Master's Thesis of Science

Analysis of difference in particulate matter concentration between urban and road monitoring stations in Seoul

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February 2020

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Abstract

Environmental concern associated with air pollution is increasing in Seoul, Korea. Much effort has been made to improve the air quality, but road generated particulate matter (PM) concentration still accounts for a significant portion of the Seoul PM concentration. To take reduction measurements, it is essential to understand temporal and spatial characteristics of particulate matters as well as their sources. In this study, PM_{10} and $PM_{2.5}$ concentrations measured at 25 urban and 15 road air quality monitoring stations in Seoul were compared in monthly and diurnal differences. Also, the concentrations of PM_{10} and $PM_{2.5}$ were analyzed relative to other gaseous pollutants (CO, NO_2, SO_2, and O_3). Pearson correlation analysis showed that the road generated gaseous emissions and combustion sources were major contributions to the PM level. Additionally, in a case study, the average hourly PM_{10} concentrations difference between Dongjak-dearo road and Dongjak-gu urban AQM station was correlated to the hourly traffic changes in R^2=0.84 and R^2=0.54 during summer and winter, while for $PM_{2.5}$ concentrations, the correlation was equal to R^2=0.76 and R^2=0.12 in summer and winter, respectively. To prevent poor air quality periods in Seoul, measures including winter time traffic control, especially during the rush hours, should be designed to mitigate PM emissions as local source.

Keywords: Particulate matter, Seoul, temporal variation, traffic volume

Student number: 2017-21390

Chapter 1. Introduction

1.1. Study Background

Particulate matter (PM) is an air pollutant generated from a mixture of particles that floats in the air. Properties of PM depend on the particle size, measure in aerodynamic diameter (Pope III et al., 2004). Common indicators of PM are related to health effects which refer to the mass concentration of particles with a diameter of less than 10 μm (PM_{10}) and of particles with a diameter of less than 2.5 μm (PM2.5) (Pope III and Dockery, 2006). A mixture of PM varies by locations having different physical and chemical characteristics (Pope III and Dockery, 2006; Yin and Harrison, 2008).

PM classified into primary air pollutants emitted directly from the source and secondary air pollutants produced by chemical reaction in the atmosphere. In general, primary air pollutants are PM larger than 2.5 μm in diameter, caused by mechanical frictional mechanisms, such as particles generated at construction sites and dust worn by automobile brakes. Particle smaller than 2.5 μm in diameter are otherwise known to be caused by chemical reactions

(Seinfeld and Pandis, 2016). Soot (primary air pollutants) from diesel engine combustion, or transportation combustion generated pollutants such as carbon, nitrate and sulfate particles (secondary air pollutants) produced by the reaction of gaseous oxidizer in the atmosphere are the main components and precursors of PM. These air pollutants are known to be related to numerous social and economic concerns, such as public health, traffic congestion from visibility diminishing, mechanical failure in facilities, and deterioration of plant growth (Dockery, and Stone, 2007; Lim et al., 2010; Whiteman et al., 2014). As such, PM in urban areas is a major concern to the government and the public.

Seoul Metropolitan Area (SMA) and Seoul city make up only 11.9% and 0.7% of the total land area of Korea, yet they account for 49.7% and 19.8% of the total population in 2017, respectively (City of Seoul, 2018; KOSTAT, 2018). However, 44% and 15% of national total vehicles were registered in SMA and Seoul, separately (City of Seoul, 2018; KOSTAT, 2018); and the total registered vehicles number was over 22.53 million as of December 2017 (Ministry of Land, Infrastructure and Transport, 2018). This growing level of urbanization and transportation has become one of the main factors that contributes to the environmental issues associated with air pollution in the capital city (Kim et al., 2007; Kim and Lee, 2018).

To take countermeasure this issue, Korean Government has enforced the "Special Act on the Improvement of Air Quality in Seoul Metropolitan Area" in 2005 and based on the Act, the "First Seoul Metropolitan Air Quality Control Master Plan" was implemented from 2005 to 2014. More than 90% of the budget went to the reduction of the emissions from diesel vehicles. The Second Plan is in operation from 2015 to 2024. In addition to First Plan objectives of PM_{10} and NO_2, $PM_{2.5}$ and O_3 are included as target species. The goals are to achieve the annual average concentrations of 30 μg m–3 for PM_{10}, 20 μg m–3 for $PM_{2.5}$, 21 ppb for NO_2, and 60 ppb for O_3 (8 hrs) in Seoul by 2024, respectively (MOE, 2016).

According to National Institute of Environmental Research (2012), regardless of foreign air pollution source, locally emitted air pollution concentration in Seoul is attributable to vehicle pollutants by 66.9%. As a result of the Seoul city government efforts to improve air quality by strengthening legislations, introduction of new fuels and modified technologies some air pollutants, such as sulfur dioxide (SO_2) and carbon monoxide (CO) have been reduced to low levels (Kim et al., 2010; Kim and Shon, 2011; Kim and Lee, 2018), however average concentration of particulate matter (PM10) still exceeds the daily healthy standard (Korean Ministry of Environment, 2009, Ahmed et al., 2015). In the past, a number of studies (e.g., Bae et al., 2007; Kim and Guldmann, 2011; Kim et al., 2017; Kim and Lee, 2018) have explored impact of automobile emissions to the air quality; though little attention has been given to the exploration on PM_{10} diurnal cycle and its relations with the traffic load which changes extensively in hourly basis.

Vehicles emit PM from the exhaust pipe and PM generated from tire wear, brake-wear and vehicle-induced resuspension of road all contribute to roadside PM_{10} concentration level (WHO, 2013). During this time of PM_{10} formation, metrological conditions such as temperature, humidity, and wind speed varies in the atmosphere, resulting temporal variations in emission level. In addition, concentrations of PM_{10} and $PM_{2.5}$ can spatially vary. Depending on the emission source type, some PM of short atmospheric residency often falloff significantly across the space of just a few meters while other some PM emission level persists across several kilometers. For instance, Pakbin et al., (2010) described that, in case of Los Angeles metropolitan city, strong consistency in PM concentration levels between air quality sites over 5 km apart, due to same source intensity and type. However, some other studies have shown that depending on geographical difference, there were diverging concentrations, highlighting the influence of common meteorology but different emissions sources and intensities (Chow et al., 2002; Wilson et al., 2006; Qadir et al., 2014).

1.2. Research Purpose

Vehicle emissions are responsible for the spatially different air pollution levels in the urban atmosphere, whereas the rural atmosphere is relatively well mixed (Shallcross et al., 2009; Harrison, 2018). Road generated pollutants along with stable atmospheric conditions with a low mixing layer height during the certain period of day and months results in significantly enhanced PM concentrations in Seoul (Kim et al., 2010). Number of studies (e.g., Kim & Guldman, 2011; Jeong & Lee, 2018; Park & Ko, 2018) have shown positive relationship between number of vehicles and air pollutant concentration levels in Seoul, though the study timeline were confined to short period (few days or a week). In this study, based on recent available hourly data on both PM_{10} and $PM_{2.5}$, monthly and diurnal average variations of PM concentration are examined to provide a comparative overview of PM concentration at different types of air quality monitoring stations in Seoul. Also, the relationship between PM_{10} and $PM_{2.5}$ levels as well as their association with other gaseous air pollutants are analyzed to trace vehicle emission sources. Lastly, to inspect relation between traffic volume and PM concentrations, the diurnal traffic changes recorded at a certain study area is comparatively reviewed with the diurnal variation of PM_{10} and $PM_{2.5}$ concentrations.

Chapter 2. Data and method

2.1. Air Pollution Data

There are in total of 40 AQM stations distributed in Seoul (Fig. 1), of which 25 AQM stations are located at each district and classified as urban measuring stations; remaining 15 AQM stations are located near major roads and classified as road air pollution measuring stations (MOE, 2019). Also, three national level background AQM stations pollution data are included (Table 1). Hourly air pollution concentrations are regularly measured at these AQM stations. Air pollutants of carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone (O_3) concentrations are measured in parts per billion (ppb). Concentrations for particulate matter less than10 (PM_{10}) and particulate matter 2.5 less than ($PM_{2.5}$) are measured in microgram per cubic meter ($\mu g/m^3$). For urban AQM stations, pollutant sampling instruments are placed away from main roads, on top of two−to−three story public offices and not disturbed by any physical barriers such as buildings or trees, according to KMOE report. In contrast, road AQM stations are positioned at around above 2−meter height of each road. These monitoring tools operate based of on the β–ray absorption method (Model FH62C14) and are routinely inspected every month (MOE, 2015).

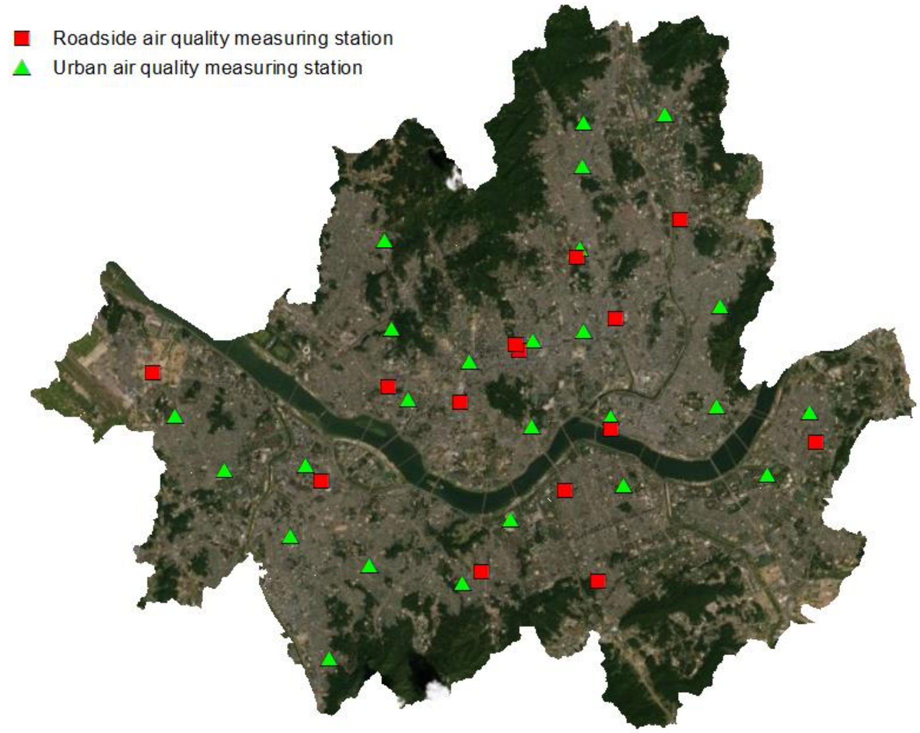

Figure 1. Locations of two types of air quality measuring stations in Seoul.

Table 1. Locations and categories of air quality monitoring stations.

	AQM location	Station name	Code	Station category	Long (°E)	Lat (°N)
1	Seoul	Jung-gu	111121	Urban	126.97	37.56
2	Seoul	Jongno-gu	111123	Urban	127.01	37.57
3	Seoul	Yongsan-gu	111131	Urban	127.00	37.54
4	Seoul	Gwangjin-gu	111141	Urban	127.09	37.55
5	Seoul	Seongdong-gu	111142	Urban	127.04	37.54
6	Seoul	Jungnang-gu	111151	Urban	127.09	37.58
7	Seoul	Dongdaemun-gu	111152	Urban	127.03	37.58
8	Seoul	Seongbuk-gu	111161	Urban	127.03	37.61
9	Seoul	Dobong-gu	111171	Urban	127.03	37.65
10	Seoul	Eunpyeong-gu	111181	Urban	126.93	37.61
11	Seoul	Seodaemun-gu	111191	Urban	126.94	37.58
12	Seoul	Mapo-gu	111201	Urban	126.95	37.55
13	Seoul	Gangseo-gu	111212	Urban	126.84	37.54
14	Seoul	Guro-gu	111221	Urban	126.89	37.5
15	Seoul	Yeongdeungpo-gu	111231	Urban	126.90	37.53
16	Seoul	Dongjak-gu	111241	Urban	126.97	37.48
17	Seoul	Gwanak-gu	111251	Urban	126.93	37.49
18	Seoul	Gangnam-gu	111261	Urban	127.05	37.52
19	Seoul	Seocho-gu	111262	Urban	126.99	37.5
20	Seoul	Songpa-gu	111273	Urban	127.12	37.52
21	Seoul	Gangdong-gu	111274	Urban	127.14	37.55
22	Seoul	Geumcheon-gu	111281	Urban	126.91	37.45
23	Seoul	Gangbuk-gu	111291	Urban	127.01	37.65
24	Seoul	Yangcheon-gu	111301	Urban	126.86	37.53
25	Seoul	Nowon-gu	111311	Urban	127.07	37.66
26	Seoul	Hangang-daero	111122	Road	126.97	37.55
27	Seoul	Cheonggyecheon-ro	111124	Road	127.00	37.57
28	Seoul	Jongno	111125	Road	127.00	37.57
29	Seoul	Gangbyeonbuk-ro	111143	Road	127.01	37.54
30	Seoul	Hongneung-ro	111154	Road	127.04	37.58
31	Seoul	Jeongneung-ro	111162	Road	127.03	37.6
32	Seoul	Sinchon-ro	111202	Road	126.94	37.56
33	Seoul	Gonghang-daero	111213	Road	126.82	37.52
34	Seoul	Yeongdeungpo-ro	111232	Road	126.90	37.52
35	Seoul	Dongjak-ro	111242	Road	126.98	37.49
36	Seoul	Dosan-daero	111263	Road	127.04	37.48
37	Seoul	Gangnam-daero	111264	Road	127.04	37.48
38	Seoul	Cheonho-daero	111275	Road	127.14	37.53
39	Seoul	Hwarang-ro	111312	Road	127.08	37.62
40	Seoul	Siheung-daero	111282	Road	126.90	37.48

41	Incheon	Baengnyeong−do	831492	Background	124.63	37.96
42	Ulleung−do	Taeha−ri	437541	Background	130.80	37.52
43	Jeju−do	Gosan−ri	339312	Background	126.16	33.29

2.2. Traffic Data

Transport Operation and Information Service (TOPIS) of Seoul city operates and manages the entire traffic of the city by collecting hourly traffic information through unmanned surveillance system. In total of 135 traffic data collection tools are set up at around a height of 3 meter of roadside street light poles. Passing vehicles from both inward and outward flows are sensed by inductive−loop detection network system which then send information to the main operating system where data collection and analysis take place (TOPIS, 2018). The available data set and its annual report book are downloaded from the website of Seoul Open Data Plaza.

2.3. Method

In this study, hourly air pollution data collected at urban, road and background AQM stations are comparatively analyzed. Due to $PM_{2.5}$ data availability at both urban and road AQM stations, scarcely starting from February 2018, we confined the study period from March 1st, 2018 to February 28th, 2019. To provide an overview of PM behavior in Seoul, first average monthly and diurnal variations of PM_{10} and $PM_{2.5}$ at urban, road, and background stations are estimated and the temporal patterns are compared to other gaseous pollutants trends. Second, Pearson correlation analysis between PM and CO, NO_2, SO_2, and O_3 are presented. Then, lastly, we have created 1 km radii buffer zone around each 40 AQM stations located in Seoul (Fig. 2) to find a case study area where it's possible to evaluate effects of traffic intensities on neighboring road and urban AQM stations, because 1 km is a decaying distance of moving sources like vehicles (Shallcross et al., 2009; Wood et al., 2009; Wood et al., 2015; Harrison, 2018). As a result, Yeondeungpo-gu, Seongdong-gu and Dongjak-gu urban and road AQM stations found to be located 1 km adjacent to each other. Among them, considering the number of actively operating manufactories in each district (gu), Dongjak-gu is chosen to be the appropriate case study area. About 39 factories were recorded in Dongjak-gu, whereas 838 and 1348 factories were found in Yeondeungpo-gu and Seongdong-gu, respectively (FactoryON, 2019).

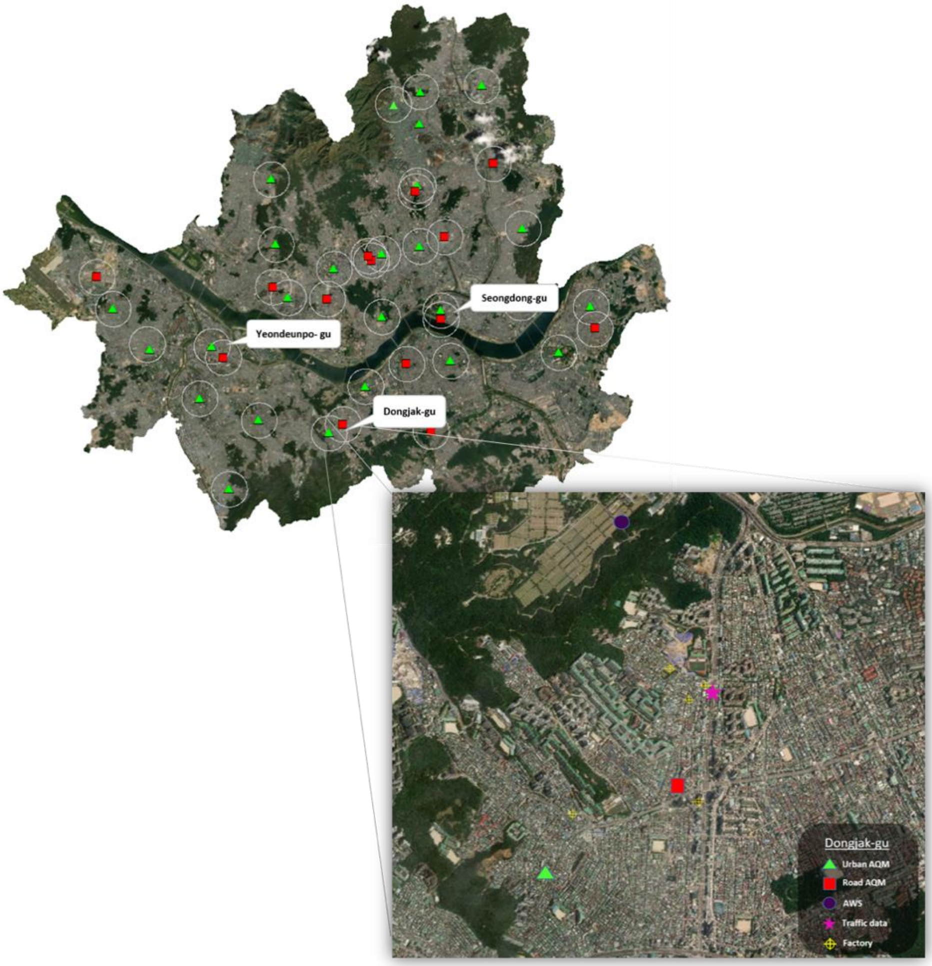

Figure 2. Dongjak-gu urban and road AQM stations locations, and the nearest traffic collecting point and automated weather station (AWS).

Chapter 3. Result

3.1. Temporal variations of particulate matter

3.1.1. Monthly particulate matter variation

Monthly average PM_{10} and $PM_{2.5}$ concentrations calculated for each month for all stations are shown in Fig. 3a, Fig. 3b, and in Fig. 3c their concentration difference measured at road and urban AQM are presented. Pollutant concentrations for all stations in July, August and September are the lowest, resulting less than 30 μg/m^3 for PM_{10} and 20 μg/m^3 for $PM_{2.5}$. This is mainly attributed to increased temperature leading to higher height in boundary mixing layer and particle removal through wet deposition during monsoon in Seoul. Particulate matter increase notably from November to March. During colder months, the mixing layer height become low and the atmospheric dispersion is reduced because of frequent temperature inversions. PM_{10} average concentrations measured at road, urban and background AQM stations ranging between 45−65 μg/m^3, 43−52 μg/m^3, and 31−48 μg/m^3, respectively; and $PM_{2.5}$ average concentrations measured at the same AQM stations resulted between

26−37 μg/m^3, 24−38 μg/m^3, and 17−25 μg/m^3, respectively. Overall, winter months have poor air qualities and summer have good air quality, showing persistent concentration lower than 50 μg/m^3 levels. In Fig 3c, the difference between the concentration of PM_{10} and $PM_{2.5}$ measured at road and urban AQM stations in July, August, and September were constant, but in winter months the concentration differences were not significant. The concentration of PM in winter seems to be greatly affected by external pollutants.

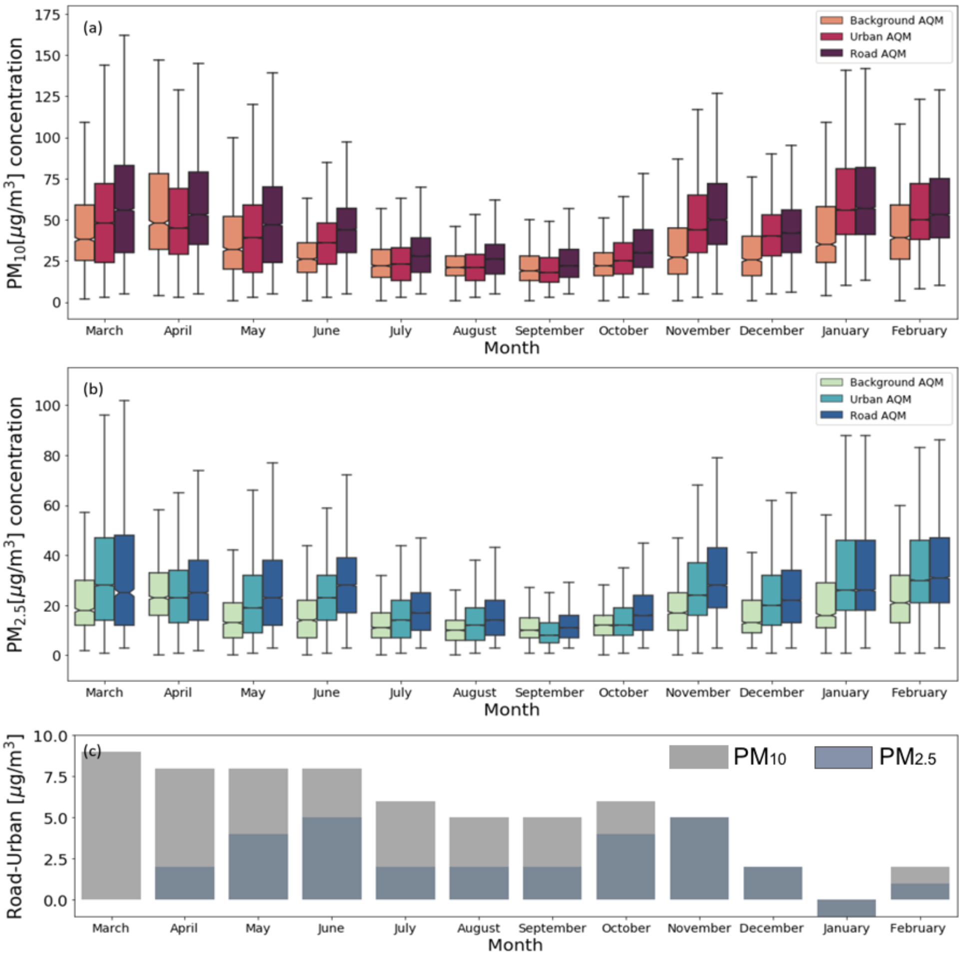

Figure 3. Monthly variation of particulate matter measured at background, urban and road AQM stations: (a) PM_{10}, (b) $PM_{2.5}$ and (c) the monthly average concentration difference between road and urban AQM stations. In 3a and 3b, the median value is indicated at central narrow mark, the top and bottom edges of the box indicate 75t[h] and 25[th] percentiles, respectively. In 3c, road and urban AQM stations monthly average concentration difference for PM_{10} and $PM_{2.5}$ is shown.

Road AQM stations mostly observed to be the highest concentration throughout the year, followed by urban and background stations, except for April when the sandstorms days were recorded. Hourly continuous sandstorm events were recorded in April 6th and 14−15th, May 14th, and November 27−28th (KMA, 2019). Maximum PM_{10} concentrations measured at background station reached 398 $\mu g/m^3$, 148 $\mu g/m^3$, and 461 $\mu g/m^3$ in April, May and November, respectively; and maximum $PM_{2.5}$ were resulted 103 $\mu g/m^3$, 75 μg/m3, and 113 μg/m3 concentration at the same months. Evidently the average PM concentration at background stations for these months display relatively higher values, especially in April when background PM_{10} concentrations surpassed the urban PM_{10} concentrations.

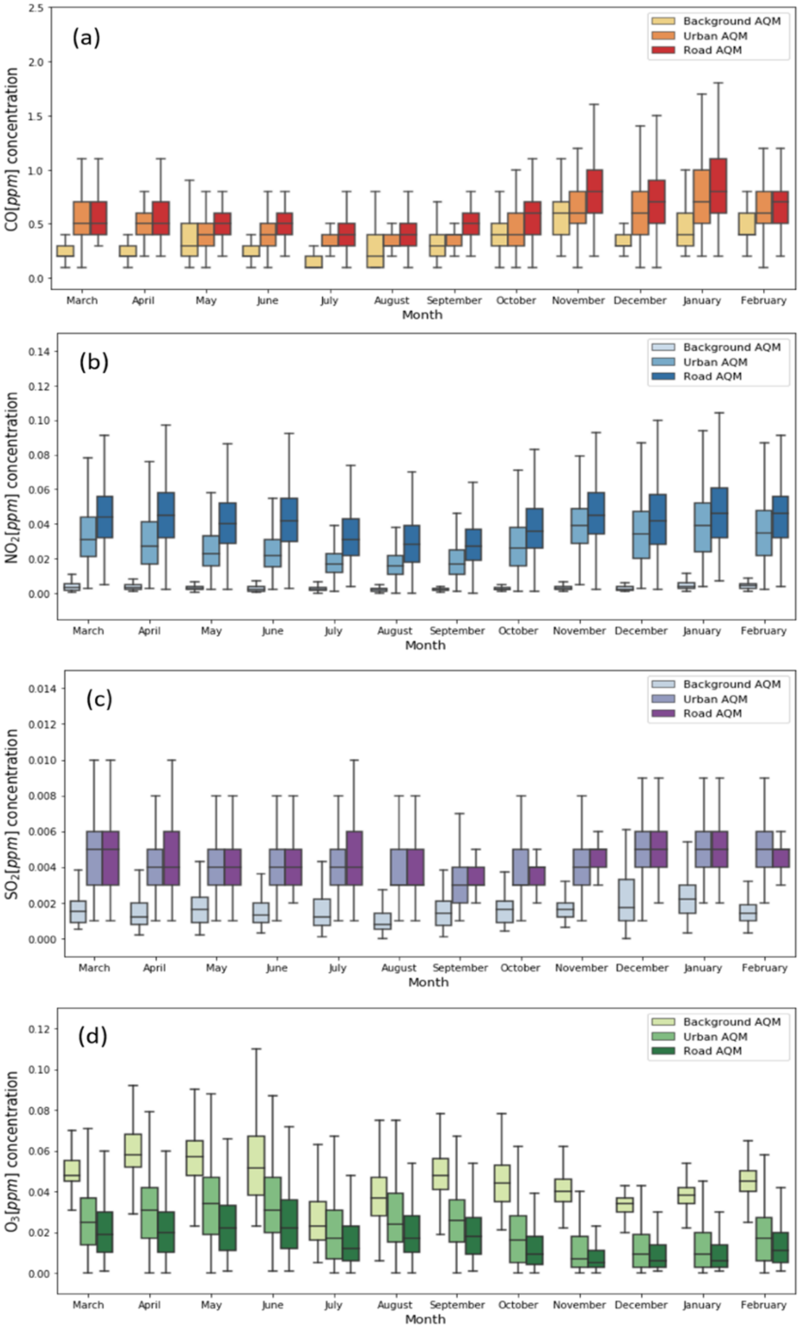

Figure 4. Monthly variation of each gaseous pollutant at three types of AQM stations: (a) CO, (b) NO_2, (c) SO_2 and (d) O_3.

3.1.2. Diurnal particulate matter variation

Concentrations of road generated pollutants generally surpass those in the residential urban background which then leads to directly influence concentrations measured in surrounding areas (Harrison, 2018), depending on the atmospheric conditions. Atmospheric mixing layers are typically greater during daytime than nighttime (Wood et al., 2009, Mahrt, 2011) and accordingly air pollution level sampled during daytime was higher than that of nighttime in our study. Diurnal variations of hourly average PM_{10} and $PM_{2.5}$ mass concentrations at 25 urban AQM, 15 road AQM, and 3 national background AQM stations over a year period from March 1, 2018 to February 28, 2019 are presented in Fig. 5.

Noticeable fluctuations of PM concentrations observed from road AQM stations which contribute highest concentration levels in the overall diurnal cycle. Though the concentration of each station is distinctive, urban and road stations show increasing PM_{10} concentration trend in the morning between 6am−10am and peaking at 11am, followed by two peaks at 3pm and 9pm (Fig. 5a). Also, the urban and road AQM stations diurnal patterns of $PM_{2.5}$ concentrations present similar trend, intensifying between 6am−11am, and subsiding at around 9pm−10pm (Fig. 5b). Average diurnal PM_{10} concentration measured from road and urban AQM stations ranged between 41−53 μg/m^3 and 37−44 μg/m^3, respectively. Average diurnal $PM_{2.5}$, concentrations were between 25−28 μg/m^3 and 23−25 μg/m^3, at road and urban AQM stations, respectively. As shown in Fig. 5c, during the rush hour times, PM_{10} concentration difference between road and urban stations is significantly higher than that of $PM_{2.5}$.

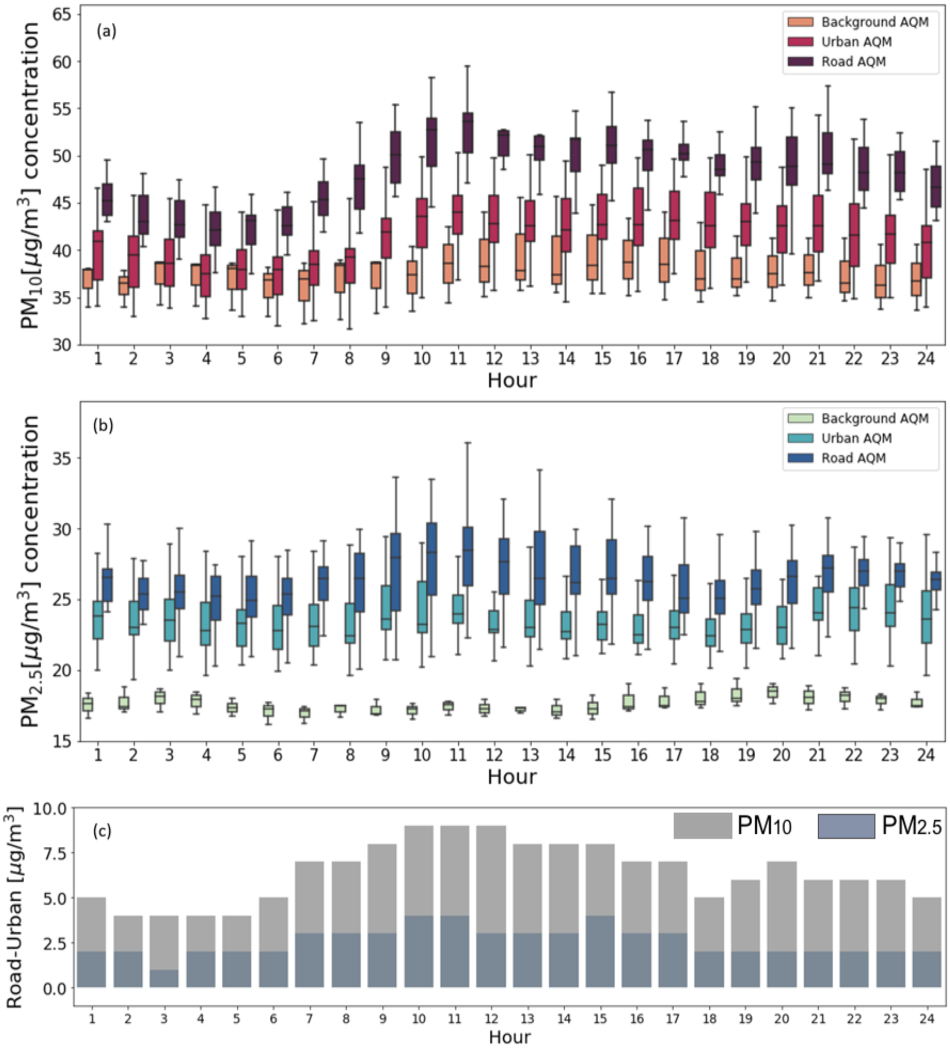

Figure 5. Average diurnal particulate matter variation at three types of AQM stations: (a) PM_{10}, (b) $PM_{2.5}$ and (c) the hourly average concentration difference between road and urban AQM stations. In 5a and 5b, the median value is indicated at central narrow mark, the top and bottom edges of the box indicate 75th and 25th percentiles, respectively. In 5c, road and urban AQM stations hourly average concentration difference for PM_{10} and $PM_{2.5}$ is

Diurnal variation of background stations, located far away from anthropogenic activities, resulted in different patterns. PM_{10} levels in the background monitoring stations clearly depicts planetary boundary layer (PBL) trend. PBL generally starts to form after sunrise followed by increase in temperature and wind speed, and then reaches the peak around afternoon (Harrison, 2018). The highest PM_{10} concentration value for background station was about 40 μg/m^3 occurring at 1pm. And the average $PM_{2.5}$ levels showed weak changes having minimum and maximum values fluctuated between 17–19 μg/m^3.

Local emissions dominated CO, NO_2, and SO_2 concentrations throughout the day, especially during the transportation rush hour as shown in Fig. 6a–c. Their diurnal changes measured at road and urban AQM stations were significantly characterized by two traffic peaks around 7am–9am and 6pm–7pm, while background concentration showed no particular changes. Notably, the road AQM stations PM_{10} and $PM_{2.5}$ diurnal variations were comparable to both road and urban stations CO, NO_2, and SO_2 diurnal cycles, suggesting the influence of traffic sources on PM levels in Seoul.

CO is produced during the process of incomplete combustion of carbon containing fuels, as a consequence traffic flows have a substantial positive impact on CO levels. For NO_2, more than 90% of nitrogen mixtures are emitted in the form of nitric oxide (NO), and the rest is directly emitted in form on NO_2 (Derwent and Hertel, 1998) from the tail pipe of a car. But because NO mostly reacts with O_3 and other radicals during daytime, within seconds after its discharge from motors, NO is converted to NO_2 (Artinano et al, 2004). In case of SO_2, it has been noted (Kim and Guldmann, 2011) that diesel cars are the main source of SO_2 concentration in urban areas of Korea and usually found to be high levels nearby roadsides. This is mainly due to price difference of gasoline and diesels in Korea. Lastly, among the four gaseous air pollutants, O_3 displays reverse diurnal variation measured at three AQM stations in Fig. 6d. As expected, this opposite O_3 patter of road concentrations being lower than urban and background AQM stations occurs when roadsides are heavily traveled by motor vehicles (Jo and Park, 2005).

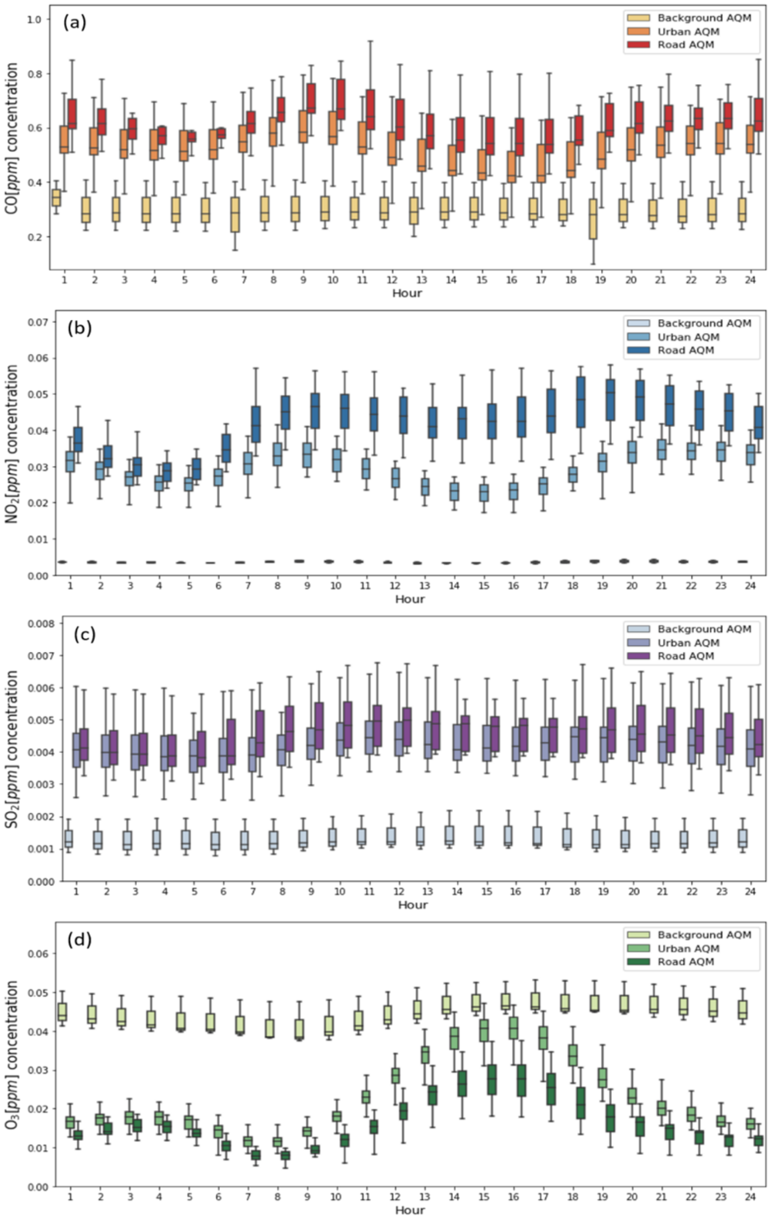

Figure 6. Average diurnal variation of each gaseous pollutant at three types of AQM stations: (a) CO, (b) NO_2, (c) SO_2 and (d) O_3. The median value is indicated at central narrow mark, the top and bottom edges of the box indicate 75th and 25th percentiles, respectively.

3.2. Relation between particulate matter and gaseous pollutions

A correlation analysis was performed with the hourly concentration data of PM_{10} and $PM_{2.5}$, and relative to other hourly gaseous pollutants data from March 2018 to February 2019 for urban and road AQM stations in Seoul (Table 2 and 3). Correlation between PM_{10} and $PM_{2.5}$ at both urban and road AQM stations were significantly high resulting more than 0.80 coefficient at most of the months, except when yellow dust days were recorded on April, May and November. For gaseous pollutants correlations, both PM correlated reasonably well with CO, NO_2 and SO_2 suggesting common road generated pollutants. The correlation between CO−$PM_{2.5}$(PM_{10}) was mostly greater than the correlations between NO_2−$PM_{2.5}$(PM_{10}), which explains the associations between PM and gasoline vehicles, in addition to combustion−related sources (Kassomenos et al. 2014). For both urban and road AQM stations CO−$PM_{2.5}$(PM_{10}) and NO_2−$PM_{2.5}$(PM_{10}) coefficients were considerably high during the colder months, when PBL gets lower and atmospheric settings favor pollutant accumulation (Chaloulakou et al. 2003). The correlation between SO_2−$PM_{2.5}$(PM_{10}) was generally greater during the cold seasons than warm seasons. CO−$PM_{2.5}$(PM_{10}), NO_2−$PM_{2.5}$(PM_{10}) and SO_2−$PM_{2.5}$(PM_{10}) correlations were greatest in December at both urban and road AQM stations. Lastly, the hourly mean O_3 concentration negatively correlated with PM_{10} and $PM_{2.5}$ in most months. This negative correlation can be explained by the reaction between O_3 and NO_2, which is a major sink of ozone. Particularly, this type of negative correlations between the particulate matter and O_3 were also found in diurnal and weekly analysis. Also, positive correlations between O_3−$PM_{2.5}$(PM_{10}) were resulted in June and July.

Table 2. Urban AQM stations: Pearson correlation coefficients between hourly $PM_{2.5}$ and PM_{10} concentrations and gaseous pollutant concentrations (PM_{10} in brackets)

Month/season	**$PM_{2.5}$-PM_{10}**	**CO-$PM_{2.5}$ (PM_{10})**		**NO_2-$PM_{2.5}$ (PM_{10})**		**SO_2-$PM_{2.5}$ (PM_{10})**		**O_3-$PM_{2.5}$ (PM_{10})**	
March	0.93	0.63	(0.64)	0.48	(0.53)	0.39	(0.45)	0.02*	(0.02*)
April	0.71	0.55	(0.32)	0.48	(0.25)	0.45	(0.32)	0.06	(0.09)
May	0.79	0.62	(0.51)	0.49	(0.45)	0.28	(0.36)	0.03	(0.22)
June	0.93	0.38	(0.37)	0.32	(0.35)	0.31	(0.30)	0.17	(0.23)
July	0.93	0.24	(0.27)	0.41	(0.42)	0.33	(0.29)	0.43	(0.40)
August	0.91	0.29	(0.28)	0.27	(0.27)	0.22	(0.23)	0.42	(0.44)
September	0.82	0.48	(0.45)	0.34	(0.34)	0.17	(0.22)	0.09	(0.13)
October	0.90	0.60	(0.54)	0.58	(0.54)	0.27	(0.28)	-0.12	(-0.08)
November	0.67	0.54	(0.25)	0.51	(0.30)	0.19	(0.14)	-0.20	(-0.13)
December	0.89	0.69	(0.59)	0.61	(0.54)	0.39	(0.34)	-0.44	(-0.34)
January	0.88	0.64	(0.50)	0.46	(0.32)	0.29	(0.21)	-0.21	(-0.08)
February	0.78	0.47	(0.36)	0.33	(0.29)	0.22	(0.21)	0.04*	(0.04*)
Spring	0.81	0.60	(0.47)	0.49	(0.41)	0.37	(0.38)	0.04	(0.11)
Summer	0.92	0.30	(0.30)	0.34	(0.35)	0.28	(0.26)	0.34	(0.35)
Autumn	0.80	0.54	(0.37)	0.48	(0.39)	0.21	(0.21)	-0.08	(-0.03)
Winter	0.85	0.60	(0.46)	0.47	(0.38)	0.30	(0.25)	-0.21	(-0.12)

All correlations are statically significant at 99% confidence interval (otherwise denoted as '*' where correlations are significant at 95% confidence level)

Table 3. Road AQM stations: Pearson correlation coefficients between hourly $PM_{2.5}$ and PM_{10} concentrations and gaseous pollutant concentrations (PM10 in brackets)

Month/ season	$PM_{2.5}$-PM_{10}	CO-$PM_{2.5}$ (PM_{10})	NO_2-$PM_{2.5}$ (PM_{10})	SO_2-$PM_{2.5}$ (PM_{10})	O_3-$PM_{2.5}$ (PM_{10})
March	0.94	0.66 (0.62)	0.45 (0.59)	0.48 (0.45)	-0.01 (-0.07)
April	0.71	0.51 (0.40)	0.51 (0.36)	0.45 (0.37)	-0.01* (0.04*)
May	0.81	0.54 (0.53)	0.43 (0.55)	0.24 (0.37)	-0.04 (0.10)
June	0.91	0.37 (0.37)	0.30 (0.38)	0.31 (0.35)	0.11 (0.10)
July	0.91	0.32 (0.36)	0.52 (0.56)	0.29 (0.28)	0.40 (0.34)
August	0.87	0.26 (0.30)	0.40 (0.46)	0.19 (0.15)	0.35 (0.31)
September	0.83	0.45 (0.51)	0.33 (0.42)	0.24 (0.28)	0.05* (0.03*)
October	0.90	0.60 (0.58)	0.56 (0.57)	0.36 (0.43)	-0.16 (-0.14)
November	0.68	0.60 (0.35)	0.40 (0.27)	0.34 (0.36)	0.20 (-0.14)
December	0.88	0.69 (0.60)	0.55 (0.51)	0.53 (0.57)	-0.47 (-0.37)
January	0.88	0.64 (0.51)	0.37 (0.29)	0.35 (0.34)	-0.20 (-0.09)
February	0.78	0.45 (0.39)	0.32 (0.34)	0.17 (0.28)	0.03* (0.03*)
Spring	0.82	0.57 (0.52)	0.47 (0.50)	0.39 (0.40)	-0.02 (0.02)
Summer	0.89	0.31 (0.34)	0.40 (0.47)	0.26 (0.26)	0.28 (0.25)
Autumn	0.80	0.55 (0.48)	0.43 (0.42)	0.31 (0.36)	0.03 (-0.08)
Winter	0.85	0.59 (0.50)	0.41 (0.38)	0.35 (0.40)	-0.21 (-0.14)

All correlations are statically significant at 99% confidence interval (otherwise denoted as '*' where correlations are significant at 95% confidence level)

3.3. Dongjak-gu case study area

3.3.1. Traffic volume and particulate matter concentration

Urban traffic trend, in general, depicts a typical megacity diurnal lifestyle where congestion intensifies early in the morning and afternoon, having two peaks. Depending on this, air pollution level in an urban area also shows similar tendency (Yin and Harrison, 2008; Pakbin et al., 2010). As such traffic emissions or emissions that directly produced by motor vehicles CO, NO_2, SO_2, and PM_{10} are closely related to transportation volume (Carslaw and Beevers, 2004; Jo and Park, 2005; Kim and Guldmann, 2011). This concept was especially true for PM_{10} and $PM_{2.5}$ concentration and the average traffic volume during summer in Seoul, as shown in Fig. 7a and 7b. Urban AQM PM_{10} and $PM_{2.5}$ concentration levels were relatively lower than roadside, as expected. In fact, the correlation between the average hourly traffic counts and difference between road and urban emission concentrations on PM_{10} and $PM_{2.5}$ resulted in R^2 of 0.84 and R^2 of 0.76, respectively (Fig. 8).

During winter months, the hourly average traffic change had impact on diurnal variations of PM_{10} measured at both Dongjak urban and Dongjak−dearo road AQM stations (Fig. 9a). PM_{10} emission levels showed three peaks in their diurnal patters, the highest concentrations occurring between 1pm to 4pm, which have close relation with the average traffic volume displayed. In case of $PM_{2.5}$, however, average concentration at urban AQM was slightly higher than road AQM and did not display significant diurnal pattern, indicating possible influence of external sources (Fig. 9b). The correlation between the average hourly traffic volume and difference between road and urban emission concentration of PM_{10} and $PM_{2.5}$ resulted in R^2 of 0.54 and R^2 of 0.12, respectively, as shown in Fig. 10.

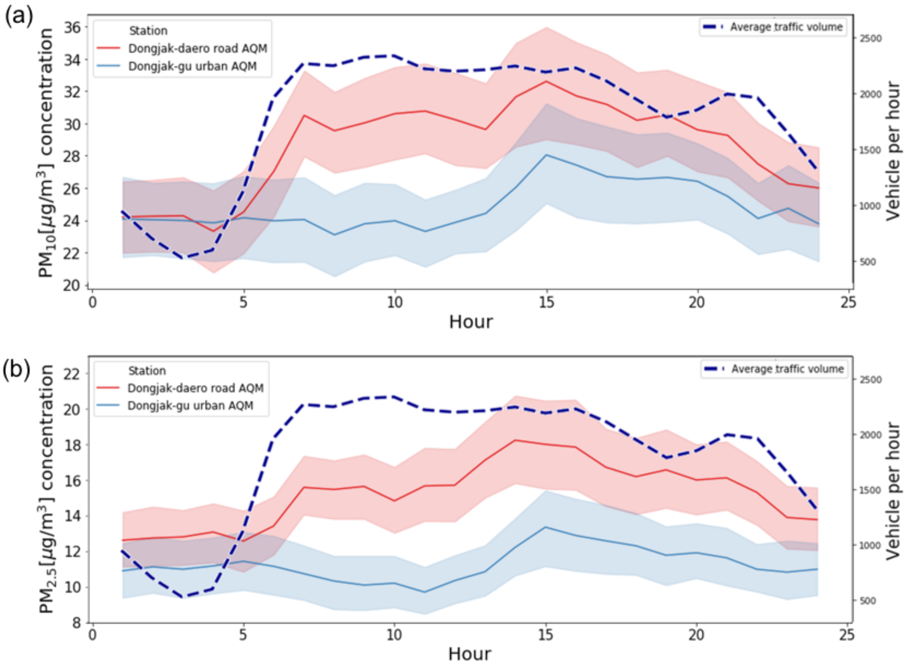

Figure 7. Diurnal variations of (a) PM_{10} and (b) $PM_{2.5}$ concentration and traffic volume during summer in Dongjak−gu.

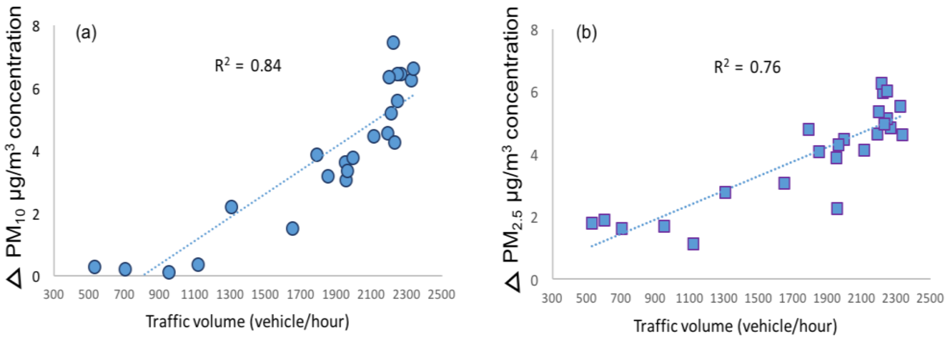

Figure 8. Correlation of average hourly traffic volume and (a) PM_{10} and (b) $PM_{2.5}$ concentration difference between road and urban AQM station in summer.

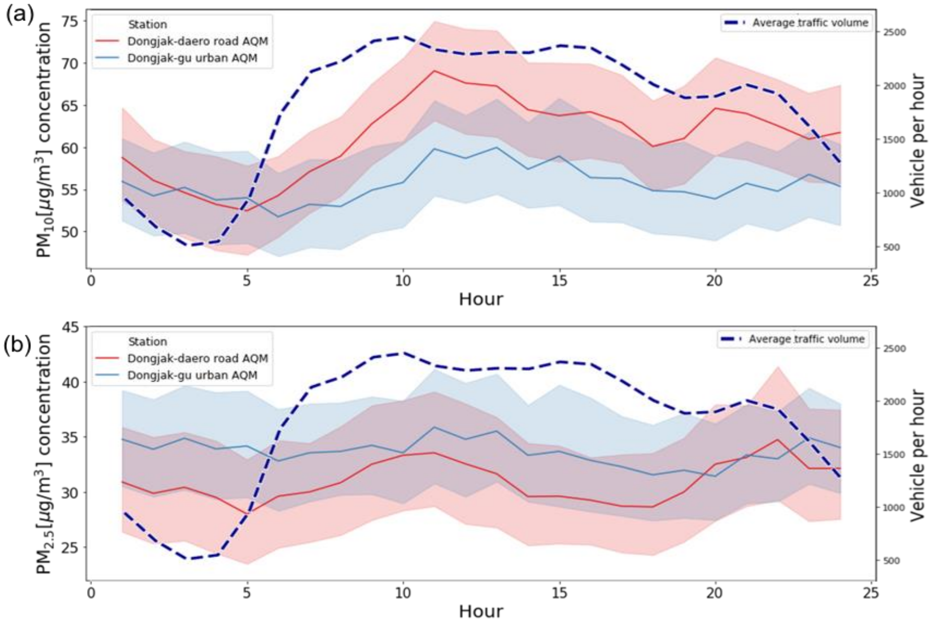

Figure 10. Diurnal variations of (a) PM_{10} and (b) $PM_{2.5}$concentration and traffic volume during winter in Dongjak−

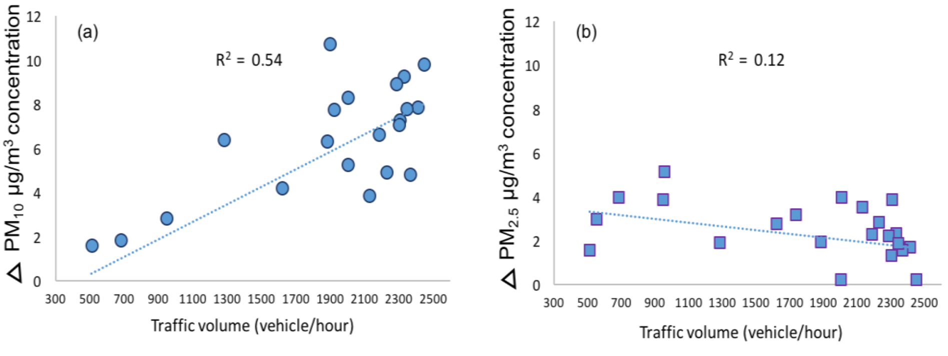

Figure 9. Correlation of average hourly traffic volume and (a) PM_{10} and (b) $PM_{2.5}$ concentration difference between road and urban AQM station in winter.

3.3.2. Evaluation of traffic restriction policy on particulate matter reduction

The Seoul Metropolitan Government have taken emergency PM reduction actions when the concentration level significantly go up. Key measures include prohibiting certain class of vehicles (emission-grade 5 vehicles) entering the Metropolitan area, extension of road cleaning and, declaring no-driving day for public fleet. In November 7th of 2018, for an instance, the city government enforced ‘The Special Act on Particulate Matter Reduction’, where the use of emission-grade 5 vehicles and parking in administrative or public agency utilities were restricted between 6am-9pm, and car owners were given 3000 mileage allowance incentives for not using their vehicles during the restriction period (MOE, 2019), as means of reducing alarming levels of PM concentration observed in the day before.

Dongjak-gu urban and road AQM stations reduction levels of PM_{10} and $PM_{2.5}$ during the traffic restriction period are shown in contrast to Incheon background AQM concentration are shown in Fig. 11. In 6^{th} of November, maximum concentration of PM_{10} and $PM_{2.5}$ reached 175 μg/m^3 and 140 μg/m^3, respectively. Between the restriction period of 6am to 9pm in November 7^{th}, PM_{10} concentrations of road an urban AQM station dropped around 45 μg/m^3 (from 110 μg/m^3 to 75 μg/m^3) and $PM_{2.5}$ concentrations also resulted drastic decline of about 40 ㎍/m^3 in road AQM and 20 ㎍/m^3 in urban AQM station. Afterwards, due to continues raining in November 8th, PM levels showed notable low levels throughout the day.

Gaseous air pollutants of CO, NO_2, SO_2, and O_3 concentrations at the study area during the vehicle restriction period are presented in Fig. 12. The red and blue color refer to road and urban emission levels while green dots indicates Incheon background emission volumes. Compare to the day before, concentration of CO, NO_2, and SO_2 in the Dongjak−dearo roadside and Dongjak−gu urban AQM both displayed declining trends while their background emissions stayed consistently rate in November 7th of 2018 (Fig. 12a−c). In case of O_3, the concentration resulted reverse trend of NO_2, due the presence of NO emission from tailpipe and photochemical reaction.

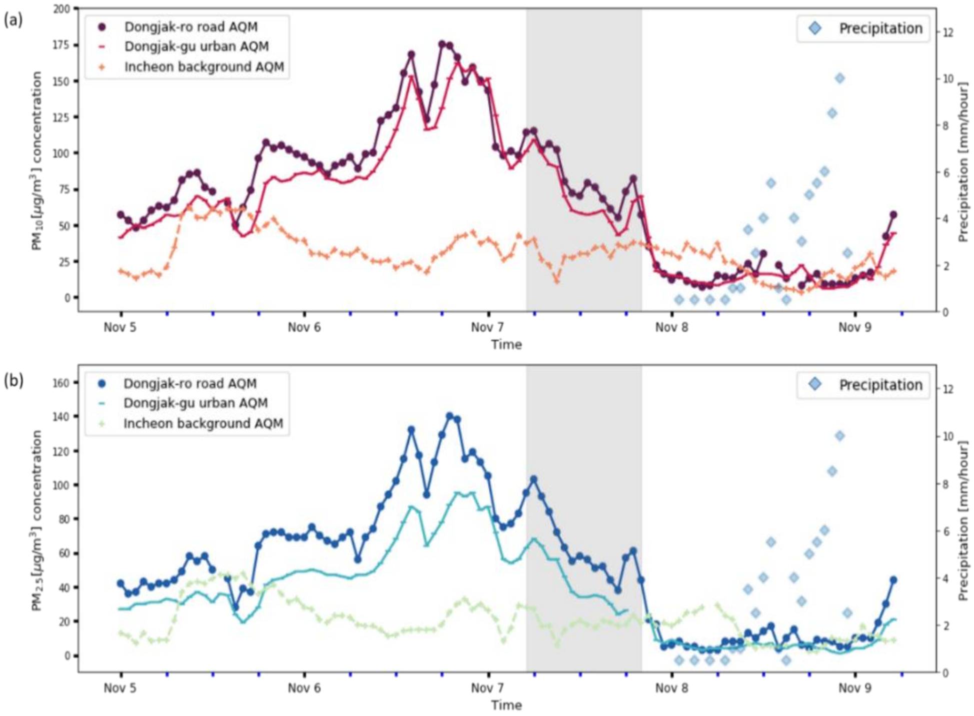

Figure 11. Dongjak–gu (a) PM_{10} and (b) $PM_{2.5}$ concentration from November 5th to November 8th of 2018. The Special Act on PM reduction was enforced on November 7th between 6am to 9pm, expressed in gray vertical band.

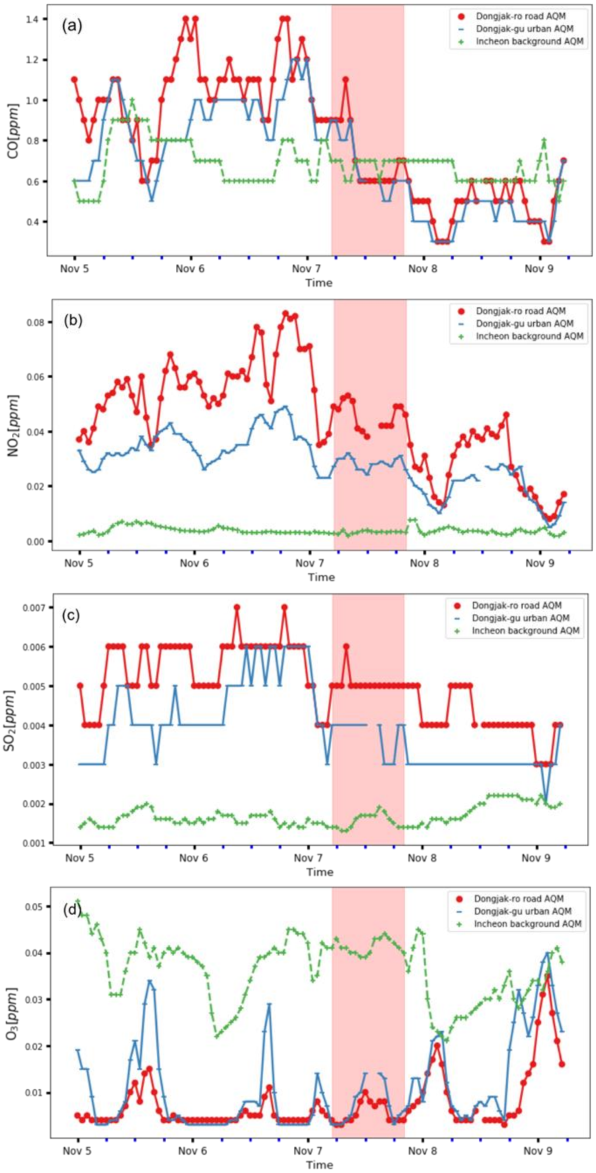

Figure 12. Dongjak-gu CO(a), NO_2(b), SO_2(c) and O_3(b) concentration from November 5th to November 8th of 2018. The Special Act on PM reduction was enforced on November 7th between 6am to 9pm, expressed in red vertical band in the each plot.

Chapter 4. Conclusion

Based on recent available PM_{10} and $PM_{2.5}$ data collected at urban and road air quality monitoring stations, monthly and diurnal variations of PM concentration from 43 hourly monitoring stations are examined to estimate the spatial and temporal variations of PM level in Seoul. In summer months, the average PM_{10} and $PM_{2.5}$ concentrations were consistently measured higher in roadside AQM stations than in urban AQM stations, while in the winter the concentration differences were not significant. Diurnal variation of both PM show that in the morning at around 6am−11am and in the late evening at around 7pm−9pm have the poor air qualities. The average PM_{10} concentration difference between road and urban stations displayed a patter that is similar to a diurnal traffic changes where two peaks occur during the rush hours, while that of the average $PM_{2.5}$ emission stayed relatively consistent. Additionally, the correlation between CO−$PM_{2.5}$(PM_{10}), NO_2−$PM_{2.5}$(PM_{10}) and SO_2−$PM_{2.5}$(PM_{10}) correlations were generally greater during the cold months while O_3−$PM_{2.5}$(PM_{10}) correlation was higher during the warm season. In the case study, PM concentration difference between road and urban AQM stations in Dongjak−gu emission levels found positively related to the hourly traffic volume. The correlation of the average hourly PM_{10} concentration difference of two different stations and the Dongjak−gu hourly traffic changes was equal to R^2=0.84 and R^2=0.54 in summer and winter, respectively. As for $PM_{2.5}$ concentration, the correlation was equal to R^2=0.76 and R^2=0.12 in summer and winter, respectively. The results in this study indicate that, despite progressive improvement of air quality in Seoul, vehicle emissions are still responsible for a substantial share of local PM concentrations in Seoul. Also, current Special Act on PM reduction only reduces air pollutions that have already emitted to the atmosphere on the day before. Air quality management policy in Seoul Metropolitan Area should include prevention strategies such as low emission period in winter during morning and evening rush hours.

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국문 초록

대기 오염 문제에 대한 서울시민의 관심이 높아지고 있다. 서울 지역의 대기 질 향상을 위해 많은 노력이 이루어지고 있지만, 여전히 차량으로부터 배출되는 PM 농도는 서울 지역 PM 농도의 상당 부분을 차지한다. 입자상 물질의 시ㆍ공간적 특성에 영향을 미치는 원인을 파악하는 것이 미세먼지 농도 저감을 위해 필수적이다. 본 연구에서는 2018 년 3 월부터 2019 년 2 월까지의 도시 대기관측지점과 도로변 대기관측지점의 미세먼지 농도의 비교 분석을 수행하고, 다른 기체 오염 물질(CO, NO_2, SO_2 및 O_3)과의 비교 분석을 통해 교통량이 미세먼지 PM_{10} 과 $PM_{2.5}$ 의 농도에 미치는 영향을 밝히고자 했다. 피어슨 상관 관계 분석에 따르면 도로에서 배출된 가스상 물질들과 미세먼지 농도의 상관성이 높게 나타났다. 또한, 교통량과 미세먼지의 상관성을 분석하기 위해서 한 지역을 선정하여 도시 대기 관측지점과 도로변 대기 관측지점에서 배출된 농도를 비교 분석하였다. 동작구를 대상으로 한 연구에 따르면, 시간당 동작대로 도로변 대기와 동작구 (도시) 대기관측지점의 PM_{10} 농도의 차이가 교통량의 시간적인 변화에 따라 상관성이 각각 여름(R^2 = 0.84), 겨울(R^2 = 0.54)로 나타났다. $PM_{2.5}$ 의 경우에는 여름과 겨울에 각각 R^2 = 0.76 과 R^2 = 0.12 로 동일하게 나타났다. 본 연구 결과에 따르면, 서울시의 대기질 개선을 위해 계절에 따른 교통량 통제와 (아침과 저녁) 출퇴근 시간 동안의 차량 운행을 제한시키는

정책을 시행하는 것이 내부 배출원에 의한 고농도 미세먼지 발생을 예방할 수 있는 것으로 나타났다.

주요어 : 미세먼지, 서울, 시간적 변화, 교통량

학　번 : 2017-29310