Characteristics of PM_{10} levels monitored for more than a decade in subway stations in South Korea

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Abstract

This study aimed to evaluate the variation in PM_{10} in the subways over the past years in Korea and to identify factors influencing the PM_{10} level. The PM_{10} measured internally by subway companies according to legal requirements was categorized by subway characteristics. These were statistically examined using a mixed effect model to identify the parameters influencing PM_{10} level. The PM_{10} levels monitored near platforms or waiting rooms ranged from 53.9 to 92.4 $\mu g\ m^{-3}$ and were all below the 150 $\mu g\ m^{-3}$ which is a regulatory standard. PM_{10} levels monitored on platforms were found to far exceed the yearly average atmospheric environmental standard (50 $\mu g\ m^{-3}$). Based on both univariate and multiple analyses, several subway characteristics, including the presence of a platform screen doors (PSD), were found to be significantly associated with PM_{10} level, though there is little difference in significant factors among cities. Particularly, stations without transfer lines and the presence of PSD contributed to reduction in the PM_{10} level at the platform, except for Busan and in specific years.

Keywords: Subway; PM_{10}; Platform screen-door (PSD); Indoor air quality

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INTRODUCTION

Subway systems are the most-used public transportation service in South Korea. Subway lines have been expanding continuously since their inception in 1974. Physically, the underground portion of the subway system is a semi-confined environment that may accumulate either internally generated contaminants or those from the outside environment. Proper mechanical ventilation is vital to this situation; otherwise, contaminants may accumulate to a severely harmful level (Nieuwenhuijsen *et al.*, 2007). The level of efficiency of the ventilation system varies among subways and according to their year of construction. In general, it has been reported that subway users are likely to be exposed to higher levels of particulate matter (PM) than the outdoor concentration (Kamani *et al.*, 2014; Ramos *et al.*, 2015).

In South Korea, the Indoor Air Quality Control Act (IAQ Act) was first established in 1996 as the Underground Living Space Air Quality Control Act (KMOE, 1996). In 1998, under the IAQ Act the 24-hour average indoor air quality standard (IAQ standard) for PM_{10} (defined as particulate matter with an aerodynamic diameter equal to or less than 10 μm) was first set as 250 $\mu g\ m^{-3}$. It was revised to 200 $\mu g\ m^{-3}$ in 2000 and finally to 150 $\mu g\ m^{-3}$ in 2002 (KMOE, 1998). Since 2005, only PM_{10} in subway stations is required to be monitored once per year and reported to the Korea Ministry of Environment (KMOE) mandatorily (KMOE, 2004).

No comprehensive studies have been conducted to assess variation in hazardous pollutants, including PM_{10}, that may likely be associated with commuters' health. The annual variations in

PM_{10} have never been reported. This study aimed to assess the variation in PM_{10} over the past decade in South Korea and identify subway characteristics influencing the PM_{10} level.

METHODS

General information about subway systems in South Korea

A subway transportation system has been fully established in five metropolitan cities in South Korea, including in Seoul. General information on subway systems is shown in **Table 1**. This information includes the first and last year of construction, the number of lines, and the number of stations covered. A total of 34 lines are currently operating nationwide. About 14 million commuters use the subway every day nationwide. The number of people who use the subway daily are compared among the cities as of the end of 2017 along with the increase by year.

Data collection

According to the IAQ Act, all subway corporations in Korea are required to monitor five pollutants, including PM_{10}, once per year, and to report the measurements of these to KMOE; a history of record measurements is also kept. One of the purposes of this study was, by the Korean government, to perform the assessment of airborne PM_{10} in underground subway environments. All PM_{10} measurements recorded in 13 subway corporations that operate in seven large cities across Korea (Table 1) were collected and analyzed based on this study strategy. We asked each subway company to report their monitored PM_{10} measurements from 2005 through 2017 according to both year and location; a total number of 12,174 PM_{10} measurement data were collected from 2005 to 2017. Among them, 570 measurement data with missing values of concentration were excluded. In addition, we excluded 356 data measurements from subway cabins, driving rooms, and tunnels. In total, 11,248 data measurements taken from platforms, waiting rooms, or transfer passageways were considered to be valid and were consequently selected for our analysis.

The PM_{10} sampling and analytical methods that subway companies have to use are standard, as designated by the Korean National Institute of Environmental Research (NIER) (NIER, 2017). According to the primary standard method, PM_{10} samples are collected using nitrocellulose membrane filters with an air sampling pump operated from 1 to 30 L min^{-1}, and should be analyzed using a gravimetric method. All samples were monitored at a specific location within subways, including on station platforms, in concourses, or in transfer passageways for longer than six hours. Although PM_{10} can be monitored by a secondary standard method using a beta attenuation monitor, over 90% of samples were measured by the primary standard method. In addition, outdoor PM_{10} levels monitored in each city during the same year were also collected and compared with levels in the subways.

Data analysis

A total number of PM_{10} measurement data in various subway environments (n=11,248) were categorized according to the following variables used as an independent analysis unit.

- Year measured was categorized into four groups; 2005-2008, 2009-2011, 2012-2014, 2015-2017
- Area measured; platform, waiting rooms, and transfer passageways
- The presence of a transfer line; yes or no
- The number of transfer lines; none, 2 and >2
- The presence of a platform screen-door (PSD); yes or no. Screen doors were established to isolate the platform from the railway and ensure the safety of passengers. The year established varies among the subway stations
- The season measured; spring (March-May), summer (June-August), autumn (September-November) and winter (December-February)
- Age of station; < 5 years, 5-10 years, >10 years

We statistically examined both the environmental and subway characteristics significantly influencing the PM_{10} level. All PM_{10} measurements monitored were summarized using the following descriptive statistics: arithmetic mean (AM) and standard deviation (SD) with 95% confidence interval (CI); geometric mean (GM) and geometric standard deviation (GSD) with 95% CI; range; and quartiles. Box plots were used to show the distribution of measurements by subway characteristics such as region, location monitored, and other factors. Since PM_{10} was monitored in each subway station every year and the measurements were thus correlated, both univariate and multiple linear mixed models were implemented to ascertain through a likelihood ratio test whether experimental factors such as region, location, and subway characteristics have a significant influence on the level of mean PM_{10} while taking into account the correlation. All the statistical analyses were conducted using R software (version 3.5.1; R Foundation for Statistical Computing, Vienna, Austria)

RESULTS

The PM_{10} levels monitored in subway platforms, waiting rooms, and transfer passage ways are compared by year (**Fig. 1**), city (**Table 2**), and subway and environmental characteristics (**Table 3**). Average PM_{10} values are found to decrease slightly with year, which was consistently detected in all stations and regions. Average PM_{10} levels monitored near subway platforms or waiting rooms ranged from 53.9 to 92.4 μg m^{-3}, and all levels were below 150 μg m^{-3}, the IAQ standard regulated by IAQ Act. There have been 14 stations (nine in Seoul in 2007, two in Seoul in 2008, and three in Daegu in 2011) exceeding 150 μg m^{-3}. These are located above the dashed line in the box plot (**Fig. 1**).

When comparing the PM_{10} levels on the platform by city, Seoul (AM=91.9 μg m^{-3}, Max=170.2 μg m^{-3}) and Daegu (AM=92.4 μg m^{-3}, Max=153.1 μg m^{-3}) were the highest and Busan (AM=56.6 μg m^{-3}, Max=128.6 μg m^{-3}) was the lowest (**Table 2**). Based on both univariate analysis and mixed effect multiple analysis, several subway characteristics, including the presence of PSD, were found to be significantly associated with PM_{10} level (**Tables 3 and 4**), even though there is little difference in significant factors among cities (in the ***Supplementary material,*** **Table S1-S5**). We indicated the results obtained from Seoul as an example (**Table 4**). In terms of Seoul and the surrounding metropolitan area, the PM_{10} concentration around the subway platform and in the waiting rooms was significantly high for subway Line 1 when monitored from 2005 to 2007 when there was no PSD and in the transfer stations. In particular, the presence of PSD was found to contribute to a significant reduction in PM_{10} levels on the platform (**Fig. 2**), with the exception of in Busan (**Fig. 2(e)**) and in certain cities for specific years (2015-2016 in Gwangju). The PM10 levels in the subway were found to be significantly higher than those monitored outdoors, regardless of city or year (**Fig. 3**).

DISCUSSION

We analyzed variation in PM_{10} concentrations over more than a decade in subways in Korea and found several characteristics influencing PM_{10} level. The yearly average of PM_{10} has fallen to

65.9 μg m^{-3} in 2017 from a peak of 102.4 μg m^{-3} prior to 2010, a 35.6 % decrease. This trend is observed in all cities' subways, although the levels of decrease differ. Our results are far below the results reported by several studies conducted in Seoul. Park and Ha reported that PM_{10} levels inside subway Lines 1, 2 and 4 exceeded the Korea IAQ standard of 150 μg m^{-3}. Their average PM_{10} concentration as monitored inside trains (144.0 μg m^{-3}) was far higher than the 125.8 μg m^{-3} on platforms ($p=0.026$) and the concentration range (35–81 μg m^{-3}) measured in outdoor air in Seoul from January to November in 2004 (SAMC, 2004). The oldest line, Line 1 in Seoul, showed concentration levels in 10 of 12 of its investigated stations that exceeded IAQ standard for PM_{10}. The highest monitored concentration was 207.5 μg m^{-3} inside an underground station on Line 1.

Regardless of country, city, or location within the system, it has been characteristic for high concentrations of PM to be measured in subway systems, such as in London (Adams *et al.*, 2001), Stockholm (Johansson and Johansson, 2003), Prague (Braniš, 2006), Rome (Ripanucci *et al.*, 2006), Berlin (Fromme *et al.*, 1998), Seoul (Kim *et al.*, 2008), and Beijing (Li *et al.*, 2007). Levels of PM_{10}, $PM_{2.5}$, and nanoparticles in the subway environment have all been reported to be far higher than those monitored in the outside environment. When the average annual atmospheric concentration of PM_{10} (KMOE, 2017) is compared with annual average concentrations measured in the subway, we also found the subway concentration to be higher than the atmospheric concentrations in all cities (**Fig. 3**). These results demonstrate that the amount of fine and ultrafine dust absorbed into the respiratory system in subway systems can generally be far higher than the amount from outdoors based on both exposure time and exposure level.

Generalizing factors that may influence PM_{10} levels measured under specific circumstances are very difficult to specify because of the subway characteristics, surrounding environments, and environment measured (i.e., the types of subway, location measured, age of subway, number of subway users, etc.). We found that several subway characteristics significantly influence the level of PM_{10} in subway stations. Year was found to be significantly associated with change in PM_{10} level. The level of PM_{10} reduces markedly with year, something statistically detected for all cities and all stations (**Fig 1 and Table 3 and 4**). However, the PM_{10} levels measured in subway stations are still far above the Korean atmospheric environmental standard for PM_{10} (yearly average: 50 $\mu g\ m^{-3}$, daily average: 100 $\mu g\ m^{-3}$) intended to protect the general public including children and elderly people, even though other pollutants such as ozone and NO_2 are not substantially different (KMOE, 2018a). The Korean Ministry of Environment also adopted a $PM_{2.5}$ standard for the first time in 2015 (yearly average: 25 $\mu g\ m^{-3}$, daily average: 50 $\mu g\ m^{-3}$) and strengthened the standard in March 2018 (yearly average: 15 $\mu g\ m^{-3}$, daily average: 35 $\mu g\ m^{-3}$) (KMOE, 2018b). However, IAQ regulations lacked a standard for $PM_{2.5}$, even though it accounts for most of the PM_{10} generated in the subway environment. IAQ standards for $PM_{2.5}$ in subway stations are scheduled to be set as a daily average of 50 μg m^{-3} for the first time from 2019 (KMOE, 2018c). Many countries' national health organizations and influential global organizations such as the World Health Organization (WHO) have stipulated a standard or guideline value for indoor hazardous pollutants (Abdul-Wahab *et al.*, 2015). Air quality standards have been adopted as measures enforceable by a regulatory authority, including in Korea, Taiwan, and Japan. On the other hand, air quality guidelines are designed to offer guidance for reducing adverse health impacts from air pollution, and many countries such as the USA suggest their IAQ values only as guidelines. Generally, IAQ standards except for PM_{10} are set to be similar to outdoor atmospheric standards (Vahlsing and Smith, 2012). Many people use the subway, including not only adults, but also pollutant-sensitive groups such as children, medical patients, elderly people, and pregnant women. Also, people who routinely use a subway system for commuting can be exposed to the air in the subway for much longer periods than to outdoor air. This indicates that IAQ standards for PM_{10} and $PM_{2.5}$ should be modified to match atmospheric standards.

In general, subway stations with transfer lines have more PM sources compared with stations without transfer lines, including a greater number of passengers, number of entrances and exits, and frequency of maintenance work. In addition, the passageways of transit stations are often connected to underground shopping areas, and thus the possibility of the inflow of pollutants from the outside is greater. Therefore, transfer stations should be managed first to reduce fine dust concentrations. This study recommends the installation of boards that display real-time levels of PM_{10} and $PM_{2.5}$ in some subway platforms on transfer lines so that citizens can be aware of the quality of subway air.

Several mitigation measures have been developed to reduce PM concentrations in subway systems; Korean researchers conducted most of the evaluation in this field. PSDs were recognized as one of the most efficient measures to improve underground air quality in subway. The average PM_{10} concentration measured at the platforms after the installation of PSDs significantly reduced by 16% (Kim et al., 2012) and 38% (Han et al., 2014), respectively, compared to the earlier period. In this study, the presence of a PSD was also found to be a significant factor in reducing PM_{10} levels at platforms (Fig. 2); this is considered true despite the city of Busan (Fig. 2(e)) and specific years not following this trend. However, the mean PM_{10} concentration measured inside of trains after the installation of PSDs increased significantly by 29.9% compared to the concentration before the installation (Son et al., 2014). Son et al. (2014) suggest that air mixing between the platform and the tunnel was extremely restricted after the installation of the PSDs. Kown et al. (2016) investigated the change of PM size distribution in an underground station with PSDs; their results showed that the PM that was suspended in the tunnel, flowed into the platform area even in a subway station where the effect of train-induced wind was blocked by the installed PSDs, as this flow occurred when the PSDs were opened. Despite the installation of completely sealed PSDs, the inflow of coarse mode particles from the tunnel seems unavoidable, indicating the need for measures to decrease the generated PM in order to lower subway user exposure.

Mechanical ventilation has been recognized as a key factor affecting indoor air quality in subway systems. Juraeva et al. (2016) experimentally investigated the effects of train-wind, air-curtain, and electric precipitators as well as the proper conditions for electric precipitator operation to decrease the PM concentration. Their results indicated that the average velocity of the airflow in the shaft increased when the velocity of the air-curtain increased. The PM concentration after ventilation was reduced significantly in the tunnel when the air-curtain and train-wind were operated. Station design is also related to the influences of tunnel ventilation and the train piston effect. The effects of ventilation conditions and station design on underground air quality were investigated in the Barcelona subway system. Narrow platforms served by single-track tunnels were dependent on forced tunnel ventilation and could not rely on the train piston effect alone to reduce platform PM concentrations. The PM concentrations of stations with spacious double-track tunnels were not significantly affected when tunnel ventilation was switched off (Moreno et al., 2014). To reduce PM concentration in subway cabins, the subway cabin air purifier (SCAP) was newly developed and evaluated for its effectiveness (Kim et al., 2014); it was found that the PM_{10} concentrations inside of cabins were reduced by 15.5-26.0% after the SCAP system was installed.

In order to improve indoor air quality in subways, it is important to identify the main sources of air pollution. Several studies in identifying the chemical composition of subway PM demonstrated that Fe was observed as the most abundant metal element of $PM_{2.5}$ (Aarnio et al., 2005; Loxham et al., 2013; Lee et al., 2018; Minguillón et al., 2018) and PM_{10} (Jung et al., 2010; Park et al., 2012; Loxham et al., 2013; Moreno et al., 2015; Lee et al., 2018), accounting for 30% and 80% of PM content, respectively. Jung et al. (2010) clearly identified indoor sources of subway PM comparing four sets of samples collected in tunnels, at platforms, near ticket offices, and outdoors. Fe-containing particles predominated in the samples collected in tunnels, with relative abundances of 75-91% for the four stations. In addition, the amount of Fe- containing particles decreased as the distance of sampling locations from the tunnel increased. These results clearly indicated that Fe-containing subway particles were generated in the tunnel. Park et al. (2012) characterized PM_{10} sources by positive matrix factorization; railroad-related sources such as the abrasion of the railroad tracks, brakes, and power supply or draft lines during subway operation contributed the most PM_{10} to subway cabin air. Studies in both New York City (Vilcassim et al., 2014) and Shanghai (Guo et al., 2017) indicated that a potential source of fine particles in subways was the diesel engine cleaning and maintenance vehicles that operated during the night in the underground facilities. Recently, Choi et al. (2019) also identified that the use of diesel engine vehicles in tunnel maintenance was a key contributor to both PM2.5 and black carbon (BC) exposure levels among subway workers. The use of diesel engine vehicles in semi-confined underground environments causes not only exposure to high levels of diesel engine exhaust emissions, but also an increase in $PM_{2.5}$ in subway platforms or waiting rooms. Therefore, proactive measures, including the installation of diesel particulate filters (DPFs) on diesel engine maintenance vehicles in tunnels, are urgently suggested in order to reduce subway workers' exposure to both $PM_{2.5}$ and BC. In addition, after the enforcement of EURO engine emission standard, nitrogen dioxide NO_2 emissions for recent diesel engines are becoming a significant concern in diesel engine exhaust (Carslaw and Rhys-Tyler, 2013; Grice et al., 2009). Electric-battery equipped vehicles, which would be effective in reducing the levels of airborne particles and NO_2, should be introduced to improve air quality in subways. In particular, diesel vehicles without diesel exhaust-reducing air treatment systems should be phased out of use in subways.

This study has several limitations. One major limitation is that it is not possible to know how representative these findings obtained from various locations are with regard to subway characteristics that involve various types of physical environments and ventilation levels. Our

PM_{10} measurements were compilations of data measured once in a specific area and on a specific day during the year, which may likely be affected by not only subway characteristics, but by outdoor conditions as well. The number of passengers, which likely is associated with the level of PM_{10}, was not examined in this study. It is impossible to obtain the number of passengers who used the stations where PM_{10} levels were measured. In addition, this study did not examine the effect on PM_{10} by level of engineering measures designed to reduce the infiltration of air pollutants in subways, including fine and ultrafine particles, from the outdoor environment that is likely one of the factors increasing the level of fine particles in a subway. The facilities to supply outdoor air were all found to be installed on a street at the same level as a road bearing traffic. The air cleaners are not able to remove fine particles exhausted from vehicles and the outdoor environment. In addition, the non-designed data collection resulted in some potential environmental factors partially crossing, implying that not all the effects of these influential factors were fully estimated and tested within the linear mixed models. For example, all of the PM_{10} data for Daejeon for the years 2012-2014 were collected in the autumn, and therefore it was impossible to separate the effect of autumn from that of the years 2012-2014. Although we successfully took into account the correlation structure among PM_{10} measurements due to their being measured over time at several locations within a station through the use of a linear mixed model, it is assumed that spatial correlations among adjacent stations were not large enough to be considered under the condition that the ventilation system in a tunnel connecting any two stations worked well. This assumption needs to be investigated thoroughly in a future study.

Nevertheless, our results are useful not only for characterizing the level of PM_{10} in the subway environment, but also for identifying specific factors that may significantly influence PM_{10} concentrations and for recommending mitigation procedures. The general variations in PM_{10} levels over more than a decade were also characterized. Based on our results, a number of appropriate engineering, administrative, and regulatory measures could be taken to reduce exposure to fine and ultrafine PM in subway stations. Further study is required to monitor $PM_{2.5}$ among several subway characteristics and to quantify the diesel engine exhaust concentrations in subway air.

In conclusion, even though the levels are decreasing over time, PM_{10} levels in subways were still higher than outdoors and far exceed the yearly atmospheric environmental standard (50 $\mu g\ m^{-3}$). We found several subway characteristics, such as the year, location of the station, and presence of PSD, to significantly influence the PM_{10} level.

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DISCLAIMER

All authors declare there's no financial/personal interest or belief that could affect their objectivity.

NOTE

- The first and second ordered authors in the author list contributed equally to this study as the first author.
- The supplementary material including five Tables (Table S1-S5) is provided with a separated one.

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Table 1. General information on the subway system in major metropolitan cities

City	Number of lines	Opening year of lines		Number of subway station by location [a]		Number of daily passengers in 2017[b]
		First	Most recent	Underground	Above ground	
Seoul	10	1974	2017	295	26	7,793,756
Incheon	2	1999	2016	48	8	429,334
Metropolitan area surrounding Seoul (excluding Seoul & Incheon)	14	1978	2018	91	245	3,702,575
Daejeon	1	2006	2007	22	0	108,772
Daegu	3	1997	2016	61	30	447,532
Busan	6	1985	2017	90	59	1,004,091
Gwangju	1	2004	2008	18	2	51,258
Total	37(34) [c]			625	370	13,537,318

[a] Transfer stations were counted in duplication

[b] The number of daily passengers were calculated from the overall number of transported persons. In terms of Metropolitan area surrounding Seoul, data from 12 lines could be counted.

[c] Three lines (Nos. 1, 3, 4) in Seoul are operated to the metropolitan area surrounding Seoul (duplicated). The line number is same, but the operating section is different.

Table 2. PM$_{10}$ levels (μg m^{-3}) measured over the study period in each city

City	Sampling location	Number of measurements	AM	SD	GM	GSD	Min	Max	Q1	Q2	Q3
Seoul	Platform	1,758	91.9	17.9	90.1	1.23	22.2	170.2	82.3	92.0	100.5
	Waiting rooms	1,985	80.2	14.5	78.8	1.22	20.6	140.8	72.2	81.4	88.7
	Passages for transfer	2,076	90.6	19.4	88.3	1.27	10.6	146.8	78.9	90.0	102.7
Incheon	Platform	363	85.4	27.6	80.6	1.43	11.4	147.8	63.9	82.5	107.5
	Waiting rooms	466	68.0	23.8	63.4	1.49	7.3	143.2	52.6	65.4	84.4
	Passages for transfer	17	60.9	14.8	58.9	1.32	32.4	85.2	56.8	60.8	73.1
Daejeon	Platform	244	64.3	18.76	61.6	1.36	19.5	133.7	54.3	62.9	73.4
	Waiting rooms	268	53.9	17.15	51.3	1.39	11.9	123.5	42.6	52.0	62.7
Daegu	Platform	693	92.4	25.6	88.3	1.38	12.4	153.1	74.9	93.3	110.2
	Waiting rooms	822	71.5	24.0	67.2	1.44	13.1	153.0	54.3	70.1	86.7
	Passages for transfer	2	60.4	12.5	59.8	1.23	51.6	69.2	56.0	60.4	64.8
Busan	Platform	1,184	56.6	15.0	54.7	1.30	20.7	128.6	46.5	54.8	64.3
	Waiting rooms	915	56.7	15.4	54.6	1.32	10.3	112.7	46.0	54.6	65.1
Gwangju	Platform	218	69.0	16.7	67.0	1.27	33.1	135.0	59.0	67.8	78.0
	Waiting rooms	236	64.0	13.9	62.5	1.26	30.1	111.8	55.0	64.3	72.3
	Passages for transfer	1	61.8	N/A	61.8	N/A	61.8	61.8	61.8	61.8	61.8
Total		11,248	77.8	23.37	74.0	1.39	7.3	170.2	60.3	78.4	92.8

Abbreviations: AM, arithmetic mean; SD, standard deviation; GM, geometric mean; GSD, geometric standard deviation; Min, minimum; Max, maximum; Q1, the first quartile; Q2, the second quartile; Q3, the third quartile; N/A, not available.

Table 3. Univariate analysis examining relationships between PM_{10} level and subway characteristics

Variable [a]		No. of measurements	AM	SD	GM	GSD	Min	Max	*p*-value [b]
Presence of platform screen door	Yes	6,989	74.0	19.8	71.0	1.35	7.3	147.8	<0.001
	No	3,993	84.6	27.3	79.7	1.44	10.3	170.2	
	NI	266							
Depth, m [c]	[0,13.3]	2,771	81.6	23.0	78.1	1.36	18.9	161.5	<0.001
	[13.3,17.2]	2,728	75.6	22.9	71.9	1.39	12.6	170.2	
	[17.2,21.3]	2,748	77.6	23.3	73.8	1.39	7.3	162.3	
	[21.3,64.2]	2,725	76.5	23.8	72.5	1.41	11.4	149.3	
	NI	276							
Location	Platform	4,460	79.5	25.1	75.2	1.41	11.4	170.2	<0.001
	Waiting rooms	4,692	70.6	20.4	67.3	1.38	7.3	153	
	Passages for transfer	2,096	90.4	19.6	88.0	1.27	10.55	146.8	
Number of lines at transfer station	No transfer	8,547	76.0	23.9	72.0	1.41	7.3	170.2	<0.001
	2	2,228	82.6	21.5	79.5	1.34	12.6	159.6	
	3	382	87.9	16.5	86.3	1.22	35.6	142.7	
	4	91	84.6	13.9	83.4	1.19	51.2	128.3	
Season	Spring	2,600	66.4	22.4	62.7	1.41	7.3	153.1	<0.001
	Summer	4,117	78.3	21.0	75.3	1.34	11.9	153	
	Autumn	1,955	71.1	21.8	67.6	1.39	11.4	143.3	
	Winter	78	73.7	30.9	65.9	1.68	10.6	134.2	
	NI	2,458							
Year of measurement	2005-2008	1,756	98.7	23.01	95.6	1.31	11.9	170.2	<0.001
	2009-2011	2,517	79.1	23.21	75.2	1.40	10.3	153.1	
	2012-2014	2,819	75.5	19.71	72.7	1.33	21.7	147.5	
	2015-2017	4,156	69.7	20.27	66.5	1.38	7.3	147.8	
Total		11,248							

Abbreviations: AM, arithmetic mean; SD, standard deviation; GM, geometric mean; GSD, geometric standard deviation; Min, minimum; Max, maximum; NI, no information.

[a] The number of PM_{10} measurements for each season, the presence of a screen door, and depth were not same due to some missed measurements, [b] Each *p*-value was from the likelihood ratio test with a mixed effect model, [c] Depth was categorized into quartile.

Table 4. Subway characteristics influencing the level of PM$_{10}$ in Seoul and the surrounding metropolitan area

Variable [a]		Univariate analysis [b]				Multiple analysis [b]			
		Estimate	Lower 95%CI	Upper 95%CI	*p*-value	Estimate	Lower 95%CI	Upper 95%CI	*p*-value
Route	Line 2	-9.15	-12.65	-5.63	<0.001	-9.01	-12.40	-5.63	<0.001
	Line 3	-10.78	-14.33	-7.23		-10.67	-14.11	-7.24	
	Line 4	-8.41	-12.16	-4.64		-8.41	-12.04	-4.79	
	Line 5	-18.44	-21.80	-15.07		-19.71	-22.99	-16.43	
	Line 6	-15.04	-18.49	-11.60		-16.72	-20.08	-13.36	
	Line 7	-16.45	-19.83	-13.05		-16.91	-20.22	-13.60	
	Line 8	-17.69	-21.52	-13.84		-18.60	-22.32	-14.88	
	Line 9	-24.72	-28.51	-20.94		-21.88	-25.63	-18.15	
	Airport railroad	-34.46	-42.70	-26.22		-36.47	-44.33	-28.59	
	Sinbundang line	-25.97	-30.27	-21.65		-27.57	-31.82	-23.31	
Year	2009-2011	-30.90	-33.45	-28.34	<0.001	-25.88	-30.83	-20.95	<0.001
	2012-2014	-21.70	-23.72	-19.67		-18.12	-22.82	-13.46	
	2015-2017	-24.70	-26.86	-22.54		-19.64	-24.43	-14.91	
Season	Winter	-52.68	-60.03	-45.32	<0.001	-47.64	-54.12	-41.04	<0.001
	Spring	-4.02	-5.46	-2.58		-3.30	-4.57	-2.02	
	Summer	-1.91	-3.07	-0.73		-3.17	-4.23	-2.10	
Others	Transfer station	2.35	1.00	3.71	0.002	1.81	0.69	2.92	0.007
	Platform screen door	-22.16	-24.02	-20.30	<0.001	-4.90	-9.21	-0.55	0.055

[a] Reference group: route (Line 1), year (from 2005 to 2008), season (autumn), transfer station (non-transfer station), platform screen door (no screen door).

[b] A total of 2,256 missing data from Seoul and the metropolitan area surrounding Seoul lines were excluded in data analysis due to no information available for season and the installation of screen door.

[*] Results from other cities were indicated in the *Supplementary material*.

Figure Captions

Fig. 1. Distribution of PM_{10} levels by year. A total of 14 stations (nine in Seoul in 2007, two in Seoul in 2008, and three in Daegu in 2011) exceeded the indoor air quality standard of 150 μg m^{-3} indicated by the dashed line

Fig. 2. Comparison of distribution of PM_{10} levels (μg m^{-3}) at platform by presence of screen door and year

Fig. 3. Comparison of distribution of yearly average PM_{10} levels (μg m^{-3}) monitored in subway stations and outdoor air

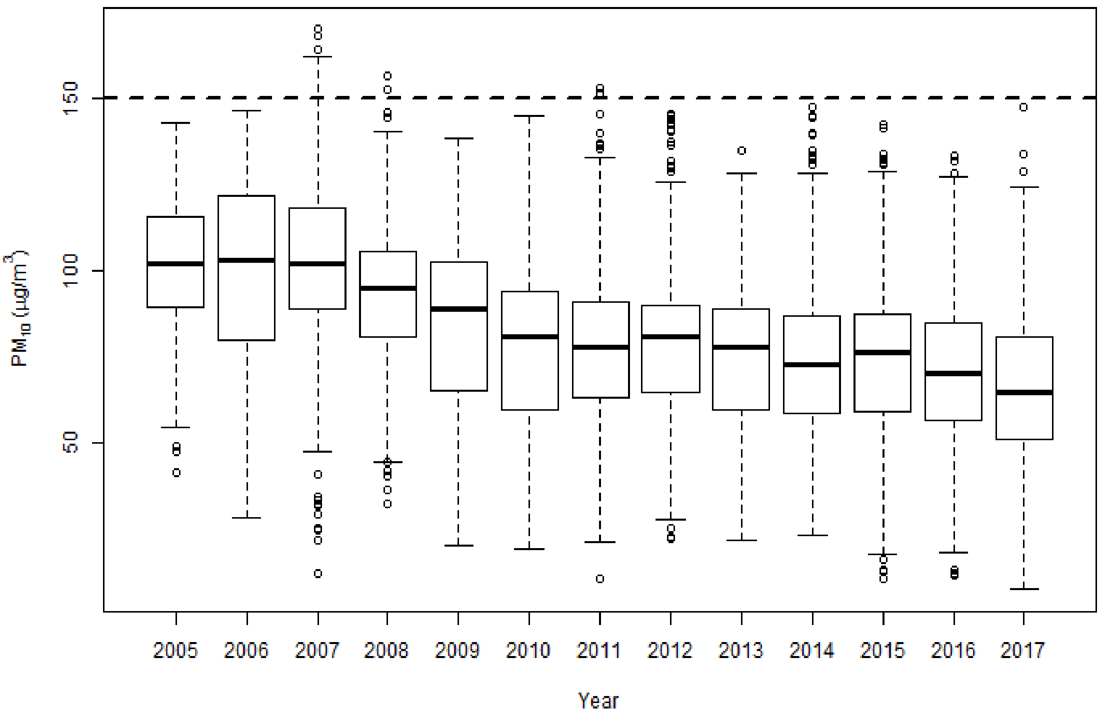
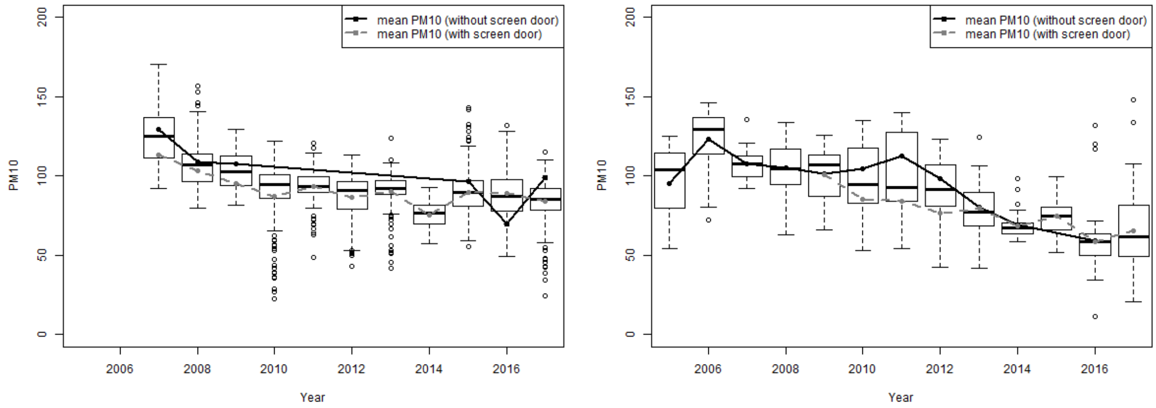
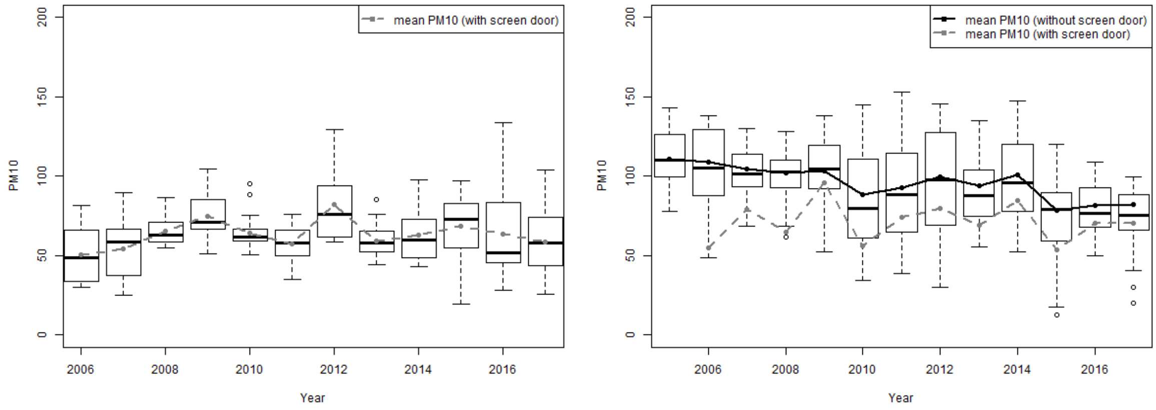

150
100
50
PM10 (µg/m3)
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Year

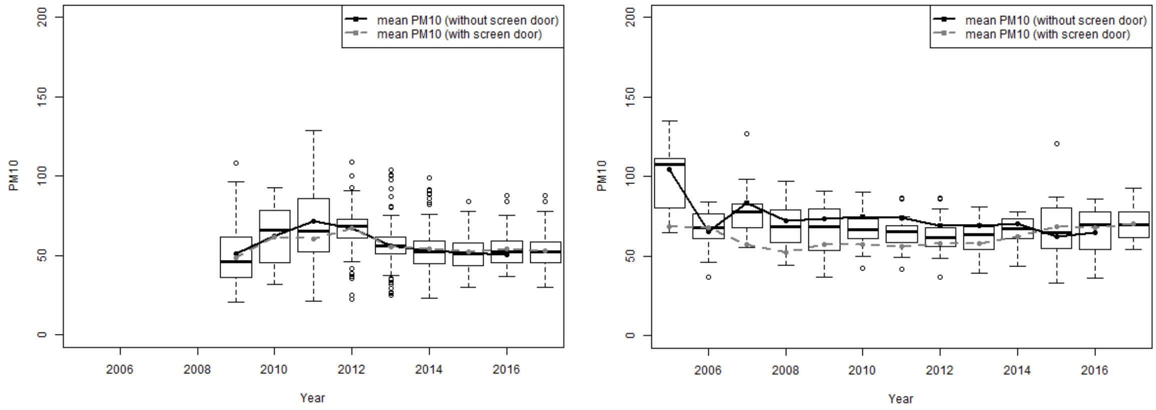
Fig. 1.



(a) Seoul (b) Incheon

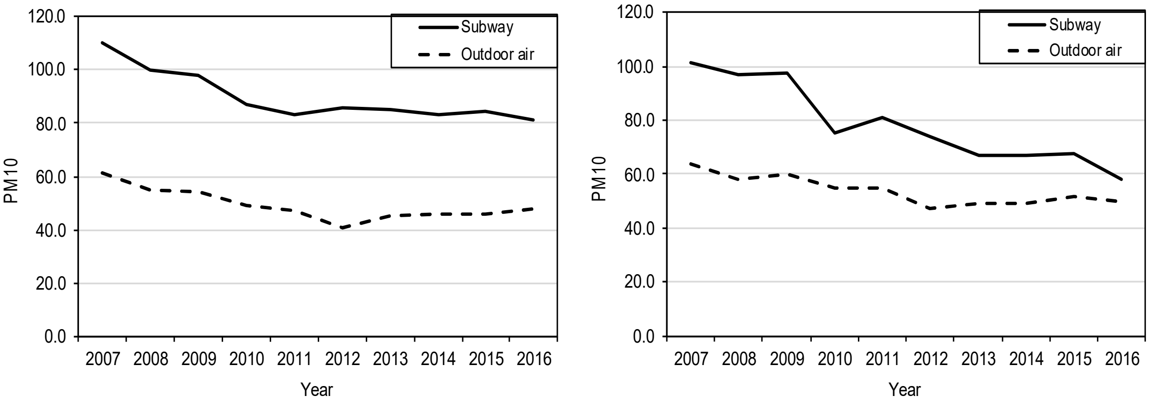


(c) Daejeon (d) Daegu

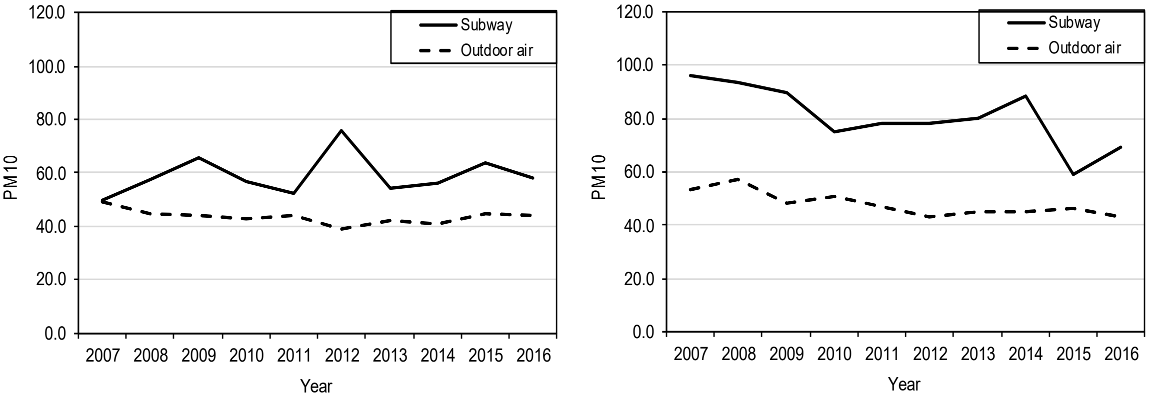


(e) Busan (f) Gwangju

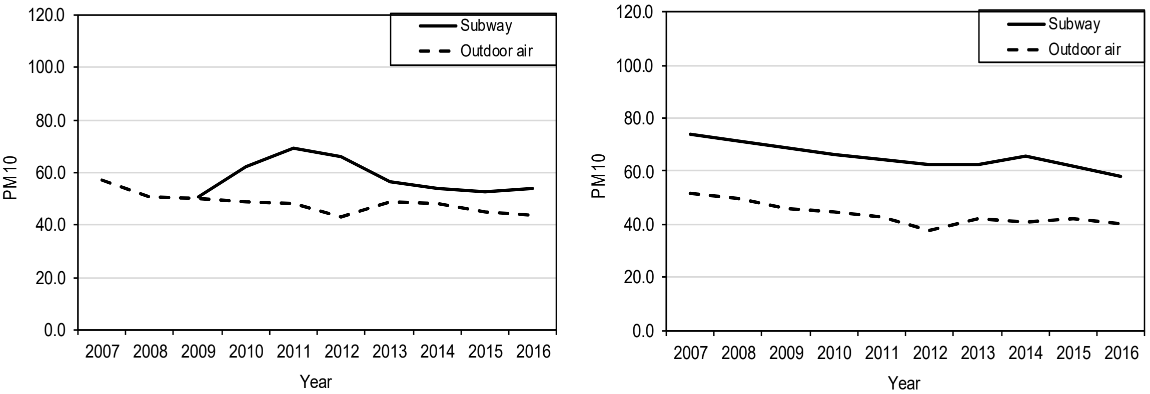
Fig. 2.



(a) Seoul (b) Incheon



(c) Daejeon (d) Daegu



(e) Busan (f) Gwangju

Fig. 3.