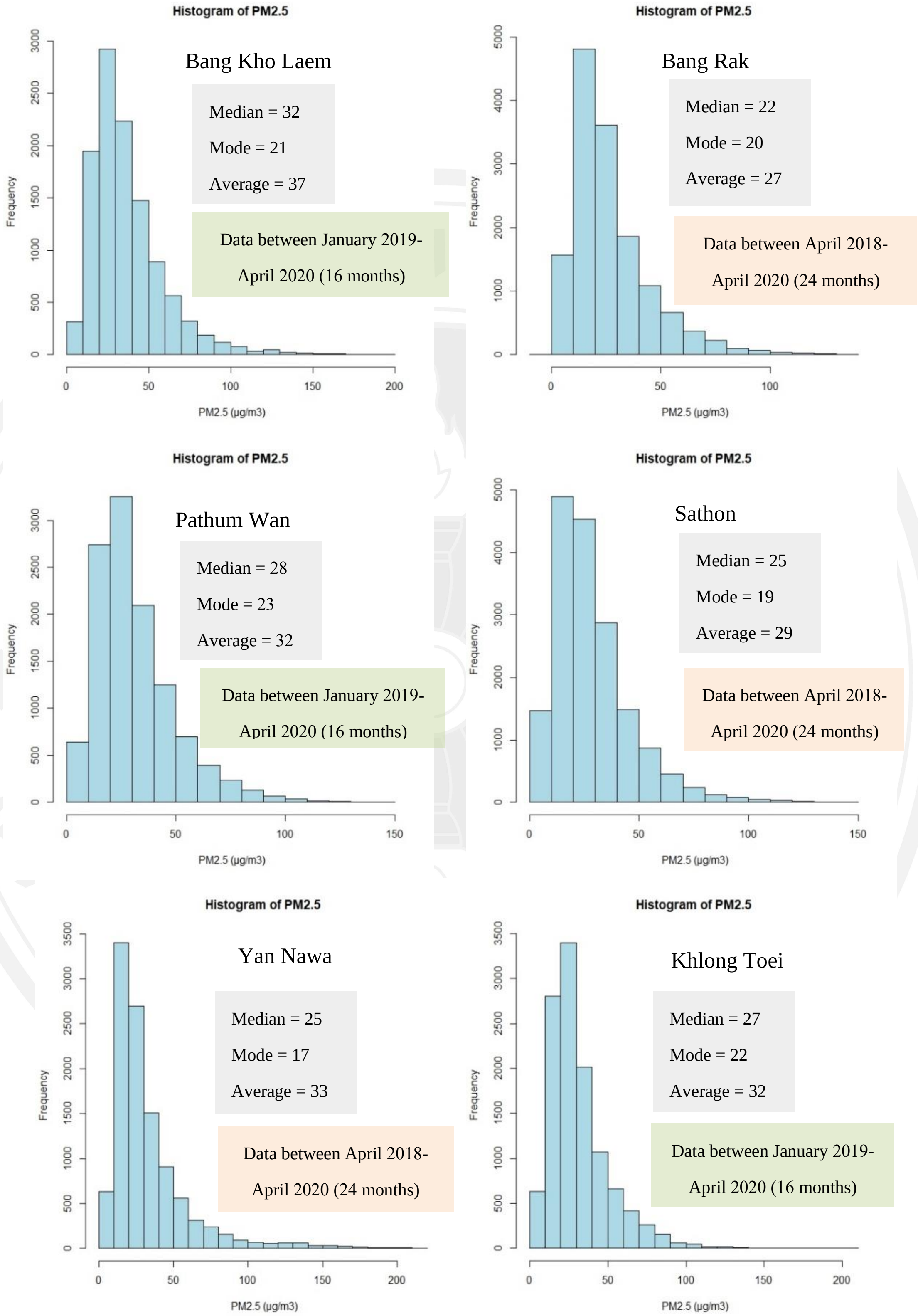


Figure 4.22 Histogram of the Concentration of $PM_{2.5}$ in South Bangkok

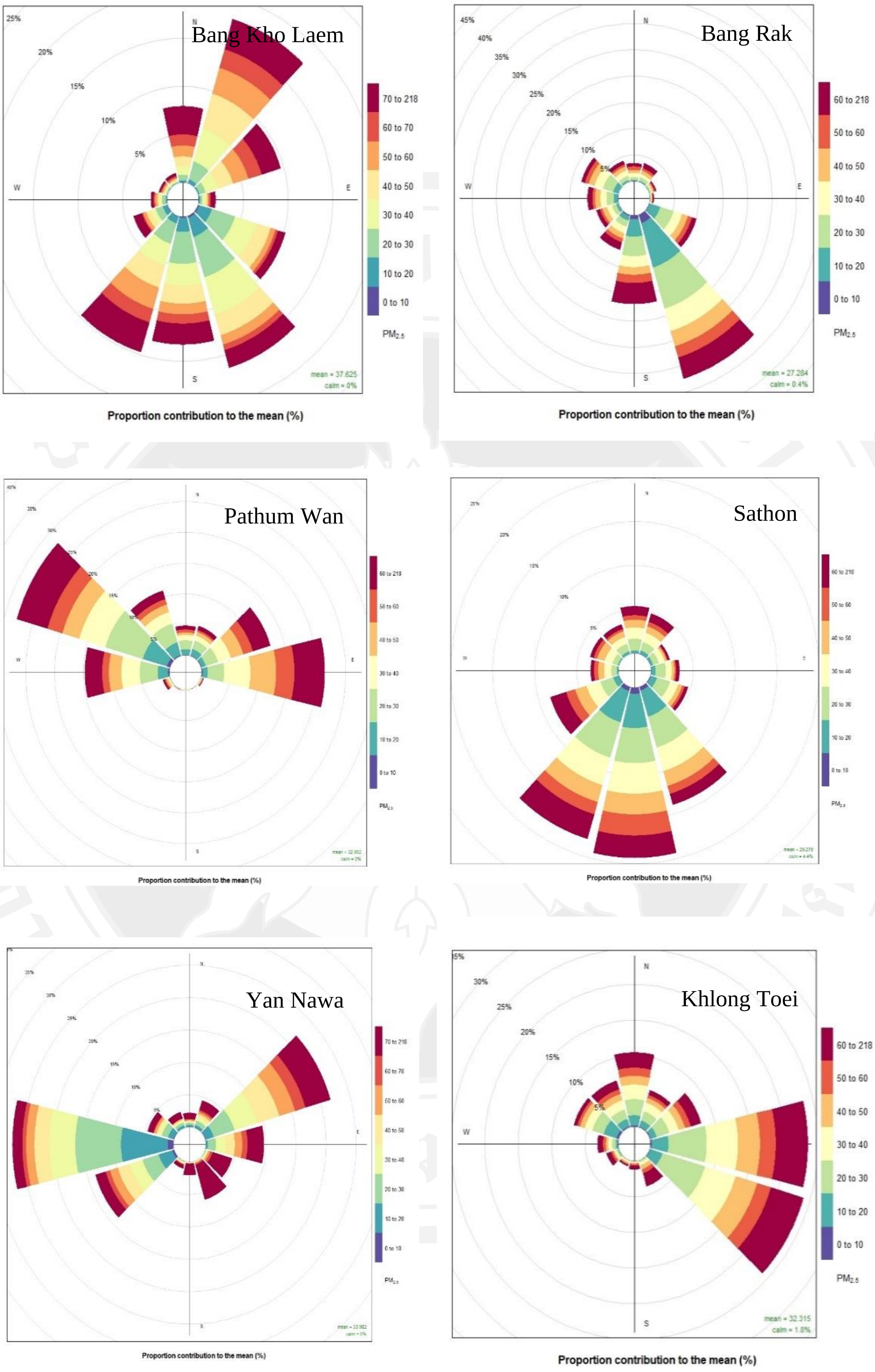


Figure 4.23 Pollution Rose of South Bangkok

The overall average $PM_{2.5}$ levels from air quality monitoring stations in the southern area of Bangkok, comprising 6 districts (Bang Rak, Sathon, Khlong Toei, Pathum Wan, and Yan Nawa), were found to be mostly in the range of 27-33 micrograms per cubic meter, except for Bang Kho Laem, which had relatively high levels at 37 micrograms per cubic meter. This variation is due to the different durations of data used for analysis, where the stations in Bang Rak, Sathon, Khlong Toei, Pathum Wan, and Yan Nawa had data from 16 months (excluding the rainy season), while Bang Kho Laem had data from 24 months.

Regarding the location of the air quality monitoring station in Bang Kho Laem, it was situated at a busy intersection with traffic congestion due to vehicles waiting at traffic signals, and there was an elevated road passing above the area, which could have hindered vertical air dispersion.

On the other hand, the station in Bang Rak, which had the lowest average $PM_{2.5}$ levels in the southern Bangkok area, was in the general area of the Bang Rak Love Pier, which is a smaller road with relatively convenient and less congested traffic, resulting in lower $PM_{2.5}$ accumulation compared to other areas in the same group.

Based on these observations, it is evident that significant factors influencing $PM_{2.5}$ concentration at each air quality monitoring station depend heavily on the characteristics of the specific locations. Wind speed and direction did not appear to have a significant impact on $PM_{2.5}$ levels, as the mean and median values were similar.

4.2.3 North Bangkok

Figure 4.24 Installation Location of Air Quality Monitoring Station in Bang Sue District

Figure 4.25 Installation Location of Air Quality Monitoring Station in Lak Si District

Figure 4.26 Installation Location of Air Quality Monitoring Station in Chatuchak District

Figure 4.27 Installation Location of Air Quality Monitoring Station in Bang Khen District

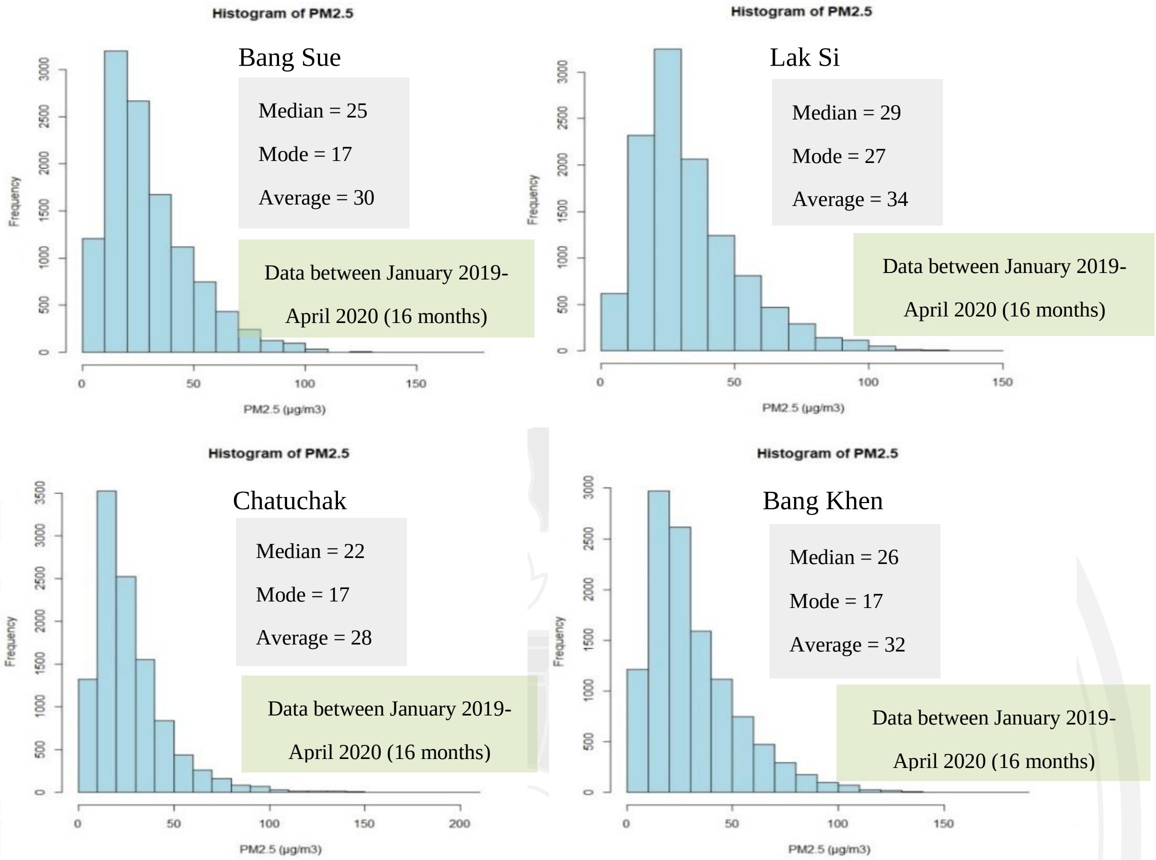


Figure 4.28 Histogram of the Concentration of $PM_{2.5}$ in North Bangkok

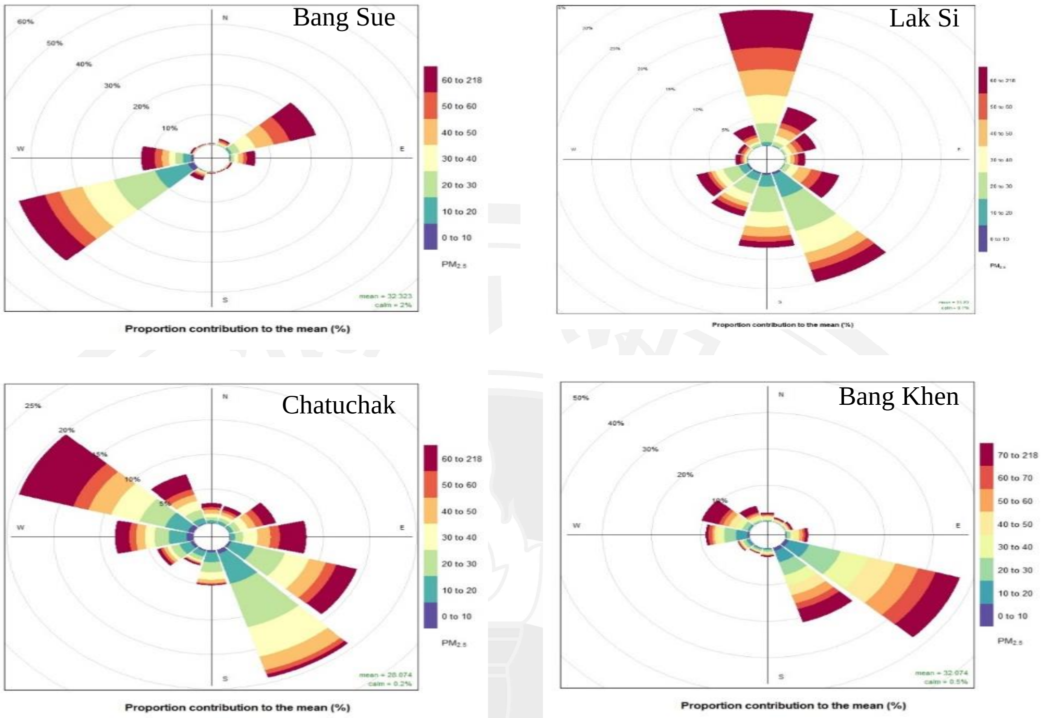


Figure 4.29 Pollution Rose of North Bangkok

The overall average $PM_{2.5}$ levels from air quality monitoring stations in the northern area of Bangkok, comprising 4 districts (Chatuchak, Bang Sue, Bang Khen, and Lak Si), were found to be mostly in the range of 28-32 micrograms per cubic meter, except for Lat Phrao, which had relatively high levels at 32 micrograms per cubic meter. This variation is due to the different durations of data used for analysis, where the stations in Chatuchak, Bang Sue, Bang Khen, and Lak Si had data from 16 months (excluding the rainy season), while Lat Phrao had data from 24 months.

Regarding the location of the air quality monitoring station in Lat Phrao, it was situated along a local road where there was ongoing construction of the Red Line BTS railway, leading to heavy traffic and high levels of dust and particulate matter in the area. Moreover, there was an elevated railway passing above the area, which could have hindered vertical air dispersion.

On the other hand, the station in Chatuchak, which had the lowest average $PM_{2.5}$ levels in the northern Bangkok area, was in front of Kasetsart University with the completed Green Line BTS railway passing through the area. Traffic flow in this region was relatively smooth, and there were no tall buildings near the air quality monitoring station, resulting in better vertical air dispersion.

Based on these observations, it is evident that significant factors influencing $PM_{2.5}$ concentration at each air quality monitoring station depend heavily on the characteristics of the specific locations. Wind speed and direction did not appear to have a significant impact on $PM_{2.5}$ levels, as the mean and median values were similar.

4.2.4 East Bangkok

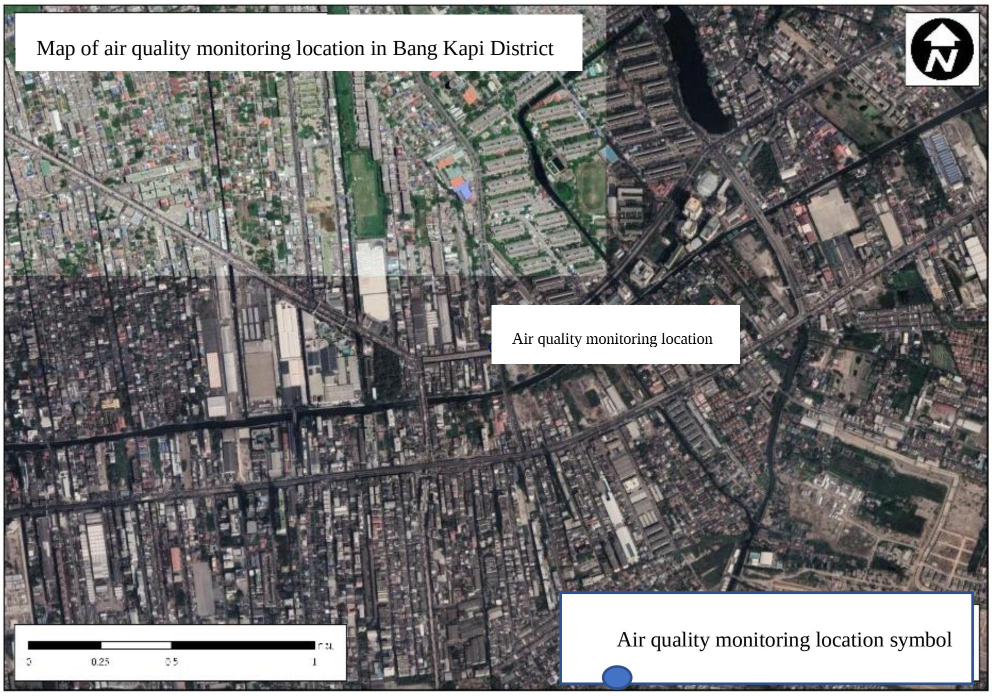


Figure 4.30 Installation Location of Air Quality Monitoring Station in Bang Kapi District

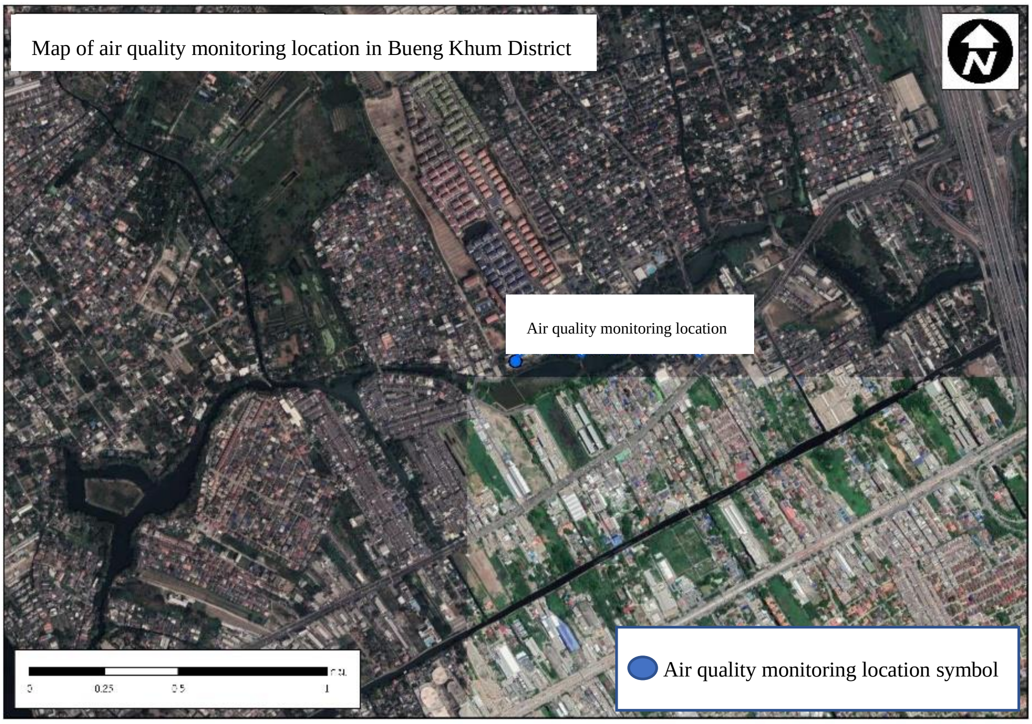


Figure 4.31 Installation Location of Air Quality Monitoring Station in Bueng Khum District

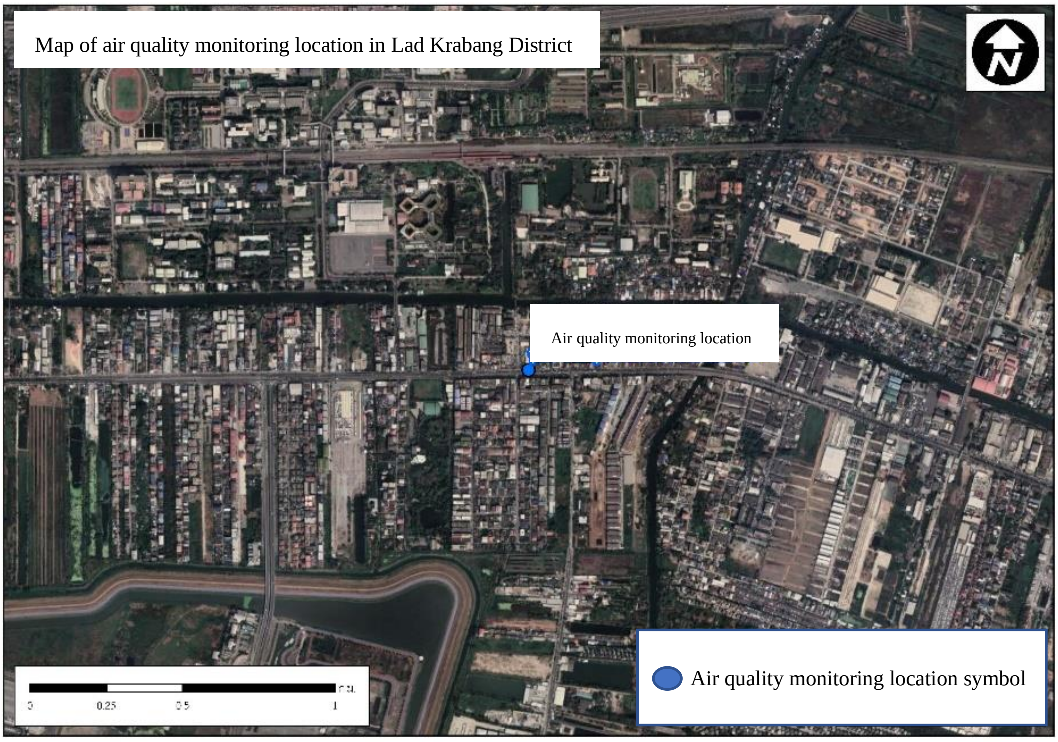


Figure 4.32 Installation Location of Air Quality Monitoring Station in Lad Krabang District

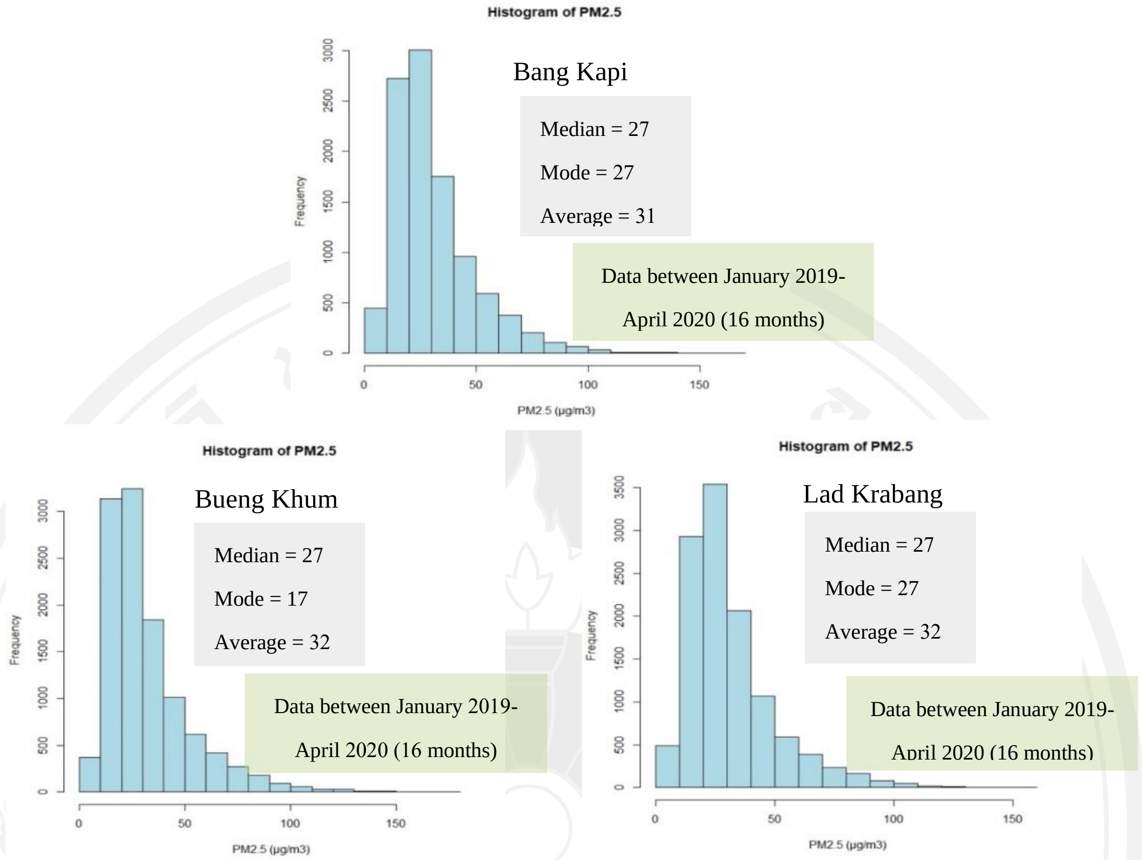


Figure 4.33 Histogram of the Concentration of $PM_{2.5}$ of East Bangkok

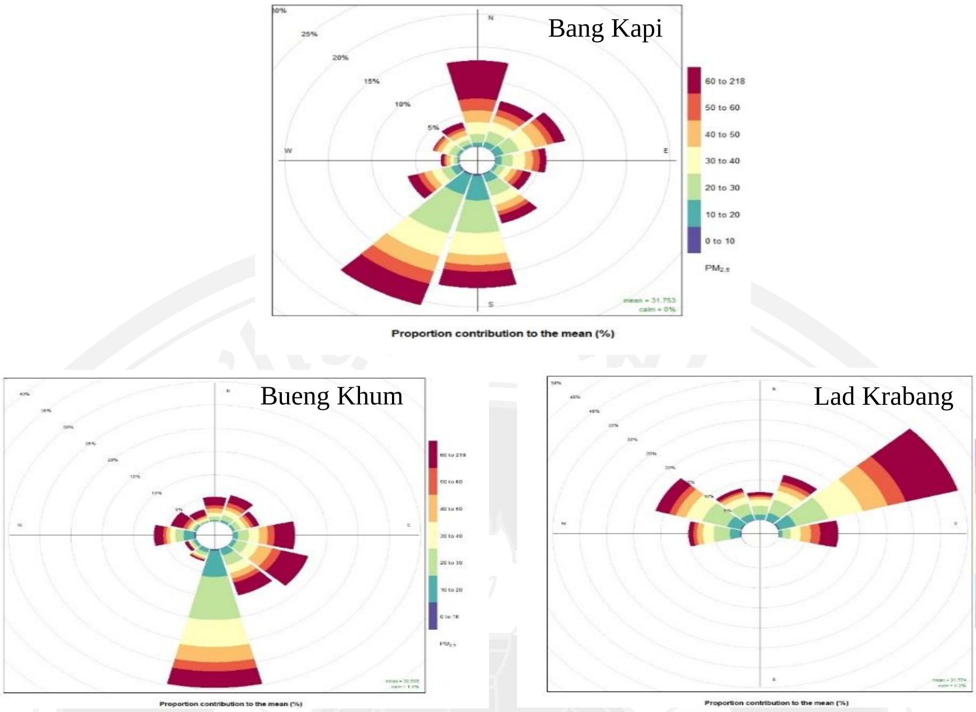


Figure 4.34 Pollution Rose of East Bangkok

The overall average $PM_{2.5}$ levels from air quality monitoring stations in the eastern area of Bangkok, comprising 3 districts (Bang Kapi, Bueng Kum, and Lat Krabang), were found to be mostly in the range of 31-32 micrograms per cubic meter. These values were relatively high when compared to the average $PM_{2.5}$ levels of other groups of districts. This can be attributed to the fact that the eastern area of Bangkok has a relatively large amount of open and vacant land, as well as a higher incidence of biomass burning (such as burning of waste, branches, and leaves). Additionally, the area is influenced by particulate matter from burning activities in neighboring provinces and central regions.

Hence, the significant factors affecting the intensity of $PM_{2.5}$ in the eastern area of Bangkok are the sources of particulate matter near the air quality monitoring stations, especially the biomass burning sources. During the winter season (when the wind from the southeast prevails), the direction and speed of the wind have a clear impact on the dispersion of $PM_{2.5}$. This can be observed when hotspots are detected in the surrounding provinces, leading to higher $PM_{2.5}$ concentrations in the eastern districts of Bangkok.

In summary, the primary factors influencing $PM_{2.5}$ levels in the eastern area of Bangkok are the nearby sources of particulate matter, particularly biomass burning activities, and the seasonal wind patterns affecting the dispersion of $PM_{2.5}$. These observations contribute to the higher $PM_{2.5}$ concentrations in this group of districts.

4.2.5 North Thonburi

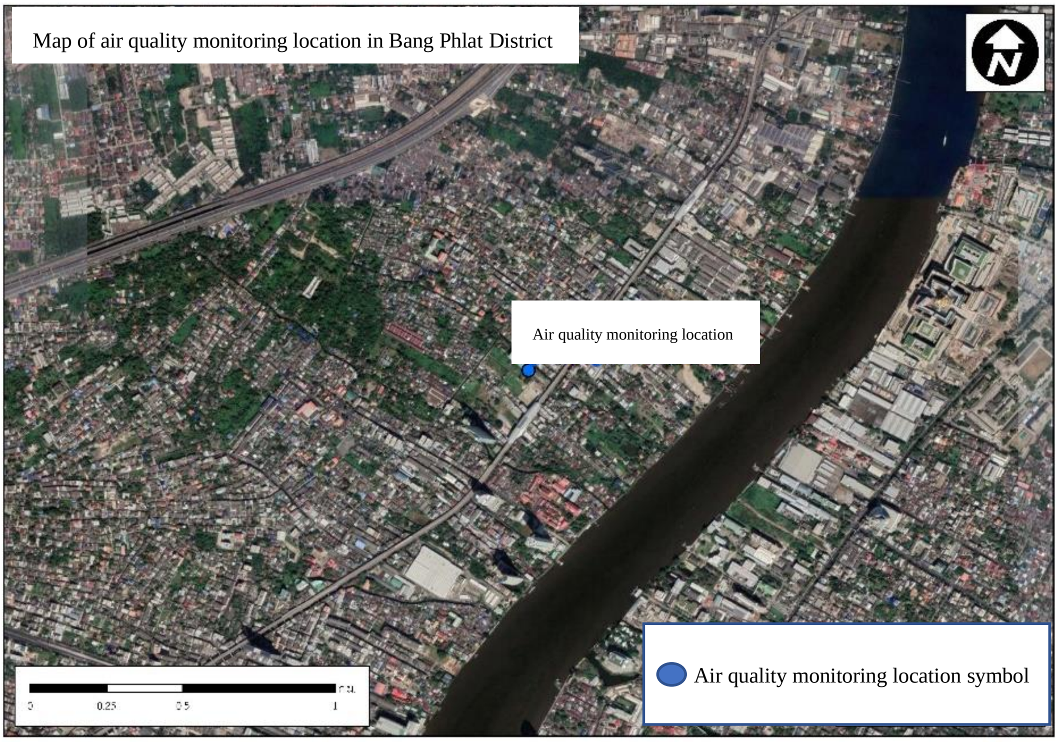


Figure 4.35 Installation Location of Air Quality Monitoring Station in Bang Phlat District

Figure 4.36 Installation Location of Air Quality Monitoring Station in Khlong San District

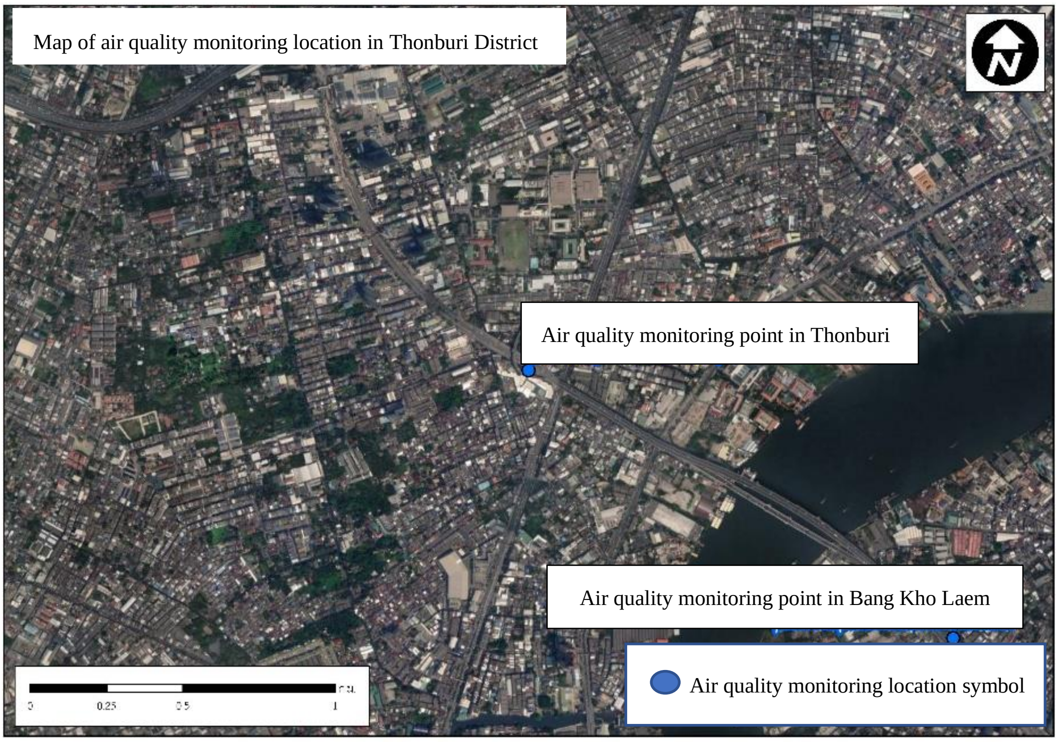


Figure 4.37 Installation Locations of Air Quality Monitoring Stations in Thonburi District

Figure 4.38 Installation Location of Air Quality Monitoring Station in Bangkok Noi District

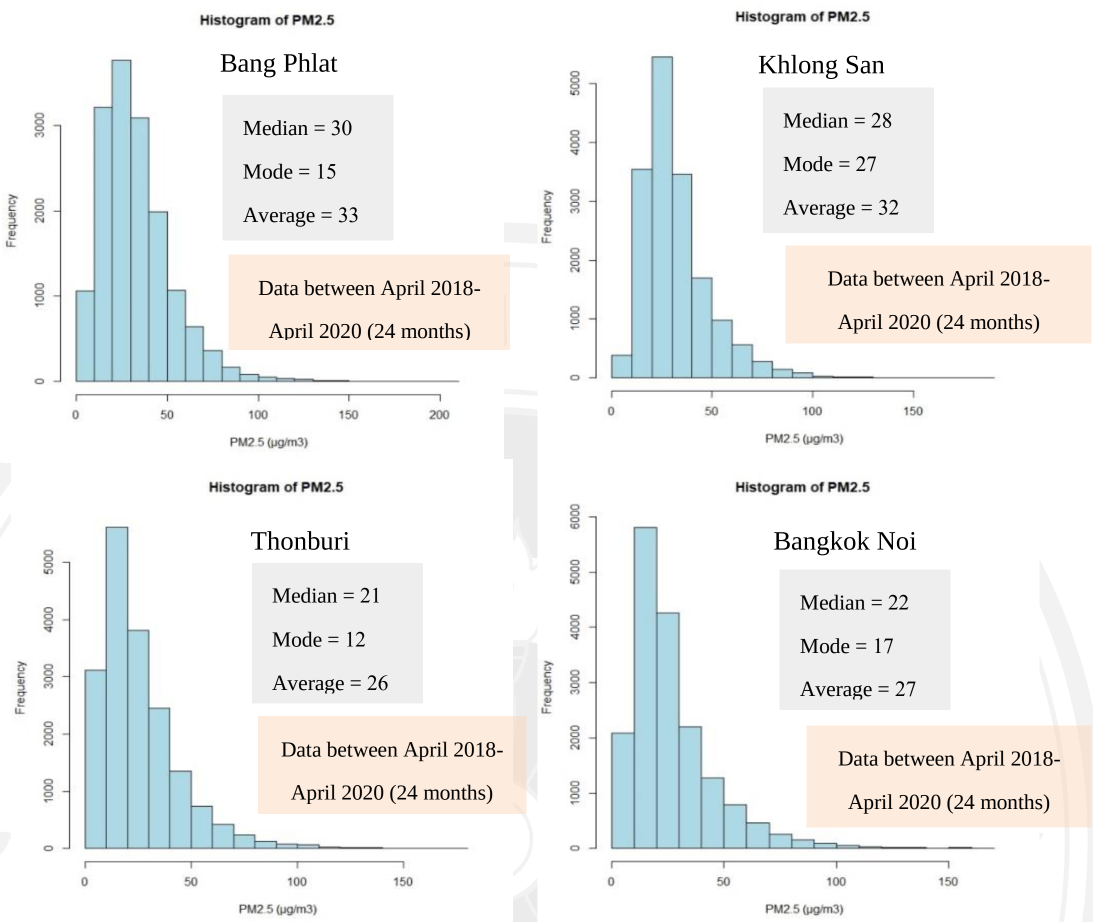


Figure 4.39 Histogram of the Concentration of $PM_{2.5}$ of North Thonburi

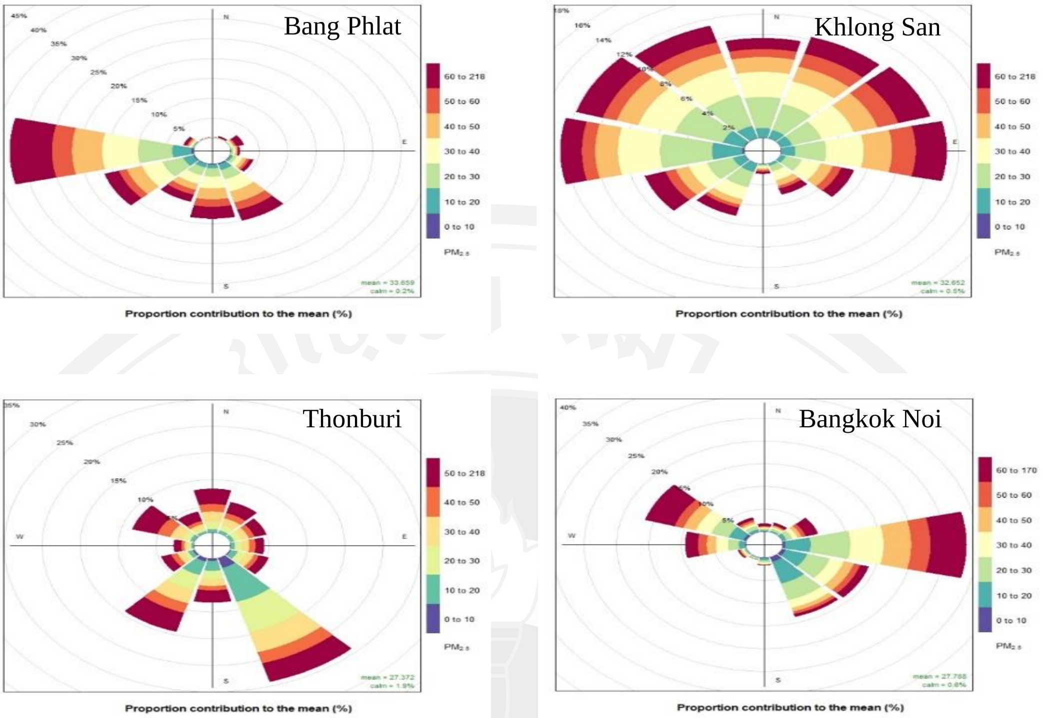


Figure 4.40 Pollution Rose of North Thonburi

The overall average $PM_{2.5}$ levels from air quality monitoring stations in the northern area of Bangkok, comprising 4 districts (Thon Buri, Bangkok Noi, Khlong San, and Bang Phlat), were found to be mostly in the range of 26-33 micrograms per cubic meter. The values were relatively close to each other, except for the Bang Phlat district, which had a higher average $PM_{2.5}$ level of 33 micrograms per cubic meter. This difference can be attributed to the location of the air quality monitoring station in Bang Phlat, where there is ongoing construction of a light rail transit system (Skytrain's Blue Line). This construction activity has led to dense and congested traffic, as well as the presence of tall buildings in the vicinity, resulting in limited vertical dispersion of air pollutants and a significant accumulation of particulate matter.

Therefore, the key factors influencing the intensity of $PM_{2.5}$ in each air quality monitoring station in the northern area of Bangkok primarily depend on the characteristics of the specific location. The presence of construction activities and a high density of traffic, as well as the proximity of tall buildings, significantly affect the vertical dispersion of air pollutants, leading to a considerable accumulation of particulate matter in the area. It is evident that the wind speed and direction do not have a substantial impact on the intensity of $PM_{2.5}$ (as indicated by the similar mean and median values), emphasizing the local characteristics of the areas as the primary contributors to $PM_{2.5}$ levels.

4.2.6 South Thonburi

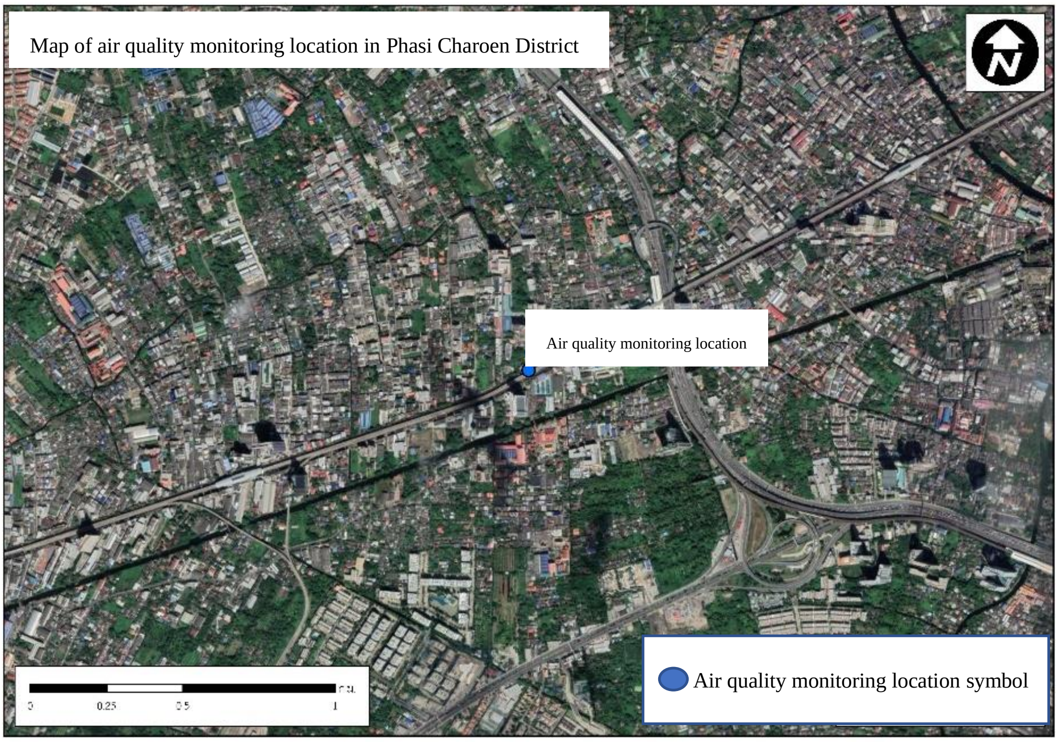


Figure 4.41 Installation Location of Air Quality Monitoring Station in Phasi Charoen District

Figure 4.42 Installation Location of Air Quality Monitoring Station in Bang Khun Thian District

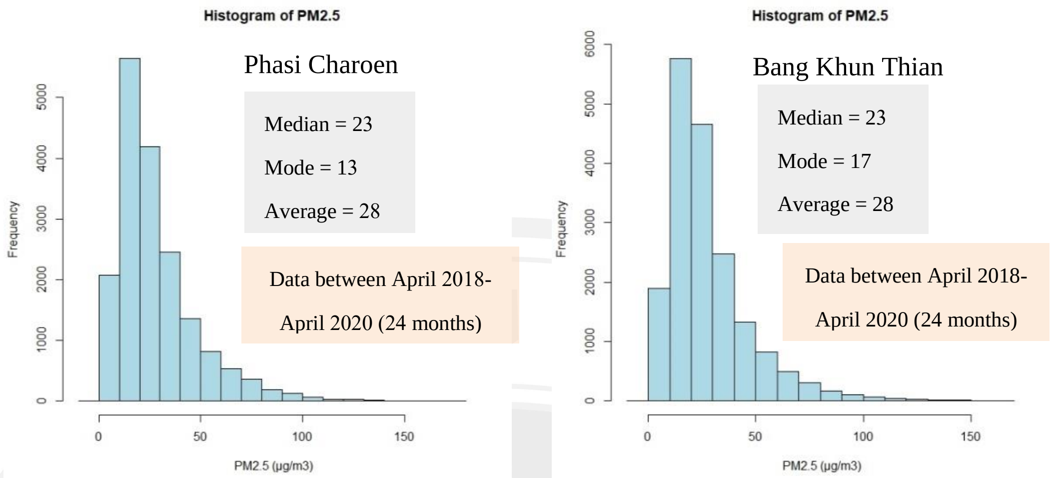


Figure 4.43 Histogram of the Concentration of $PM_{2.5}$ of South Thonburi

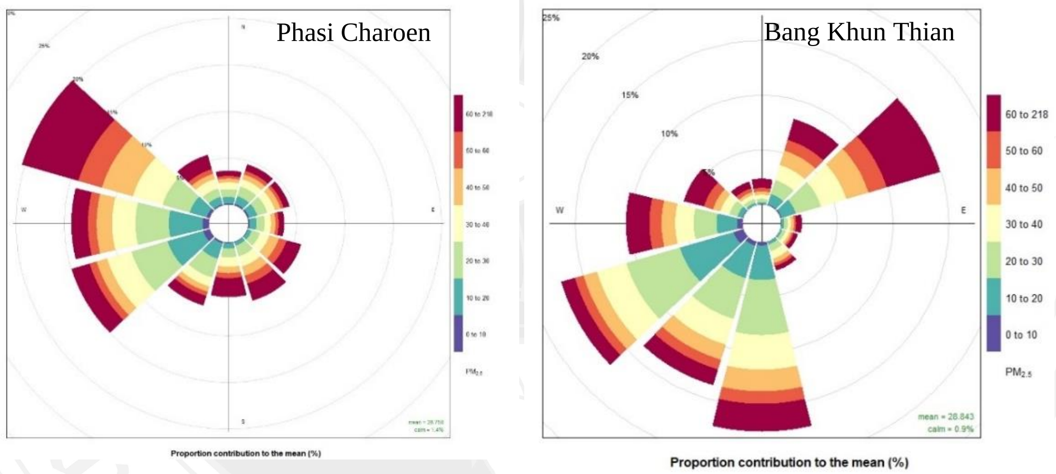


Figure 4.44 Pollution Rose of South Thonburi

The overall average $PM_{2.5}$ levels from air quality monitoring stations in the southern area of Bangkok, comprising 2 districts (Phasi Charoen and Bang Khun Thian), were found to be 28 micrograms per cubic meter. It is evident that the average $PM_{2.5}$ level is relatively low when compared to other groups of districts. This can be attributed to the favorable conditions around the air quality monitoring stations in Phasi Charoen and Bang Khun Thian. These areas experience relatively smooth traffic flow, with no ongoing construction of railway systems, resulting in minimal accumulation of particulate matter.

Therefore, the key factors influencing the intensity of $PM_{2.5}$ in each air quality monitoring station in the southern area of Bangkok primarily depend on the local characteristics of the specific location. The smooth traffic flow and absence of railway construction contribute to limited particulate matter accumulation. As a result, it is evident that wind speed and direction do not have a significant impact on the intensity of $PM_{2.5}$ (as indicated by the similar mean and median values), emphasizing the importance of local conditions in determining $PM_{2.5}$ levels.

4.2.7 Factors related to the concentration of $PM_{2.5}$ in Bangkok

Based on the analysis of $PM_{2.5}$ concentrations from 24 air quality monitoring stations in Bangkok, the districts can be ranked in terms of $PM_{2.5}$ intensity from highest to lowest as follows: South Bangkok, East Bangkok, North Bangkok, North Thonburi, Central Bangkok, and South Thonburi, as shown in Table 4.5.

The key factors influencing the intensity of $PM_{2.5}$ in each air quality monitoring station depend significantly on the local characteristics of the area. This is evident from the results of the average $PM_{2.5}$ concentrations, which showed similar values in multiple locations, while only a few districts exhibited notably higher $PM_{2.5}$ levels. The areas with high $PM_{2.5}$ levels were influenced by dense traffic conditions, large-scale construction activities, open burning, and the presence of tall buildings near the air quality monitoring stations. Interestingly, wind speed and direction did not have a significant impact on the intensity of $PM_{2.5}$, as indicated by the similar mean and median values.

In summary, the variations in $PM_{2.5}$ levels in different districts are predominantly driven by local factors, and the intensity of $PM_{2.5}$ can be attributed to factors such as traffic congestion, construction activities, open burning, and the proximity of tall buildings to the monitoring stations. The role of wind speed and direction appears to be less influential in determining $PM_{2.5}$ levels, as evidenced by the consistency in mean and median values across various locations.

Table 4.5 Results of Data Analysis of Each Region District by R Software

Group	Average concentration of $PM_{2.5}$ ($\mu g/m^3$)				Pollution Rose
	Range	Avg	Min	Max	
South (6 station)	27-37	32	Bang Rak (27)	Bang Kho Laem (37)	Northeast
East (3 station)	31-32	32	Bang Kapi (31)	Lad Krabang (32)	Northeast
North (4 station)	28-34	31	Chatuchak (28)	Lak Si (34)	North
North Thonburi (4 station)	26-33	30	Thonburi (26)	Bang Phlat (33)	North
Central (5 station)	25-38	29	Ratchathewi (25)	Wang Thonglang (38)	Northeast
South Thonburi (2 station)	28	28	Phasi Charoen (28) *Mode = 13	Bang Khun Thian (28) *Mode = 17	Northeast

4.3 Annual $PM_{2.5}$ Emission from On-road Transport Sector in Bangkok

This section is the results of the development of $PM_{2.5}$ Emission database from On-road Transport Sector in Bangkok during 2010 to 2019. There are two main results consist of 1) The trend of $PM_{2.5}$ emission in Bangkok during 2010 to 2019; and 2) The main sources of $PM_{2.5}$ emission in on-road transport sector categorized by fuel types.

4.3.1 Total $PM_{2.5}$ Emission from On-road Transport Sector in Bangkok During 2007 to 2019

The overall trend of annual $PM_{2.5}$ emission from on-road transportation in Bangkok during 2010 to 2019 was shown in Figure 4.45, which also showed the total annual $PM_{2.5}$ emission of on-road transport sector in Bangkok and the proportion of $PM_{2.5}$ emission of each vehicle type in each year from 2010 to 2019. The results show that the total annual $PM_{2.5}$ emission of all vehicle types are increasing, particularly since 2011.

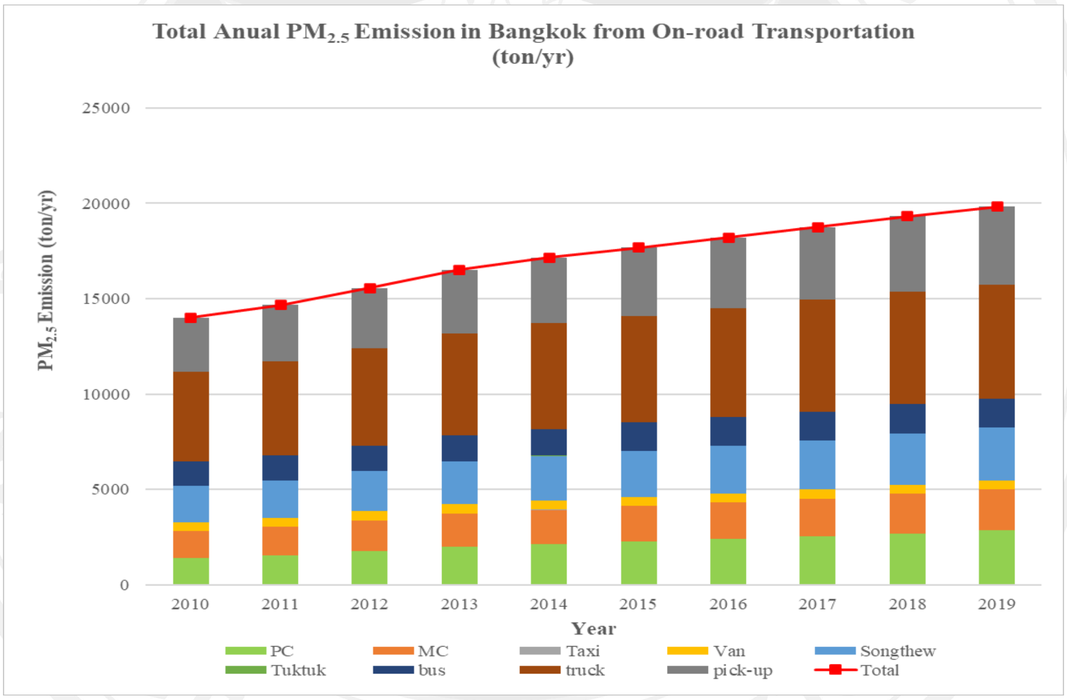


Figure 4.45 The Trend of Annual $PM_{2.5}$ Emission of Different Vehicles (ton/yr)

The total $PM_{2.5}$ emission (Red line) between 2010 to 2011 were less than 15,000 ton/year while the $PM_{2.5}$ emission since 2012 were between 15,000-20,000 ton/year. One of the reasons of this situation is the “first-car tax scheme” which was a popular policy for Thai people to buy their first cars. From the collected data, it can be found that the number of vehicle sales, especially passenger cars and pick-ups has grown significantly as over 1.25 million people signed up for it between September 2011 and December 2012.

According to the PCD report (2019), the largest contributor to $PM_{2.5}$ emission in Bangkok came from the on-road transportation sector. Thus, to clarify the emission of $PM_{2.5}$ by each vehicle category, the percentage of $PM_{2.5}$ emission was used to represent the on-road transport sector in Bangkok during ten-years. Figure 4.46 illustrates the annual averaged shares of $PM_{2.5}$ emission from on-road transportation in percentage. The results demonstrate that the highest $PM_{2.5}$ emission came from trucks, followed by pick-ups, public pick-up transports (Song-Taew), personal cars, motorcycles, and buses with averaged percentage of ten-years $PM_{2.5}$ emission of 32%, 20%, 14%, 12%, 10%, and 9%, respectively. On the other hand, the emission shares of vans accounted for only 3% and the emission of tuk-tuk and taxis is insignificant (about 0%) Thus, they were not the significant contributors of $PM_{2.5}$ emission in on-road transport sector in Bangkok. However, due to the fuel types (mainly CNG) and fleets of these vehicles, the $PM_{2.5}$ that was released by these vehicle types were less than others.

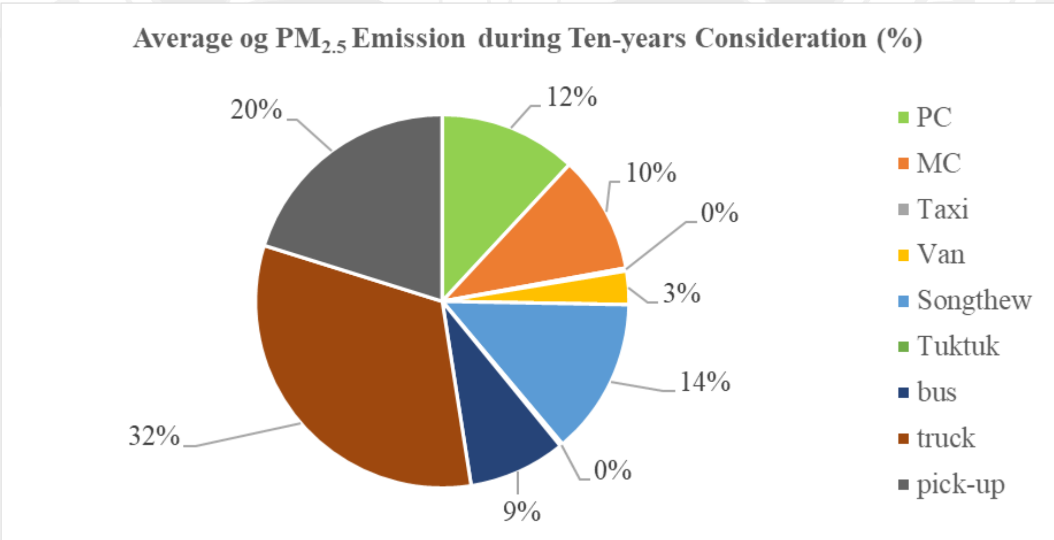


Figure 4.46 The Average of $PM_{2.5}$ Emission during 2010 to 2019 (%)

For more detailed information the $PM_{2.5}$ emission in each year, during 2010 to 2019, are presented in Figure 4.47 It can be used to represent a database of $PM_{2.5}$ emission from on-road transportation in Bangkok.

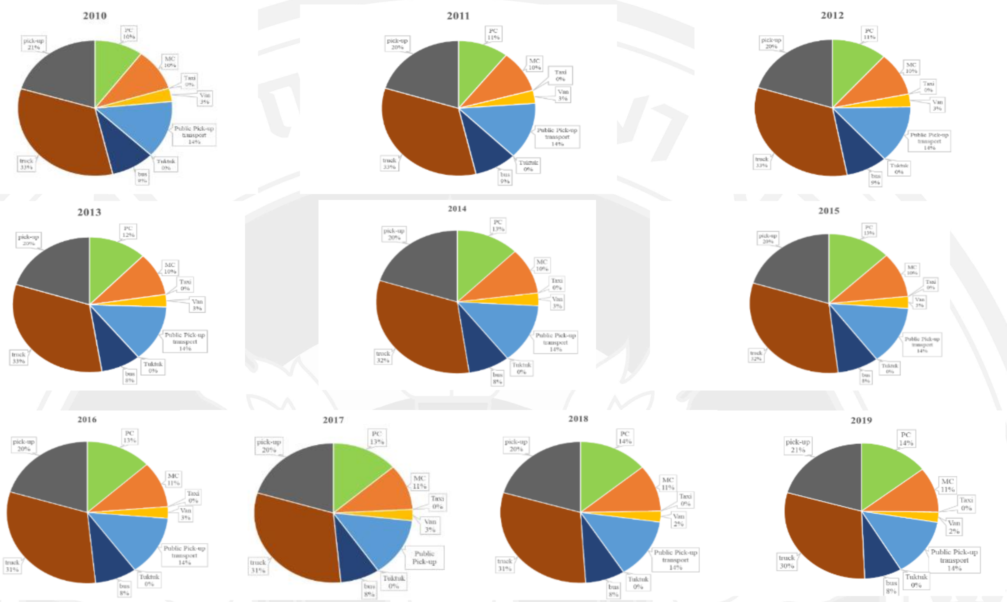


Figure 4.47 The Percentage of $PM_{2.5}$ Emission from On-road Transport Sector in Bangkok during 2010 to 2019

1) Main $PM_{2.5}$ Emission Sources Associated with Fuel Types

According to the emission standards of Thailand, the vehicle types of this study were grouped into vehicles sub-category based on fuel types and Euro standards. The $PM_{2.5}$ emission of sub-category vehicles detailed. The main vehicles contributing to $PM_{2.5}$ emission in Bangkok are six major vehicle types comprised of trucks, pick-ups, public pick-up transports, personal cars, motorcycles, and buses. The sub-categorized vehicles based on fuel types are presented in Table 4.6

Table 4.6 Sub-category of Main Vehicles Contributed to PM2.5 Emission

Vehicle Types	**Fuel Types (Sub-category)**
Personal car (PC)	▪ Gasoline (Pre-Euro, Euro1, Euro2, Euro3, & Euro4)
	▪ CNG
	▪ LPG (Pre-Euro, Euro1, Euro2, Euro3, & Euro4)
	▪ Diesel (Pre-Euro, Euro1, Euro2, Euro3, & Euro4)
	▪ Gasohol (Pre-Euro, Euro1, Euro2, Euro3, & Euro4)
Motorcycle (MC)	▪ Gasoline 2-stroke (uncontrol)
	▪ Gasoline 4-stroke (uncontrol)
	▪ Gasoline 4-stroke (catalyst)
	▪ Gasohol 2-stroke
	▪ Gasohol 4-stroke
Public pick-up transport (Song-Taew)	▪ CNG uncontrol
	▪ CNG 3-way catalyst
	▪ LPG Euro 3
	▪ Diesel uncontrol
	▪ Diesel Euro 3
Bus	▪ Gasoline (Pre-Euro, Euro1, Euro2, & Euro3)
	▪ CNG 3-way catalyst
	▪ LPG
	▪ Diesel (Pre-Euro, Euro1, Euro2, & Euro3)
Pick-up	▪ Gasoline (Pre-Euro, Euro1, Euro2, Euro3, & Euro4)
	▪ CNG
	▪ LPG (Pre-Euro, Euro1, Euro2, Euro3, & Euro4)
	▪ Diesel (Pre-Euro, Euro1, Euro2, Euro3, & Euro4)
	▪ Gasohol (Pre-Euro, Euro1, Euro2, Euro3, & Euro4)
Truck	▪ Gasoline
	▪ CNG
	▪ LPG
	▪ Diesel (Pre-Euro, Euro1, Euro2, & Euro3)

Source: Adopted from Pollution Control Department (2004).

The sub-category vehicles were identified to determine the amount of $PM_{2.5}$ emission of each fuel type. In this case, the number of vehicles of each sub-category was calculated by multiplying with fraction (See in Appendix A, Table A). The results of $PM_{2.5}$ emission of each main sub-category during 2010 to 2019 are as follows.

(1) Trucks

For overall annual $PM_{2.5}$ emission from truck, although the trucks with Pre-Euro diesel engines had small shares of vehicles with approximately 22% compared to other sub-categories, it was the highest shares of $PM_{2.5}$ emission contributor which was up to 49%. On the other hand, the most fuel type used for truck engines was the diesel Euro-3 sub-category, followed by diesel Euro-2 sub-category with the percentage of 52% and 17%, respectively. However, the shares of $PM_{2.5}$ emission was accounted for only 29% and 18% which was lower than the Pre-Euro engines. The other trucks in this sub-category, gasoline and CNG trucks had the lowest number of used cars and released the lowest shares of $PM_{2.5}$ only 0.05% and 0.01%, respectively.

Thus, the major contributors of $PM_{2.5}$ emission on this kind of vehicles came from diesel engines, especially, Pre-Euro engines. The reason is the age of vehicles as they have been used since 1995 and remain on the roads presently. In addition, the older engines, the larger incomplete combustion causes occur. Thus, these vehicles need to be tested and to be maintained properly. Figure 4.48 illustrates the shares of $PM_{2.5}$ emission led by trucks.

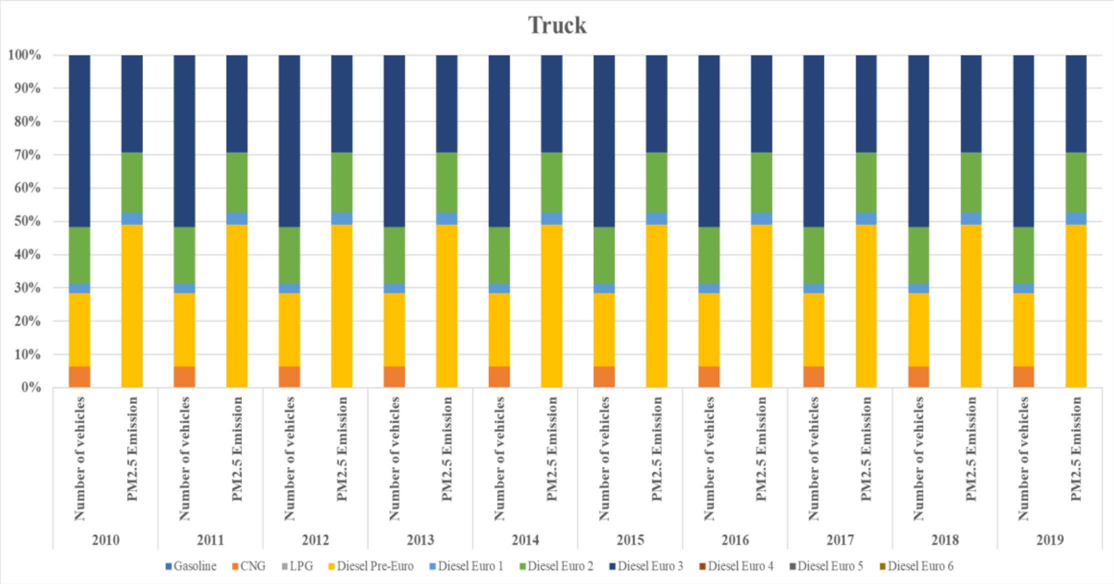


Figure 4.48 $PM_{2.5}$ Emission Shares of Trucks

(2) Pick-up

Pick-ups widely used in Bangkok are diesel trucks. The highest number of trucks in this sub-category in percentage was diesel Euro4, followed by Euro 3, Euro2, Euro1, and Pre-Euro engines with 34%, 32%, 11%, 8% and 5%, Respectively The second fuel type usage was gasoline Euro3, and LPG accounted for 2% each. The rest (6%) consisted of CNG, gasoline Euro3, Pre-Euro.

For the $PM_{2.5}$ shares, the results indicated that the significant types which emitted the huge proportion of $PM_{2.5}$ were the in-used pick-ups Pre-Euro engines, followed by Euro3, Euro1, Euro4 and Euro2, with the $PM_{2.5}$ shares in percentage of 38%, 16%, 15%, 14%, and 13%, respectively. gasoline, and other natural gases had a very small portion of $PM_{2.5}$ less than 1%. Thus, the major type that releases the highest $PM_{2.5}$ emission is pick-up using diesel fuels. Figure 4.49 presents the shares of $PM_{2.5}$ emission led by pick-ups.

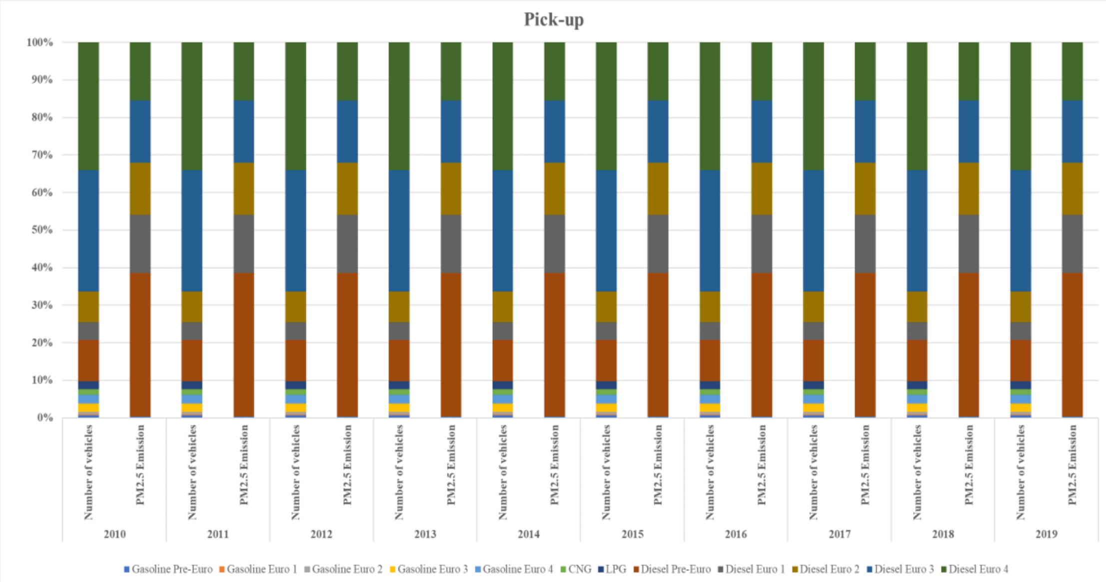


Figure 4.49 $PM_{2.5}$ Emission Shares of Pick-ups

(3) Public pick-ups transports

In this study, public pick-up transport is defined as the public passenger cars which also known as “Song-Taew” and include transport vehicles. According to the reviewed data, the main used fuel was CNG (3-way catalyst), followed by Diesel (uncontrolled), Diesel (Euro 3), CNG (uncontrolled), and LPG (Euro3).

The results demonstrated that 85% of total $PM_{2.5}$ emission came from public pick-up vehicles with uncontrolled diesel engines. The rest was 15% that caused by Euro3 diesel engines. In contrast, other sub-types did not much affect the $PM_{2.5}$ emission due to types of fuels which are mainly natural gases. Figure 4.50 illustrates the $PM_{2.5}$ Emission Shares of Public Pick-ups Transport.

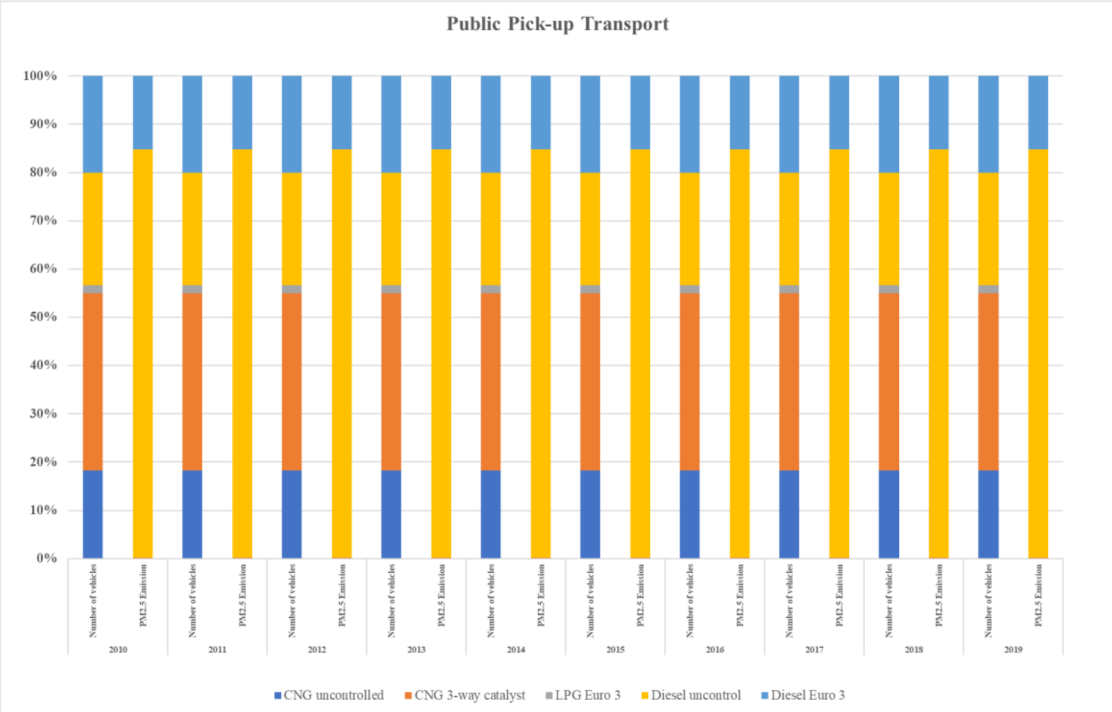


Figure 4.50 $PM_{2.5}$ Emission Shares of Public Pick-ups Transport

(4) Personal cars

The main in-used cars in Bangkok are the personal cars. The number of new registrations for this kind of vehicle has fluctuated over the past ten years. Although most new vehicles primarily use gasoline and gasohol fuels, the previous ones have been using diesel engines. Thus, the highest $PM_{2.5}$ emission shares were produced by the personal cars with diesel engines up to 90%. Specifically, Pre-Euro which is like other vehicles that had the percentage of $PM_{2.5}$ emission up to 44% even though there were only 2.3% of in-used cars. The following sub-types that emitted $PM_{2.5}$ was gasohol with 7% in total. The rest were released by gasoline, CNG, and LPG, respectively. The shares of $PM_{2.5}$ emission of PC are presented in Figure 4.51

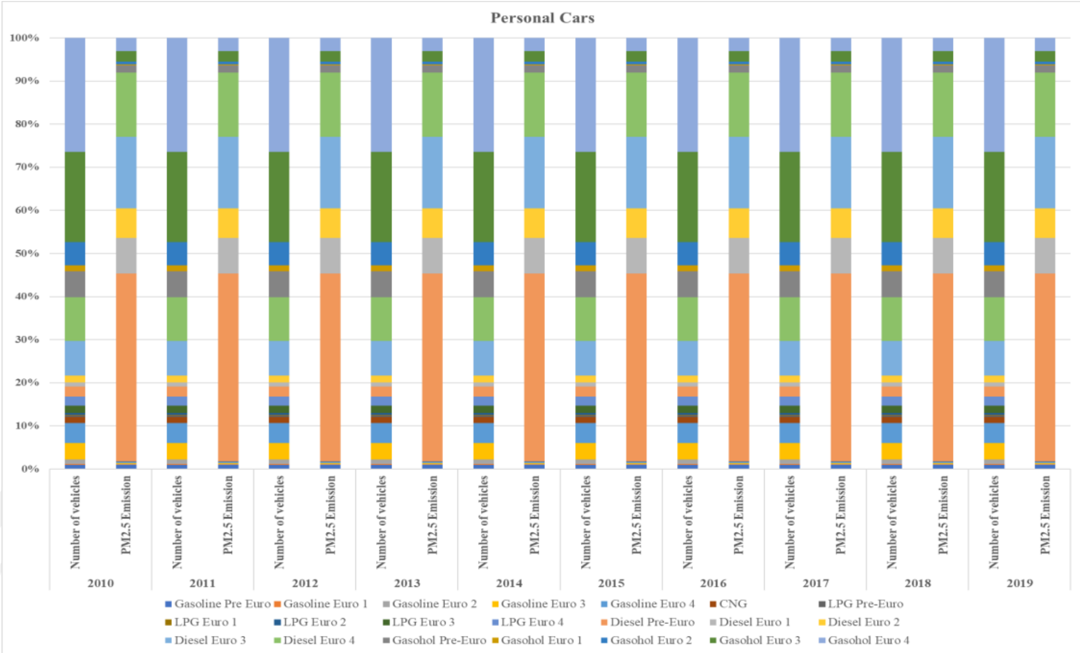


Figure 4.51 $PM_{2.5}$ Emission Shares of Personal Cars

(5) Motorcycles

Gasohol four strokes are major spark ignition engines of motorcycles. Although gasohol 4-stroke, generally used as gasoline 4-stroke substitution, has smaller emissions exhaust gas, the larger contributors to $PM_{2.5}$ emission in this study came from the gasohol 4-stroke with the emission shares 86%.

Considering the individual sub-types, the results indicated that the engines that can release high $PM_{2.5}$ were Gasoline 2-stroke (uncontrolled) and Gasoline 4-stroke (uncontrolled) with 0.0019 tons per year. While the gasohol 2 stroke engines released the $PM_{2.5}$ emission only 0.0005 tons per year. Figure 4.52 presents the $PM_{2.5}$ emission shares from motorcycles.

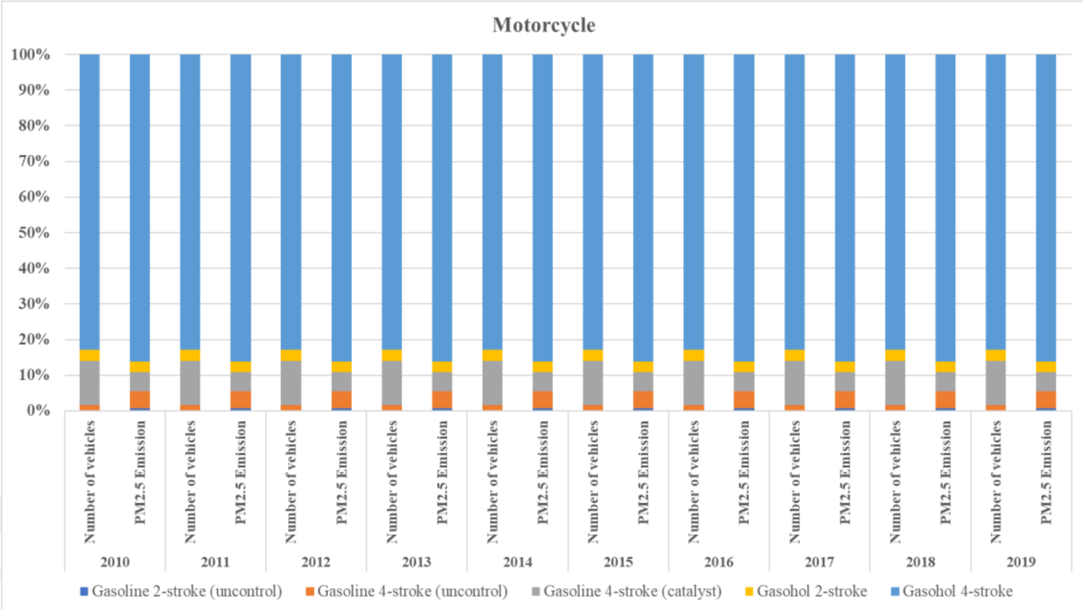


Figure 4.52 $PM_{2.5}$ Emission Shares of Motorcycles

(6) Buses

For sub-categories of buses, there are gasoline, CNG, LPG, and diesel. The three main in-used sub-categories are Diese-Euro3 (37%), CNG 3-way catalyst (27%), Diesel Pre-Euro (12%), respectively. The buses with Euro3 diesel engines had high-level $PM_{2.5}$ emission shares approximately 31% due to the highest number of in-used vehicles and the age of engines.

In addition, the highest shares of $PM_{2.5}$ emission was up to 42% caused by Pre-Euro diesel engines, but they were only 12% of these in-used buses. One of the key reasons is the free bus service, which mainly utilized diesel engines (Pre-Euro). However, in recent years, the director of Bangkok Mass Transit Authority (BMTA) revealed that “the free bus service has been totally phased out by early 2018 after installation of the common ticketing system”. Figure 4.53 illustrates the overall shares of $PM_{2.5}$ emission caused by buses.

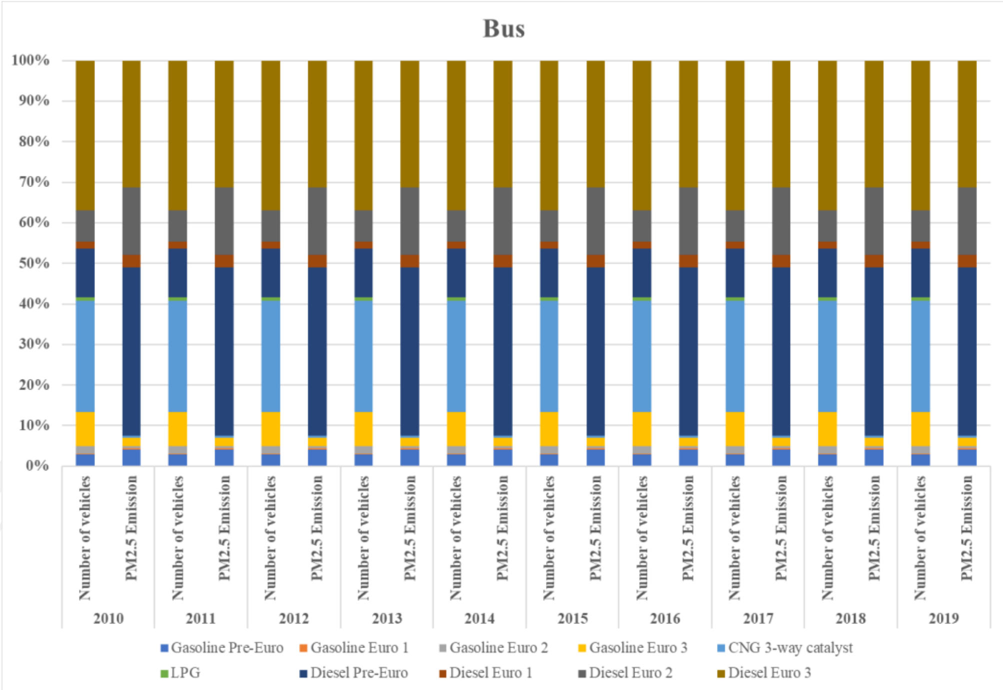


Figure 4.53 $PM_{2.5}$ Emission Shares of Buses

In summary, the results of $PM_{2.5}$ emission in On-road transport sector in Bangkok during 2017 to 2019 are demonstrated in Table 4.7. The results demonstrate that the highest $PM_{2.5}$ emission came from trucks, pick-ups, and PCs, respectively. In addition, the data from 2017-2019 was applied to develop $PM_{2.5}$ model prediction in the next section.

Table 4.7 The Summary of Interested Years of PM2.5 Emission Database of PM2.5 during 2017 to 2019

	Different Type of Vehicle and Their $PM_{2.5}$ Emission (ton/yr)									
	PC	**MC**	**Taxi**	**Van**	**Public Pick-up Transport**	**Tuktuk**	**Bus**	**Truck**	**Pick-up**	**Total**
2017	2,541	1,990	3	487	2,567	3	1,501	5,845	3,811	1,8748.03
2018	2,696	2,070	3	485	2,665	3	1,542	5,898	3,956	1,9318.05

Different Type of Vehicle and Their $PM_{2.5}$ Emission (ton/yr)										
	PC	**MC**	**Taxi**	**Van**	**Public Pick-up Transport**	**Tuktuk**	**Bus**	**Truck**	**Pick-up**	**Total**
2019	2,855	2,141	3	486	2,747	3	1,546	5,965	4,078	1,9823.68

2) The Results of Prediction of $PM_{2.5}$ Emission and Concentration in Bangkok

The main parts of this section are 1) the result of development of $PM_{2.5}$ concentration prediction model based on the relationship between ground-based $PM_{2.5}$ monitoring stations and on-road emission and meteorological parameters; and 2) The results of $PM_{2.5}$ concentration prediction from box model to verify the overall annual $PM_{2.5}$ levels in Bangkok.

(1) $PM_{2.5}$ Concentration Prediction Model using Multiple Linear Regression (MLR)

(1.1) $PM_{2.5}$ Concentration Prediction Model for On-road Transport Sector

In this task, the relationship between ambient $PM_{2.5}$ concentration and on-road transport $PM_{2.5}$ emission with meteorological factors affecting $PM_{2.5}$ levels associated to on-road transport sector in Bangkok was developed by using multiple linear regression model to predict the $PM_{2.5}$ ambient air quality emission and concentration in Bangkok. The result of model prediction is demonstrated as follows.

$$PM_{2.5,con} = -2{,}136.66 - 0.0004Q - 4.55WS - 2.31Temp + 3.02P - 0.63RH \quad \text{(Eq. 4.1)}$$

Due to the criteria of statistical analysis of F-entry ≤ 0.1 and removal ≥ 0.15 (Leelasakultum, 2009), therefore, the significant independent variables were incorporated in this prediction model consist of $PM_{2.5}$ emission from on-road transport (Q), Wind speed (WS), Pressure (P), Temperature (Temp), and Relative humidity (RH). The significant meteorological parameters were determined that they can affect the $PM_{2.5}$ concentration in Bangkok contributed by on-road transport sector. The statistical analysis of this model had the R^2 value up to 0.84 (Table 4.8).

Table 4.8 The Statistical Analysis of Model I

Statistics	**Value**
R Square	0.84
Adjusted R Square	0.81
N	35

Specifically, wind speed at the surface can impact on the level of $PM_{2.5}$. Wind speed could signify the mixing and dispersion abilities of the air. For example, if there is a good turbulence and pollutant dispersion in the air, $PM_{2.5}$ can be mixed well with the air, and the concentration will be reduced. As seen in Equation 4.1, the relationship between wind speed and $PM_{2.5}$ concertation had a negative impact, meaning that the $PM_{2.5}$ concentration increased when wind speed was low. In addition, temperature and relative humidity also had negative signs because the higher the $PM_{2.5}$ concentration, the lower temperature and relative humidity of air mass over Bangkok occurred. While pressure had a positive relationship with $PM_{2.5}$ concentration as high pressure occurs when the temperature decreased, especially in winter season. Thus, high $PM_{2.5}$ levels are associated with high pressure as well.

(1.2) $PM_{2.5}$ Concentration Prediction Model for $PM_{2.5}$ Episode (Model II)

The result of $PM_{2.5}$ episode prediction model was demonstrated in Equation 4.2. The independent variables which were associated with the $PM_{2.5}$ concentration comprise of $PM_{2.5}$ emission from on-road and open burning (Q_{all}), Wind speed (WS), Pressure (P), Relative humidity (RH), and Hotspot.

$$PM_{2.5,\,con} = -\,2{,}371.34 - 0.003Q_{all} - 12.67WS + 3.28P - 0.88RH + 0.026Hotspot \qquad \text{(Eq.4.2)}$$

Additionally, the statistical analysis of the Model II had good correlation with R-square 0.86, thus, it indicated that the model prediction was functional. The statistical analysis of this model is shown in Table 4.9.

Table 4.9 The Statistical Analysis of Model II

Statistics	**Value**
R Square	0.86
Adjusted R Square	0.83
N	32

In this case, the interesting finding is that the correlation coefficient of Model II is higher than Model I. It can be indicated that during the year, not only on-road transport sector affects the $PM_{2.5}$ concentration, but also other contributors can also impact on the $PM_{2.5}$ levels. Especially, the number of hotspots which were input to the regression analysis had the positive impact on the $PM_{2.5}$ levels.

It means that when many hotspots are detected, the high level of $PM_{2.5}$ happens over Bangkok and surrounding areas. Moreover, open burning is one of the main causes of $PM_{2.5}$ episode in the area. The open burning situation in metropolitan region surrounding Bangkok can be transported to Bangkok by wind.

(2) Validation of $PM_{2.5}$ Prediction Model

The results of $PM_{2.5}$ estimation need to be validated with the actual $PM_{2.5}$ concentration from ground-based monitoring station. In this section, the performance of the model prediction was determined by correlation with the data of $PM_{2.5}$ concentration in 2020 from 24 ground-based monitoring stations. The results illustrated that Model UI and Model II had R^2 values of 0.82 and 0.77 (Table 4.9), respectively. It indicated that the $PM_{2.5}$ estimated by the models had a very good correlation with the $PM_{2.5}$ observation (Actual monitoring). The correlation between $PM_{2.5}$ observation and $PM_{2.5}$ from the Models are illustrated in Figure 4.54 and 4.55 for Model I and Model II, respectively.

Table 4.10 The Results of Statistical Analysis of $PM_{2.5}$ Model Prediction Validation

Model	**R-square**	**RMSE**	**MAE**	**MAPE**
I	0.82	7.12	5.79	0.5
II	0.77	13.12	11.54	1.0

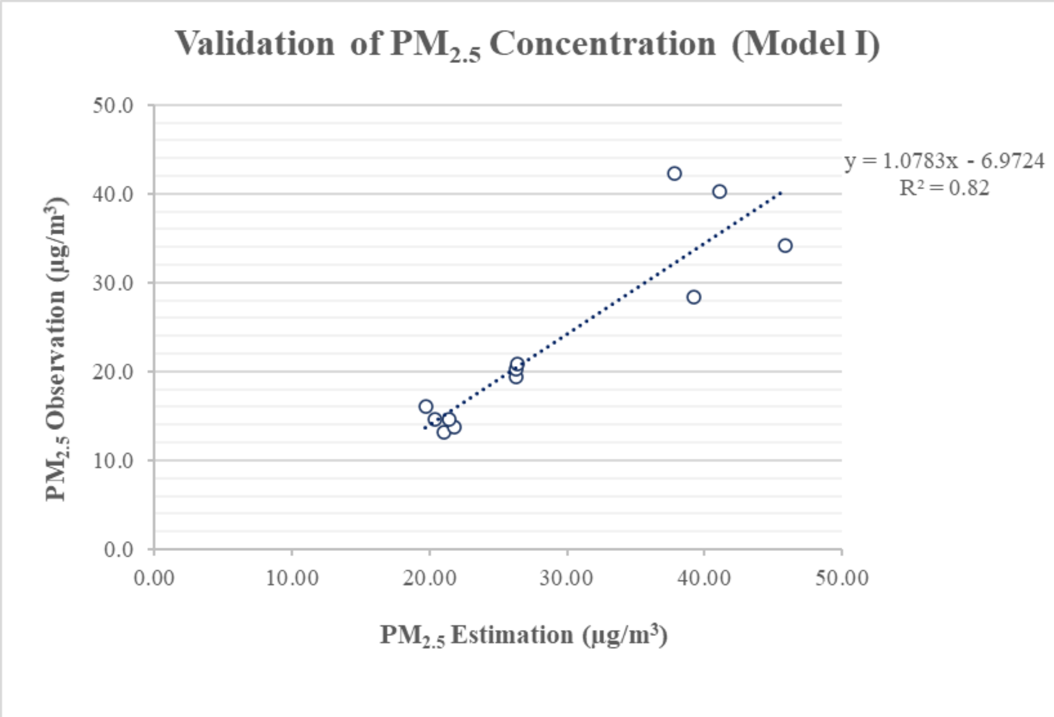


Figure 4.54 Validation of $PM_{2.5}$ Concentration Estimation of Model I

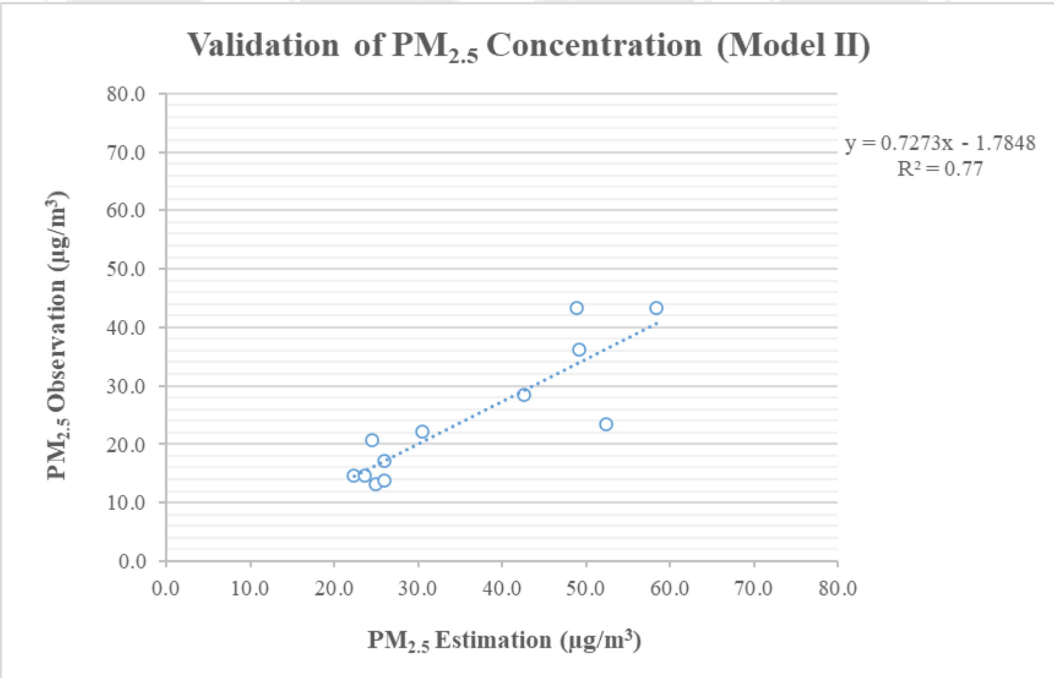


Figure 4.55 Validation of $PM_{2.5}$ Concentration Estimation of Model II

(3) Estimation of $PM_{2.5}$ Concentration in Bangkok using Box Model

Primarily, the overall $PM_{2.5}$ emission in Bangkok normally comes from two main sources which are transportation and open burning throughout the year as mentioned in the previous section. The total emission of $PM_{2.5}$ in Bangkok is increasing dramatically. In the case of on-road transport sector, the annual $PM_{2.5}$ that emitted from this source in each year do not change much as the activity data (vehicles' fleet) and number of cumulative vehicles in on-road transport are not different. While the emission of $PM_{2.5}$ from open burning fluctuates because they depend on the amount of rice production in each year and weather condition. For instance, in 2018, it had the lowest $PM_{2.5}$ emission due to the reduction of rice export less than 1.20% compared to the previous year (Office of Agricultural Economics [OAE], 2019). On the other hand, the $PM_{2.5}$ emission in 2020 had highest levels due to the high demand of rice production within the country and overseas.

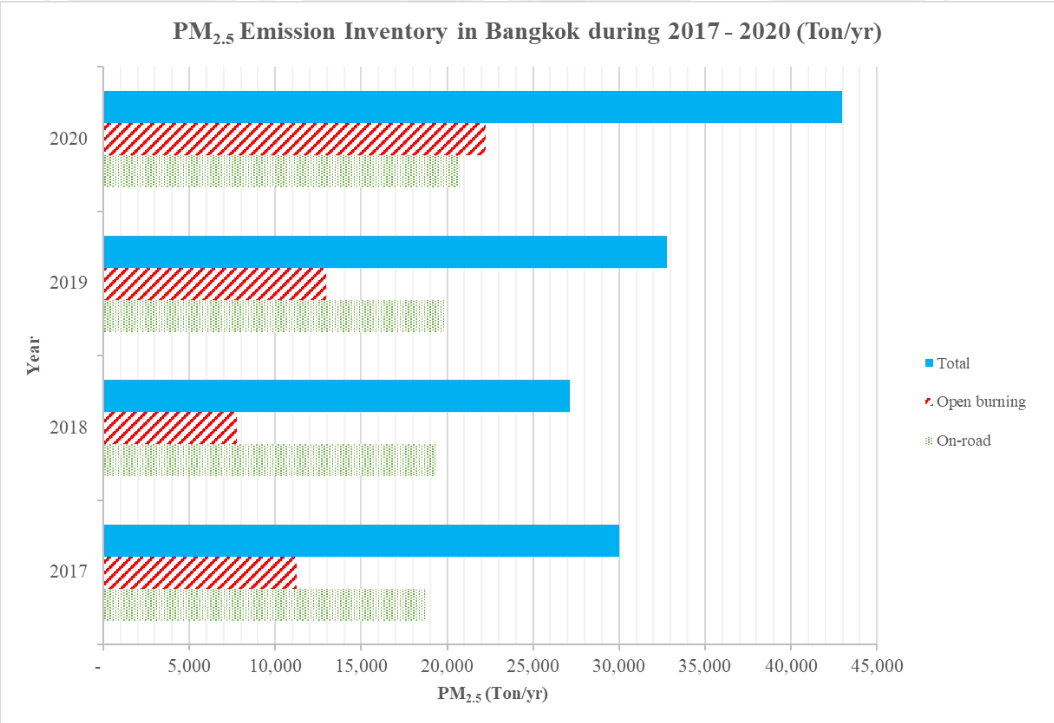


Figure 4.56 Total $PM_{2.5}$ Emission Episode in Bangkok during 2017 to 2020

In addition, the results of $PM_{2.5}$ concentration in Bangkok during 2017 to 2020 investigated by Box model are illustrated in Figure 4.56. In this case, the total ambient $PM_{2.5}$ concentration was mainly calculated based on major sources of $PM_{2.5}$ emission including on-road transport sector and open burning. The box model in this study would be useful to predict and control the ambient air quality in urban areas (Bangkok).

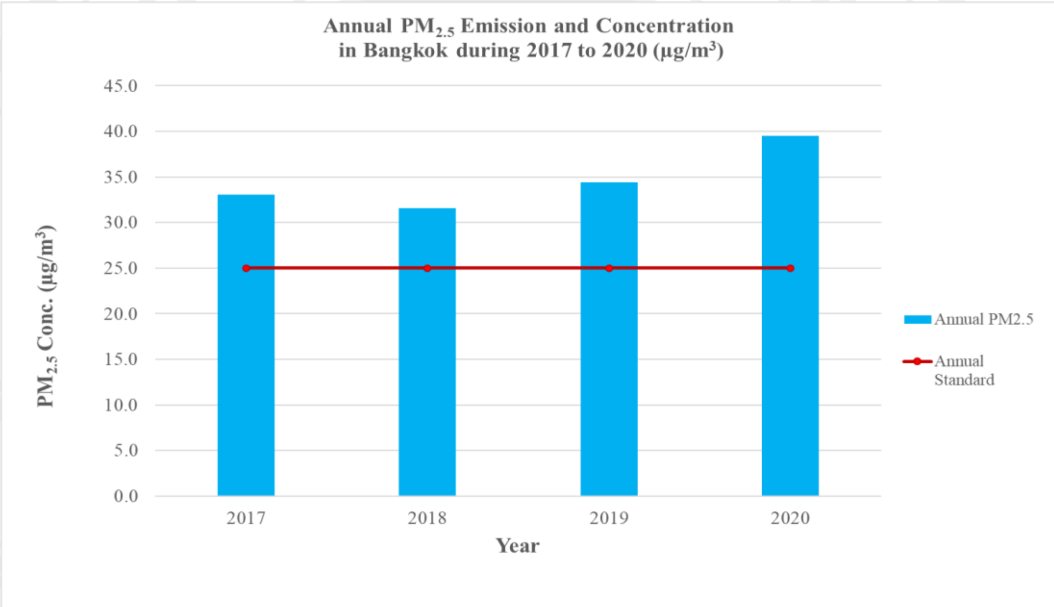


Figure 4.57 Annual $PM_{2.5}$ Emission and Concentration in Bangkok during 2017 to 2020

Figure 4.57 shown the results of levels of $PM_{2.5}$ during 2017 to 2020 by box model were higher than the Thai National Ambient Air Quality Standards (NAAQs). It can be implied that the box modeling approach can help to understand the air pollutant sources and to predict the air pollutant levels. Generally, one of the reasons related to high $PM_{2.5}$ levels in this study is the expansion of urbanization, especially the high demand of vehicles and crop production. Additionally, the study area is defined as an urban area, where has demands of land space, is planned for high proficiency use. Hence, high-rise buildings are constructed increasingly, and are also commonly designed and used in modern society to reduce land requirements. This situation can affect the dispersion of the air pollutant concentration due to the low ventilation of the air in the area.

Moreover, during the year the significant parameters are boundary layer temperature inversion and mixing heights that are used in understanding the atmospheric dispersion of air pollution. The average mixed height in this study was about 1.0 km. The temperature inversions occurred to represent a natural air quality hazard by trapping air pollutant emitted from pollution sources. Thus, the $PM_{2.5}$ can be trapped and can accumulate in the area due to the large amount of $PM_{2.5}$ emission.

(4) The Results of Policy Implication to reduce $PM_{2.5}$ Concentration Contributed On-road Transportation

(4.1) The results of $PM_{2.5}$ Emission in Different Scenarios to Reduce $PM_{2.5}$ Emission from On-road Transport Sector in Bangkok

The policy scenarios in this study were applied based on the direction of $PM_{2.5}$ emission control standards of Pollution Control Department in the future, especially the removal of old in-used vehicles and the promotion of upgrading Euro standards for new vehicles. Figure 4.58 shows the amount of $PM_{2.5}$ emission in different policy scenarios by applying the emission control scenario from 2020. The results indicated that each policy scenario can be applied to reduce the amount of $PM_{2.5}$ emission from on-road transport sector in Bangkok.

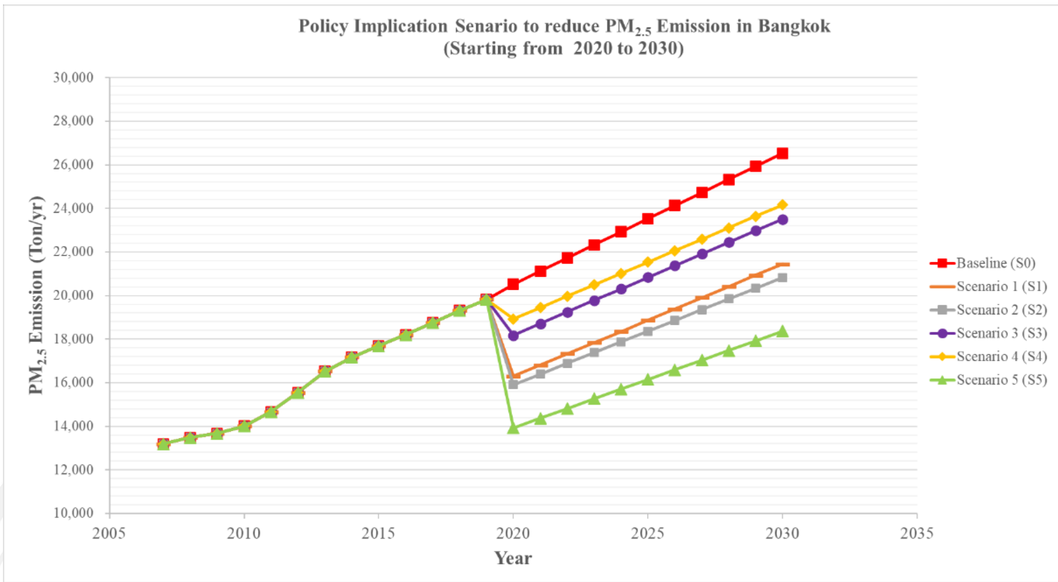


Figure 4.58 The Amount of $PM_{2.5}$ Emission in Different Policy Implication Scenarios (Ton/Yr)

The baseline $PM_{2.5}$ emission (Red line) has risen dramatically during the next ten years assuming that the demand of new vehicles will be needed increasingly. Thus, the policy implication scenarios were applied to this situation, and the best performance of the policy implication in this study is Scenario 5 which incorporated three significant scenarios (i.e., S_1, S_2 and S_3). Specifically, the pattern of each scenario during the next ten years did not change much because this study assumed that the driving activities and meteorological parameters used in this section were homogeneous.

However, the results of $PM_{2.5}$ reduction in different scenarios (See Figure 4.59) illustrated individually that the best policy scenario is Scenario 2. The measure of this scenario is to remove such vehicles (Trucks and Pick-ups with Pre-Euro engines) that released the highest $PM_{2.5}$ emission (See section 4.1). The percentage of $PM_{2.5}$ emission reduction compared to the baseline was approximately 22%. Secondly, the following effective policy scenario is Scenario 1 which aims to promote the number of trucks with Euro IV up to 50%. The result of this scenario demonstrated that the $PM_{2.5}$ can be reduced by 19.8% on average. In addition, most people in urban areas use many personal cars, thus, the scenario 4 needs to be applied to control the emission of $PM_{2.5}$ from this kind of vehicle. The percentage of reduction of $PM_{2.5}$ emission by applying Scenario 4 was about 17.4%. On the other hand, the lowest $PM_{2.5}$ reduction in percentage was about 10.4% presented in Scenario 4 due to the smaller number of in-use pick-ups.

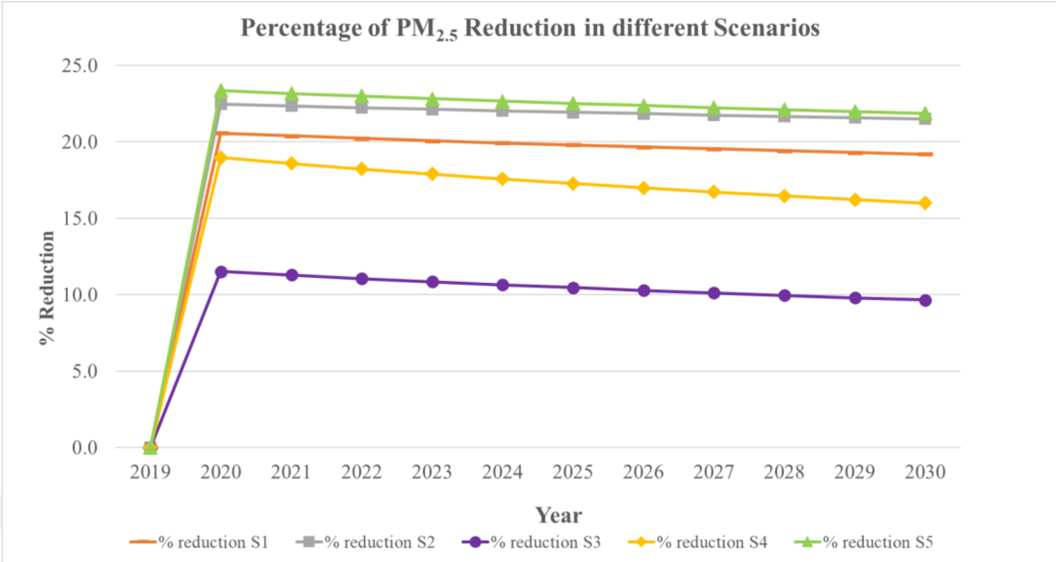


Figure 4.59 The Percentage of $PM_{2.5}$ Reduction in Different Scenarios (%)

(4.2) The overall $PM_{2.5}$ Concentration in Bangkok by Applying the Best Effectiveness of Policy Implication Scenario

As discussed in the previous section, the best policy scenario is Scenario 5 which integrated with the best three scenarios. Thus, Scenario 5 is selected in this section to apply the measures of reducing $PM_{2.5}$ emission in on-road transport sector in Bangkok annually. To compare with the NAAQs of $PM_{2.5}$ concentration, the annual $PM_{2.5}$ emission were converted in term of $PM_{2.5}$ ambient air quality concentration by using the $PM_{2.5}$ model prediction (Section 4.2). The standard of annual $PM_{2.5}$ in Thailand is 25 micrograms per cubic meter ($\mu g/m^3$).

In this study, the results of $PM_{2.5}$ concentration episode were calculated based on the emission of $PM_{2.5}$ from two main sources (i.e., on-road transport, and open burning) by using the $PM_{2.5}$ prediction model (Model II). The $PM_{2.5}$ concentration in Bangkok exceeded the standards due to the high number of vehicles with old engines, especially Pre-Euro, Euro I and II, and including the high production rate of rice and the large-burned areas in Bangkok and metropolitan region. Figure 4.60 demonstrates that if the scenario 5 will be applied to reduce $PM_{2.5}$ in on-road transport sector in Bangkok, the levels of $PM_{2.5}$ in ambient air quality will be decreased with the reduction percentage of approximately 66.8% in average of the next ten-years.

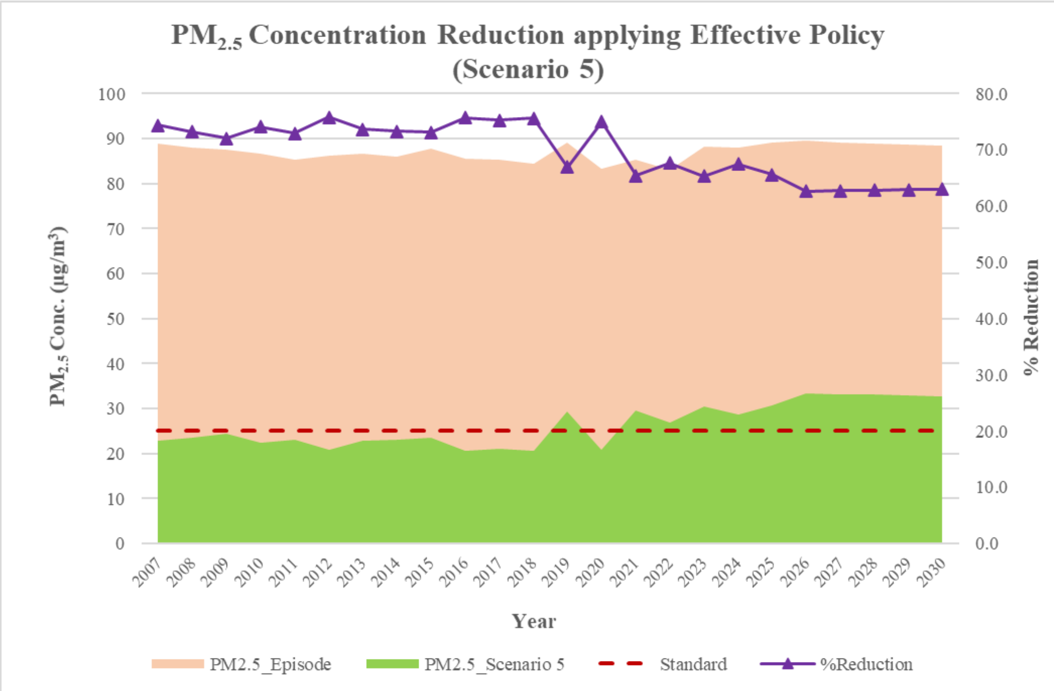


Figure 4.60 Annual $PM_{2.5}$ Concentration Reduction Applying Scenario 5

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This study aims to study the direction of air pollution in Bangkok with the objective to explain the trend and characteristic of air pollution in the areas of congested traffic for the past 10 years. Analysis was then conducted to find the factors impacting air pollution in Bangkok. The important objective in this study were to establish the database of $PM_{2.5}$ emission from on-road transport sector in Bangkok during 2010 to 2019 and were to develop the $PM_{2.5}$ model prediction by using Multiple Linear Regression in terms of annual $PM_{2.5}$ concentration from on-road transport sector and $PM_{2.5}$ episode as well. Additionally, the box model was used to estimate the total amount of $PM_{2.5}$ emission within Bangkok city. Finally, model results were applied to investigate the effective policy implication scenarios to reduce the $PM_{2.5}$ levels in on-road transport sector.

5.1 Conclusion

5.1.1 Characteristics of Air Pollution in Bangkok for the Past Ten Years

Based on the study findings of the trend of air pollution in the areas of congested traffic for the past 10 years, it revealed that, in most air quality measuring stations, SO_2 and NO_2 tended to decrease whereas CO, O_3 and PM_{10} tend to be different depending on stations. The primary pollutants tended to have positive relation. O_3 which was the secondary pollutant could not see the positive relation with other parameters. PM_{10} attended to increase, exceeding standards, in winter of every year. In winter, the weather was dry, and the relative humidity decreased, resulting in longer lingering dust in the air. Calm weather or temperature inversion near the ground resulted in a large amount of accumulated air pollutants. The emission of primary pollutants revealed that they would have the highest concentration in the morning, gradually decrease during the daytime and increase in the evening mainly depending on congestion of traffic. O_3 had the highest concentration in the afternoon as the variables impacting the amount of highest daily concentration of O_3 was sun radiation. Every week and every day, concentration of air pollution was high at each time of congested traffic. A positive relation was found between NO_2 and amount of traffic as NO_2 came from direct fuel combustion in cars. At the same time, a negative relation was found between O_3 and secondary pollutant the amount of traffic as O_3 is derived from photochemical oxidation. Conclusion could be reached that the main pollutants found around road curbs in Bangkok were primary pollutants directly emitted from the sources.

5.1.2 Characteristics and Dispersion of $PM_{2.5}$

Based on the analysis of $PM_{2.5}$ concentrations from 24 air quality monitoring stations in Bangkok, the districts can be ranked in terms of $PM_{2.5}$ intensity from highest to lowest as follows: South Bangkok, East Bangkok, North Bangkok, North Thonburi, Central Bangkok, and South Thonburi. The relevant factors are as follows:

1) Location of the source of origin in the "upwind" direction, where the prevailing winds blow into the city of Bangkok.

2) Vertical lifting of dust and hot air (from burning activities) results in the suspension of fine particles (the smaller the particles, the longer they can remain suspended in the atmosphere) that move with the higher-speed winds at higher altitudes compared to the lower-level winds.

3) Subsidence of the air containing small, suspended particles in Bangkok during periods when the atmospheric stability near the surface is high, such

as in the evening, nighttime, and early morning. This is linked to the occurrence of Urban Heat Island, where the heated air in the city rises vertically, causing cooler air from the surrounding areas to flow in and replace it.

5.1.3 Annual $PM_{2.5}$ Emission from On-road Transport Sector in Bangkok

1) $PM_{2.5}$ emission in Bangkok associated with on-road transport sector during 2010 to 2019 were establish as the database of $PM_{2.5}$ emission. The database was developed by conducting the Emission Inventory for on-road transport referred to the Atmospheric Brown Cloud– Emission Inventory Manual (ABC-EIM).

2) The types of vehicles in this study were personal cars, motorcycles, vans, public pick-up transport, buses, trucks, pick-ups, and tuk-tuk. The total amount of annual $PM_{2.5}$ emission of all vehicle types is dramatically increasing, particularly since 2011 due to the “first-car tax scheme”.

3) During 2010 to 2019, the major $PM_{2.5}$ emission in this study, which were considered by sub-categories of fuel type, caused by trucks with Pre-Euro diesel engines. It had a percentage of $PM_{2.5}$ emission of 49%. Following by pick-ups with Pre-Euro diesel engines which had 38% $PM_{2.5}$ emission. However, other contributors of sub-categorized vehicles can also affect the $PM_{2.5}$ emission in Bangkok, especially public pick-up transports, personal cars, and motorcycles, respectively.

4) The data which was used to develop the $PM_{2.5}$ prediction models were divided into two datasets. There were 1) data of 2017 to 2019 for model development, and 2) another set was used for model validation. The first $PM_{2.5}$ prediction model (Model I) was developed based on the relationship between dependent variable ($PM_{2.5}$ ground-based monitoring data) and independent variables (i.e., $PM_{2.5}$ emission data, and meteorological parameters) to estimate $PM_{2.5}$ concentration caused by on-road transport sector. It had the coefficient of determination (R^2) up to 0.84. While Model II

incorporated the hotspot data as an additional independent variable to represent the $PM_{2.5}$ concentration estimation of $PM_{2.5}$ episode with the R-square value 0.86.

5) The validation of $PM_{2.5}$ concentration prediction models were used the statistical analyses (i.e., R^2, RMSE, MAE and MAPE). The relationship between $PM_{2.5}$ ground-based monitoring station in 2020 and the results of $PM_{2.5}$ estimation from the models were correlated. The results indicated that the performances of the two models are acceptable with the R^2 0.82 and 0.77 for Model I and Model II, respectively. Additionally, the RMSE, MAE and MAPE of Model I were 7.12, 5.79 and 0.5%, respectively. While Model II had 13.12, 11.54 and 0.1% for RMSE, MAE and MAPE, respectively.

6) The box model in this study was used to calculate the overall annual $PM_{2.5}$ emission within Bangkok city influenced by both on-road transport and open burning during 2017 to 2020. The $PM_{2.5}$ emission results from the emission inventory were accounted for in the box model. The results of levels of $PM_{2.5}$ during 2017 to 2020 by box model were higher than the standard of annual $PM_{2.5}$ concentration (25 $\mu g/m^3$). These results were used to apply to the policy implication scenarios.

7) The policy implication scenarios for $PM_{2.5}$ concentration reduction were developed based on the results of significant sources of on-road $PM_{2.5}$ emission in this study and the future emission control standards during the next ten-years (2020 to 2030). The selected policy implication, which is the most effective policy implication scenario, is Scenario 5 (S_5). It was the combination of S_1, S_2 and S_3. The result illustrated that Scenario 5 can decrease the $PM_{2.5}$ concentration in ambient air quality up to 68% compared to the $PM_{2.5}$ episode during the year.

5.2 Recommendations

This study was conducted from both primary and on secondary data to estimate and predict the $PM_{2.5}$ estimation and concentration in Bangkok in on-road transport sector. Some recommendations for future studies are needed as below:

1) The activity data of emission inventory for on-road transport sector in this study were investigated based on the literature review and secondary data of vehicles. Thus, the primary data should be conducted to implement the upgrading activity data for on-road transport in Bangkok annually. For instance, the vehicle kilometer travelled can be monitored by observing the number of vehicles and the fleet of vehicles running on the specific road to identify the real activities of vehicle in the specific time.

2) The main $PM_{2.5}$ emission in Bangkok comes from transportation and open burning. However, it is not only influenced by the on-road transport sector, but also other transportation and contributors can impact on the $PM_{2.5}$ emission such as non-road transports (e.g., ship, boat, airplane, and train), industrial sector, and household. Thus, to cover all emission of $PM_{2.5}$, other contributors should be conducted.

3) The meteorological parameters in this study were collected from the Thai Meteorological Department (TMD) stations simply. As the $PM_{2.5}$ concentration is highly related to the local meteorological conditions, the meteorological parameters or meteorological models should be applied to investigate for higher accuracy of these data to improve the performance of the $PM_{2.5}$ model prediction.

4) This study focused on only policy implication to reduce the $PM_{2.5}$ levels. However, in real cases, the high $PM_{2.5}$ concentration can directly impact on human health in terms of short-term and long-term effects. Thus, the future study should study the health impacts related to $PM_{2.5}$ concentration as well.

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APPENDICES

Appendix A

PM2.5 Emission Calculation in On-road Transport Sector and Open-burning (Episode)

$PM_{2.5}$ Emission Calculation in On-road Transport Sector and Open-burning (Episode)

Table A1 Emission Factor with Vehicle Fraction and the Example of $PM_{2.5}$ Emission Calculation in 2007

Vehicles Category	Sub-category	Fraction of Sub-Category	Chosen Values	VKT (km/year)	Emission Factor (g/km)	$PM_{2.5}$ Emission (ton/year)
		A	B	C = A x B	N	P = CxN
PC	Gasoline Pre Euro	0.011	0.011	316,562,064.38	0.033	10
	Gasoline Euro 1	0.002	0.002	67,994,582.07	0.014	1
	Gasoline Euro 2	0.01	0.01	279,626,404.46	0.005	1
	Gasoline Euro 3	0.038	0.038	1,093,201,320.15	0.002	2
	Gasoline Euro 4	0.047	0.047	1,372,920,074.53	0.002	3
	Gasoline Euro 5		-	-	0.002	0
	Gasoline Euro 6		-	-	0.002	0
	CNG	0.013	0.013	371,507,871.11	0.001	0
	LPG Pre-Euro	0.005	0.005	139,652,979.17	0.007	1
	LPG Euro 1	0.001	0.001	29,996,158.80	-	0
	LPG Euro 2	0.004	0.004	123,358,623.26	-	0

Table A1 Emission Factor with Vehicle Fraction and the Example of $PM_{2.5}$ Emission Calculation in 2007

Vehicles Category	**Sub-category**	**Fraction of Sub-Category**	**Chosen Values**	**VKT (km/year)**	**Emission Factor (g/km)**	**$PM_{2.5}$ Emission (ton/year)**
		A	**B**	**C = A x B**	**N**	**P = CxN**
	LPG Euro 3	0.017	0.017	482,271,372.26	-	0
	LPG Euro 4	0.021	0.021	605,670,736.16	-	0
	Diesel Pre-Euro	0.023	0.023	675,821,425.61	0.706	477
	Diesel Euro 1	0.01	0.01	290,320,291.41	0.313	91
	Diesel Euro 2	0.016	0.016	451,808,147.60	0.165	75
	Diesel Euro 3	0.08	0.08	2,333,851,581.69	0.077	179
	Diesel Euro 4	0.101	0.101	2,931,017,030.83	0.052	152
	Diesel Euro 5		-	-	0.005	0
	Diesel Euro 6		-	-	0.005	0
	Gasohol Pre-Euro	0.061	0.061	1,771,569,769.04	0.011	20
	Gasohol Euro 1	0.013	0.013	380,516,680.97	0.005	2
	Gasohol Euro 2	0.054	0.054	1,564,867,495.19	0.005	7.43
	Gasohol Euro 3	0.21	0.21	6,117,860,060.18	0.005	29.06
	Gasohol Euro 4	0.264	0.264	7,683,244,371.38	0.005	36.5

Table A1 Emission Factor with Vehicle Fraction and the Example of $PM_{2.5}$ Emission Calculation in 2007

Vehicles Category	Sub-category	Fraction of Sub-Category	Chosen Values	VKT (km/year)	Emission Factor (g/km)	$PM_{2.5}$ Emission (ton/year)
		A	B	C = A x B	N	P = CxN
	Gasohol Euro 5		-	-	0.005	0
	Gasohol Euro 6		-	-	0.005	0
MC	Gasoline 2-stroke (uncontrol)	0.002	0.002	24,588,240	0.211	5.19
	Gasoline 4-stroke (uncontrol)	0.014	0.014	218,220,632	0.186	40.6
	Gasoline 4-stroke (catalyst)	0.125	0.125	1,925,566,567	0.026	50.29
	Gasohol 2-stroke	0.03	0.03	459,105,208	0.087	39.81
	Gasohol 4-stroke	0.829	0.829	12,740,169,526	0.087	1104.84
Taxi	Gasoline Euro 2	0.012	0.012	81,878,665	0.009	0.77
	Gasoline Euro 4	0.018	0.018	123,162,025	0.001	0.15
	CNG 3-way catalyst	0.774	0.774	5,323,489,330	0	1.66
	LPG 3-way catalyst	0.006	0.006	41,283,360	0.001	0.03
	LPG Euro 3	0.06	0.06	410,081,380	-	0

Table A1 Emission Factor with Vehicle Fraction and the Example of $PM_{2.5}$ Emission Calculation in 2007

Vehicles Category	**Sub-category**	**Fraction of Sub-Category**	**Chosen Values**	**VKT (km/year)**	**Emission Factor (g/km)**	**$PM_{2.5}$ Emission (ton/year)**
		A	**B**	**C = A x B**	**N**	**P = CxN**
	LPG Euro 4	0.119	0.119	818,098,593	-	0
	Gasohol (composite)	0.012	0.012	82,566,721	-	0
Van	Gasoline Euro 3	0.06	0.055	757,311,237	0.004	2.66
	CNG 3-way catalyst	0.66	0.661	9,095,996,424	0	3.32
	LPG Euro 3	0.06	0.064	883,988,753	-	0
	Diesel control with EGR	0.06	0.055	757,311,237	0.334	253.28
	Diesel Euro 3	0.11	0.11	1,515,999,404	0.09	136.53
	Diesel Euro 4	0.04	0.037	505,333,135	0.034	16.95
	Gasohol (composite)	0.02	0.018	253,355,032	-	0
Public-pickup	CNG uncontrol	0.18	0.183	1,971,237,037	0.001	1.05
	CNG 3-way catalyst	0.37	0.367	3,940,324,415	0.001	2.53
	LPG Euro 3	0.02	0.017	179,496,502	-	0
	Diesel uncontrol	0.23	0.233	2,508,651,714	0.564	1413.88
	Diesel Euro 3	0.2	0.2	2,148,583,880	0.121	260.42

Table A1 Emission Factor with Vehicle Fraction and the Example of $PM_{2.5}$ Emission Calculation in 2007

Vehicles Category	Sub-category	Fraction of Sub-Category	Chosen Values	VKT (km/year)	Emission Factor (g/km)	$PM_{2.5}$ Emission (ton/year)
		A	**B**	**C = A x B**	**N**	**P = CxN**
Tuktuk (3 wheelers)	CNG_LPG	0.85	0.852	169,839,274	0.014	2.32
	Gasohol (composite)	0.15	0.148	29,525,997	-	0
Bus	Gasoline Pre-Euro	0.029	0.029	70,947,158	0.575	40.78
	Gasoline Euro 1	0.004	0.004	9,425,644	0.316	2.98
	Gasoline Euro 2	0.018	0.018	43,350,767	0.104	4.49
	Gasoline Euro 3	0.085	0.085	209,126,979	0.098	20.42
	CNG 3-way catalyst	0.273	0.273	671,397,054	0.007	5
	LPG	0.011	0.011	25,966,866	0.007	0.19
	Diesel Pre-Euro	0.124	0.124	305,029,334	1.483	452.31
	Diesel Euro 1	0.016	0.016	40,524,497	0.833	33.77
	Diesel Euro 2	0.076	0.076	186,381,752	0.964	179.73
	Diesel Euro 3	0.365	0.365	899,117,948	0.379	340.8
	Diesel Euro 4		-	-	0.027	0
	Diesel Euro 5		-	-	0.027	0

Table A1 Emission Factor with Vehicle Fraction and the Example of $PM_{2.5}$ Emission Calculation in 2007

Vehicles Category	**Sub-category**	**Fraction of Sub-Category**	**Chosen Values**	**VKT (km/year)**	**Emission Factor (g/km)**	**$PM_{2.5}$ Emission (ton/year)**
		A	**B**	**C = A x B**	**N**	**P = CxN**
	Diesel Euro 6		-	-	0.013	0
Truck	Gasoline	0.001	0.001	7,767,444	0.273	2.12
	CNG	0.062	0.062	426,238,512	0	0.17
	LPG	0	0	3,106,978	0	0
	Diesel Pre-Euro	0.221	0.221	1,507,529,018	1.483	2235.42
	Diesel Euro 1	0.029	0.029	197,188,884	0.833	164.34
	Diesel Euro 2	0.169	0.169	1,152,744,363	0.713	821.41
	Diesel Euro 3	0.517	0.517	3,526,001,145	0.379	1336.48
	Diesel Euro 4		-	-	0.04	0
	Diesel Euro 5		-	-	0.04	0
	Diesel Euro 6		-	-	0.02	0
Pick-up	Gasoline Pre-Euro	0.007	0.007	169,898,275	0.023	3.83
	Gasoline Euro 1	0.002	0.002	36,099,697	0.009	0.34
	Gasoline Euro 2	0.007	0.007	160,507,991	0.007	1.15

Table A1 Emission Factor with Vehicle Fraction and the Example of $PM_{2.5}$ Emission Calculation in 2007

Vehicles Category	**Sub-category**	**Fraction of Sub-Category**	**Chosen Values**	**VKT (km/year)**	**Emission Factor (g/km)**	**$PM_{2.5}$ Emission (ton/year)**
		A	**B**	**C = A x B**	**N**	**P = CxN**
	Gasoline Euro 3	0.022	0.022	497,794,795	0.001	0.69
	Gasoline Euro 4	0.023	0.023	522,648,615	0.001	0.73
	CNG	0.015	0.015	342,252,536	0.001	0.2
	LPG	0.022	0.022	498,364,959	0.001	0.65
	Diesel Pre-Euro	0.111	0.111	2,535,208,085	0.375	950.89
	Diesel Euro 1	0.047	0.047	1,077,353,404	0.375	404.09
	Diesel Euro 2	0.081	0.081	1,856,410,326	0.194	360.42
	Diesel Euro 3	0.324	0.324	7,428,052,973	0.056	419.08
	Diesel Euro 4	0.34	0.34	7,798,919,628	0.049	379.36
	Diesel Euro 5		-	-	0.043	0
	Diesel Euro 6		-	-	0.029	0
Total				108,254,158,957		12586

Table A2 Number of Accumulative Vehicles during 2007 to 2019

Types	Accumulative Vehicle Number												
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
PC	1,974,751	2,074,491	2,190,150	2,379,457	2,596,926	2,972,305	3,356,099	3,592,212	3,799,125	4,001,423	4,242,556	4,501,405	4,766,656
MC	2,335,172	2,412,609	2,460,897	2,565,522	2,693,741	2,902,941	3,117,464	3,256,969	3,376,157	3,483,519	3,620,791	3,767,639	3,896,292
Taxi	86,132	90,086	96,032	101,056	106,368	111,670	116,317	113,954	104,839	95,899	82,372	86,652	86,325
Van	197,075	192,675	192,911	195,487	200,364	208,665	216,080	217,717	214,394	210,625	214,368	213,511	213,663
Public-pickup	235,222	236,801	240,161	247,329	256,638	272,283	288,678	300,068	310,550	320,553	330,710	343,263	353,855
Tuk-tuk	9,618	9,645	9,681	9,688	9,712	9,769	9,818	9,807	9,840	10,202	10,172	10,184	10,146
Bus	33,716	34,344	34,695	36,960	37,704	38,462	39,534	40,616	42,794	43,796	43,246	44,410	44,541
Truck	110,571	114,208	114,570	113,248	119,038	123,895	129,933	133,966	135,605	138,306	141,709	143,008	144,630
Pick-up	705,665	710,403	720,484	741,988	769,914	816,848	866,034	900,205	931,651	961,659	992,131	1,029,790	1,061,566

Note: Public-Pickup Transport is 0.25% of van + pick-up, remaining is pick-up

Appendix B

The Results of Statistical Analysis of PM2.5 Prediction Models using MLR

The Results of Statistical Analysis of $PM_{2.5}$ prediction models using MLR

Table B1 The Results of Evaluation of Model I

Model Summary									
					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	.918[a]	.843	.816	3.998002748969425	.843	32.122	5	30	.000

Note: a. Predictors: (Constant), RH (%), WS(m/s), Q (ton/mon), Temp (oC), P (mmHg)

Table B2 The Results of Parameter Coefficients of Model I

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	-2136.655	556.989		-3.836	.001	-3274.179	-999.131
	Q (ton/mon)	.000	.001	-.053	-.623	.538	-.002	.001
	WS(m/s)	-4.553	3.061	-.135	-1.488	.147	-10.804	1.698
	Temp (^{o}C)	-2.309	.817	-.257	-2.828	.008	-3.977	-.641
	P (mmHg)	3.017	.712	.505	4.236	.000	1.562	4.471
	RH (%)	-.633	.205	-.292	-3.082	.004	-1.052	-.213

Note: a. Dependent Variable: $PM_{2.5}$, con (ug/m^3)

Table B3 The Results of Evaluation of Model II

Model Summary									
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.925[a]	.856	.833	4.153038934892366	.856	35.809	5	30	.000

Note: a. Predictors: (Constant), Hotspot, RH (%), WS(m/s), P (mmHg), Qall (ton/mon)

Table B4 The Results of Parameter Coefficients of Model II

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	-2371.337	537.382		-4.413	.000	-3468.818	-1273.856
	Qall (ton/mon)	-.003	.004	-.609	-.942	.354	-.011	.004
	WS(m/s)	-12.667	3.655	-.318	-3.465	.002	-20.132	-5.202
	P (mmHg)	3.281	.694	.505	4.731	.000	1.865	4.698

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
	RH (%)	-.880	.209	-.381	-4.204	.000	-1.307	-.452
	Hotspot	.026	.022	.739	1.161	.255	-.020	.071

Note: a. Dependent Variable: $PM_{2.5}$, con (ug/m3)

Table B5 Data for $PM_{2.5}$ Prediction Model Development (Model I)

Year	Month	$PM_{2.5}$, con (ug/m3)	Q (ton/mon)	WS (m/s)	Temp (ºC)	P (mmHg)	RH (%)
2017	Jan	37.40	911.0308467	1.45492192	28.10	758.6616	70.1129
	Feb	41.31	2483.324	1.21404054	28.93	759.2156	62
	Mar	22.89	1694.749871	1.61839359	30.38	757.5318	71.16129
	Apr	19.33	98.3947	1.58051711	30.99	756.9321	68.65417
	May	19.93	8.831007042	1.34864537	29.97	755.7482	79.25806
	Jun	16.72	5.595748173	1.53475793	30.11	755.353	74.15

Year	Month	$PM_{2.5}$, con (ug/m3)	Q (ton/mon)	WS (m/s)	Temp (ºC)	P (mmHg)	RH (%)
	Jul	15.95	6.89401729	1.65272772	29.26	755.3129	75.56452
	Aug	16.20	38.84393428	1.49733502	29.72	755.0906	75.33871
	Sep	15.44	64.10373123	1.47064629	29.72	755.9432	76.3
	Oct	24.68	22.99394286	1.16509153	28.50	756.8044	80.1129
	Nov	29.03	20.89796721	1.30049247	28.43	757.4075	70.21667
	Dec	35.36	67.52387932	1.53445071	26.70	759.3901	65.20968
2018	Jan	37.65	839.0177799	1.18999748	27.82	757.669	69.95161
	Feb	46.84	1741.053034	1.2369806	27.70	759.0964	69.75
	Mar	25.05	3982.0664	1.28444914	29.63	757.4832	72.82258
	Apr	25.51	62.77443186	1.24237933	29.46	757.0746	74.85
	May	20.23	26.64508518	1.33026787	29.72	756.5266	77.32258
	Jun	18.33	7.23919748	1.66000055	29.98	755.1875	75.01667
	Jul	19.20	6.736872103	1.61543427	29.38	754.2561	75.64516
	Aug	17.33	0	1.89225652	28.95	754.6576	77.3172
	Sep	21.12	25.76251573	1.972327	28.95	756.0821	79.11667
	Oct	25.78	29.40031467	1.75195202	29.08	758.1872	77.29032
	Nov	35.84	38.07088747	1.339624	29.28	758.4936	68.13333

Year	Month	$PM_{2.5}$, con (ug/m3)	Q (ton/mon)	WS (m/s)	Temp (ºC)	P (mmHg)	RH (%)
	Dec	41.45	10.46651202	1.34834113	29.03	758.7744	66.70968
2019	Jan	45.65	1893.803969	1.36536629	28.17	759.7864	64.43548
	Feb	26.06	2394.756378	1.50619875	29.84	759.2299	72.03571
	Mar	22.75	4522.998992	1.84904832	30.52	757.777	72.37097
	Apr	17.07	103.8177583	2.3834982	32.05	756.3702	71.31667
	May	22.43	75.04752232	1.87303401	31.49	755.2607	69.59677
	Jun	13.86	32.99768488	1.66336893	30.39	755.1168	75.15
	Jul	18.08	33.75279297	1.81839359	29.85	755.5072	72.54839
	Aug	15.62	3.790764185	2.057776	29.35	754.6902	75.01613
	Sep	24.93	48.82323678	1.44103451	28.96	757.0535	77.56667
	Oct	23.21	34.64563985	1.31893965	29.45	757.925	74.675
	Nov	33.32	88.74081131	1.34166481	29.58	757.925	74.5
	Dec	35.34	104.5202421	1.36587956	29.45	757.925	74.4185

Table B6 Data for $PM_{2.5}$ Prediction Model Development (Model II)

Year	**Month**	**PM2.5, con (ug/m3)**	**Qall (ton/mon)**	**WS(m/s)**	**Temp (oC)**	**P (mmHg)**	**RH (%)**	**Hotspot**
2017	Jan	37.40	911.0308467	1.45492192	28.10	758.6616	73	141.10
	Feb	45.31	4238.133578	1.41404054	28.93	759.2156	62.42857	656.40
	Mar	29.89	5694.749871	1.81839359	30.38	757.5318	73.12903	882.00
	Apr	26.33	153.0867567	1.68051711	30.99	756.9321	71.1	23.71
	May	19.93	8.831007042	1.34864537	29.97	755.7482	80.77419	1.37
	Jun	16.72	5.595748173	1.53475793	30.11	755.353	76.03333	0.87
	Jul	15.95	6.89401729	1.65272772	29.26	755.3129	77.45161	1.07
	Aug	16.20	38.84393428	1.49733502	29.72	755.0906	77.87097	6.02
	Sep	17.44	78.10373123	1.37064629	29.72	755.9432	78.43333	12.10
	Oct	24.68	22.99394286	1.16509153	28.50	756.8044	81.41935	3.56
	Nov	29.03	20.89796721	1.60049247	28.43	757.4075	72.06667	3.24
	Dec	35.36	67.52387932	1.73445071	26.70	759.3901	65.93548	10.46
2018	Jan	37.65	839.0177799	1.18999748	27.82	757.669	72.03226	161.10
	Feb	46.84	1741.053034	1.4369806	27.70	759.0964	72.71429	334.30
	Mar	31.05	5008.0664	1.72844491	29.63	757.4832	76	961.60
	Apr	25.51	62.77443186	1.54237933	29.46	757.0746	77.6	12.05

Year	Month	PM2.5, con (ug/m3)	Qall (ton/mon)	WS(m/s)	Temp (oC)	P (mmHg)	RH (%)	Hotspot
	May	20.23	26.64508518	1.33026787	29.72	756.5266	78.67742	5.12
	Jun	18.33	7.23919748	1.66000055	29.98	755.1875	76.6	1.39
	Jul	19.20	6.736872103	1.61543427	29.38	754.2561	77.32258	1.29
	Aug	17.33	0	1.79225652	28.95	754.6576	78.96774	0.00
	Sep	21.12	25.76251573	1.372327	28.95	756.0821	81.76667	4.95
	Oct	25.78	29.40031467	1.25195202	29.08	758.1872	80.16129	5.65
	Nov	35.84	38.07088747	1.339624	29.28	758.4936	71.2	7.31
	Dec	41.45	10.46651202	1.34834113	29.03	758.7744	70.09677	2.01
2019	Jan	57.65	2463.803969	1.26536629	28.17	759.7864	67.83871	371.10
	Feb	26.06	2394.756378	1.90619875	29.84	759.2299	73.82143	360.70
	Mar	25.75	7168.998992	2.14904832	30.52	757.777	74.90323	1079.80
	Apr	21.07	403.8177583	2.0834982	32.05	756.3702	73.23333	60.82
	May	24.43	95.04752232	1.77303401	31.49	755.2607	71	14.32
	Jun	16.86	64.99768488	1.66336893	30.39	755.1168	77.06667	9.79
	Jul	18.08	33.75279297	1.81839359	29.85	755.5072	74.51613	5.08
	Aug	15.62	3.790764185	2.057776	29.35	754.6902	77.58065	0.57
	Sep	24.93	58.82323678	1.44103451	28.96	757.0535	80.7	8.86
	Oct	27.21	59.64563985	1.31893965	29.45	757.925	77.55	8.98

Year	Month	PM2.5, con (ug/m3)	Qall (ton/mon)	WS(m/s)	Temp (oC)	P (mmHg)	RH (%)	Hotspot
	Nov	33.32	78.74081131	1.34166481	29.58	757.925	77.55	11.86
	Dec	38.34	131.5202421	1.36587956	29.45	757.925	77.55	19.81

Table B7 The Results of Box Model

BOX model										
Year	C_0 (μg/m^3)	Emission Inventory				L	H	μ	BKK Area (m^2)	C
		q (μg/s)			q					
		On-road	Open burning	Total q						
		q (1); (Ton/yr)	q (2); (Ton/yr)	q; (μg/s)						
2017	18	18748	11247	951,126,165	0.6062	39610.60464	1011	1.58000	1,569,000,000	33.03
2018	18	19318	7795	859,756,537	0.5480	39610.60464	1011	1.58000	1,569,000,000	31.59
2019	18	19824	12958	1,039,490,463	0.6625	39610.60464	1011	1.58000	1,569,000,000	34.43
2020	18	20720	22252	1,362,649,696	0.8685	39610.60464	1011	1.58000	1,569,000,000	39.54

BIOGRAPHY

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Academic Background	Bachelor of Science Second Class Honors (Environmental Health) Second Class Honors, Huachiew Chalermprakiet University, Thailand in 2006 Master's Degree of Engineering in the field of Environmental Engineering, King Mongkut's University of Technology Thonburi, Thailand in 2008
Experience	2008, Environmetal and Sanitation Department of Phra Nakhon District. 2008 - 2010, Environmetal and Sanitation Department of Sai Mai District. 2010 - 2016, Environmetal and Sanitation Department of Wang Thong Lang District. 2016 - Present, Air Quality and Noise Management Division, Department of Environment.