The purpose of the study was to initially investigate the concentration patterns of PM$_{1}$, PM$_{2.5}$, and PM$_{10}$ in the Seoul subway lines, and then to figure out the PM behaviors of internal and external sources inside subway tunnels. The PMs were monitored by a light scattering real-time monitor during winter (Jan. 8-26 in 2015) and summer (July 2-Aug. 7 in 2015) in tunnel air, in passenger cabin air, and in the ambient air. The daily average PM$_{10}$, PM$_{2.5}$, and PM$_{1}$ concentrations on these object lines were 101.3±38.4, 81.5±30.2, and 59.7±19.9 µg/m$^3$, respectively. On an average, the PM concentration was about 1.2 times higher in winter than in summer and about 1.5 times higher in underground tunnel sections than in ground sections. In this study, we also calculated extensively the average PM mass ratios for PM$_{2.5}$/PM$_{10}$, PM$_{1}$/PM$_{10}$ and PM$_{1}$/PM$_{2.5}$; for example, the range of PM$_{2.5}$/PM$_{10}$ ratio in tunnel air was 0.82-0.86 in underground tunnel air, while that was 0.48-0.68 in outdoor ground air. The ratio was much higher in tunnel air than in outdoor air and was always higher in summer than in winter in case of outdoor air. It seemed from the results that the in/out air quality as well as a proper amount of subway ventilation must be significant influence factors in terms of fine PM management and control for the tunnel air quality improvement.

**Key words:** Particulate matter, Subway tunnel, PM mass ratio, IAQ

1. INTRODUCTION

In present, the Seoul City in the Republic of Korea is undergoing traffic congestion problems caused by rapid urbanization and population growth. Thus the city government has reorganized the mass transportation systems since 2004 and the subway has become one of important means for public transit. The subway takes up to 39% share of total passenger transportation services and it is the biggest part of service systems in Seoul (Seoul Metropolitan Government, 2015). The first line of the Seoul Metropolitan Subway Network (SMSN) has been operated from the Seoul Station to the Cheongnyangni Station since 1974. Up to the present time, the SMSN consists of 9 lines, which are owned by four independent companies. By 2016, the total track length of the 9 lines is 331.6 km and the lines consist of 283 underground and 24 ground stations.

Since subway system is typically a closed environment, the indoor air quality issues have often raised by the general public. Although the air quality has improved in both a subway platform and a concourse after installing platform screen doors (PSD) (Kim *et al.*, 2012; Lee *et al.*, 2010), the tunnel air quality related with particulate matter (PM) has been contrarily deteriorated by the PSD which hindering air circulation in subway tunnels (Lee *et al.*, 2015; Son *et al.*, 2013). Especially since a huge amount of PM is emitted from tunnels due to train operations and subway services, it is necessary to examine the characteristics and behaviors of fine PM in tunnel air in order to protect passenger health. Many other studies had also investigated in various subways on PM concentrations and their size-oriented mass ratios such as in Shanghai (Qiao *et al.*, 2015a), in Taipei (Cheng *et al.*, 2008), in Guangzhou (Chan *et al.*, 2002a), in Hong Kong (Chan *et al.*, 2002b), and in Los Angeles (Kam *et al.*, 2011), and so on.

In this study, PM$_{1}$, PM$_{2.5}$, and PM$_{10}$ concentrations were initially measured to investigate the physical characteristics of PM on the Seoul subway Line-1 to Line-9 during winter and summer periods. To figure out the PM behaviors of internal and external sources inside tunnels, we investigated size-oriented PM mass ratios extensively in tunnel air, in passenger cabin air, and in the ambient air.
2. RESEARCH METHODS

To investigate the temporal and spatial patterns of airborne PM, we monitored the concentrations of PM$_{1}$, PM$_{2.5}$, and PM$_{10}$ in all the Seoul subway lines. Details of object subway lines are described in Table 1 including operational extension distance, number of stations operated, number of passengers carried, and train operation frequency. In the table, the numerical order of line numbers matches with the operation age of subway lines; for example, the first subway Line-1 has been operated in 1974 and the Line-9 in 2009 and further the lines are clearly distinguished by color symbols as shown in Fig. 1(a). The subway trains run either underground tunnel sections or ground sections, where a section means a railroad interval between two near stations on each subway line. Thus the total number of sections is smaller or larger than the number of stations in a subway line depending on the railroad facility circumstances of departure and arrival stations. The map in Fig. 1(b) shows ground and underground sections in Seoul and also shows that the Line-2, 3, 4, and 7 have only above-ground sections.

We measured PM concentrations using a light scattering real-time method during winter (Jan. 8-26, 2015) and summer (July 2-Aug. 7, 2015) periods. Unfortunately the measured raw data from the Line-1, 4, 5, 7 in winter as well as the Line-7 in summer were deleted in this study due to unexpected measurement errors on the basis of QA/QC. The concentration patterns on all the subway lines were statistically investigated after simultaneously measuring PM$_{1}$, PM$_{2.5}$, and PM$_{10}$ by the Grimm Dust Monitor 1.108. The particles in the monitor air are detected by a light scattering technique in a measuring cell of the monitor. The scattered laser pulse for each single particle is counted and then the intensity of its scattered signal is classified into a specific particle size-range, one of 15 size channels, after amplification subject to its intensity (Grimm Aerosol Technik, 2010). The monitor can quickly measure PM concentration with the flow rate of 1.2 L/min and allows direct mass or number concentration measurements in near real-time (Colls and Micallef, 1999). Details of the monitor are described in Table 2. For our PM monitoring, the ground and underground air was led directly into measuring cell of the monitor via our custom-designed stainless steel air inlet, which was fixed on outside window glass in a train cabin as shown in Fig. 2. The sampling inlet was connected to the measuring cell with a conductive silicone tube. The PM signals were monitored every 6 second after train service and train departure and arrival times were recorded as well.

In addition to measuring the PM on the underground and ground sections during the sampling periods, we also obtained ambient PM$_{2.5}$ and PM$_{10}$ hourly raw-data from 27 monitoring sites in Seoul, which were operated by the Korean Ministry of Environment (MOE), in order to compare PM behaviors in tunnel air, in passenger cabin air, and in outdoor air.

3. RESULTS AND DISCUSSION

3.1 Characteristics of PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ Concentrations on Seoul Subway Lines

As results of PM measurement in Seoul subway lines, which are mostly consisted of underground tunnels, the daily average PM$_{10}$, PM$_{2.5}$, and PM$_{1}$ by the Grimm Dust Monitor 1.108. The particles in the monitor air are detected by a light scattering technique in a measuring cell of the monitor. The scattered laser pulse for each single particle is counted and then the intensity of its scattered signal is classified into a specific particle size-range, one of 15 size channels, after amplification subject to its intensity (Grimm Aerosol Technik, 2010). The monitor can quickly measure PM concentration with the flow rate of 1.2 L/min and allows direct mass or number concentration measurements in near real-time (Colls and Micallef, 1999). Details of the monitor are described in Table 2. For our PM monitoring, the ground and underground air was led directly into measuring cell of the monitor via our custom-designed stainless steel air inlet, which was fixed on outside window glass in a train cabin as shown in Fig. 2. The sampling inlet was connected to the measuring cell with a conductive silicone tube. The PM signals were monitored every 6 second after train service and train departure and arrival times were recorded as well.

In addition to measuring the PM on the underground and ground sections during the sampling periods, we also obtained ambient PM$_{2.5}$ and PM$_{10}$ hourly raw-data from 27 monitoring sites in Seoul, which were operated by the Korean Ministry of Environment (MOE), in order to compare PM behaviors in tunnel air, in passenger cabin air, and in outdoor air.

| Line No. | Line color symbol | Operation distance (km) | Total No of stations | Total No of passengers carried (1,000 persons/yr) | Train service frequency on weekdays |
|----------|-------------------|-------------------------|----------------------|------------------------------------------------|-----------------------------------|
|          |                   |                         | Ground | Underground |                                          |                                   |
| 1        | Navy              | 7.8                     |          | 12          | 164,139                                          | 517                               |
| 2        | Green             | 48.8                    | 11      | 32          | 761,807                                          | 551                               |
| 3        | Orange            | 38.2                    | 4       | 40          | 286,361                                          | 410                               |
| 4        | Blue              | 31.7                    | 6       | 29          | 302,565                                          | 496                               |
| 5        | Purple            | 52.3                    |          | 46          | 308,501                                          | 465                               |
| 6        | Ocher             | 35.1                    |          | 39          | 196,924                                          | 356                               |
| 7        | Olive             | 57.1                    | 3       | 39          | 374,340                                          | 421                               |
| 8        | Pink              | 17.7                    |          | 17          | 89,238                                           | 306                               |
| 9        | Gold              | 31.5                    |          | 25          | 156,652                                          | 484                               |

Reference : Seoul Metropolitan Government (2016)
er than those in summer. Especially during the summer period, the highest average concentrations of PM$_{10}$ and PM$_{2.5}$ were observed respectively by 136.0 μg/m$^3$ and 101.7 μg/m$^3$ in the Line-1 and further that of PM$_1$ was 77.9 μg/m$^3$ in the Line-9. When comparing among subway lines, the seasonal pattern showed that the behavior of Line-2 was quite different from other lines. In other words, the range of average concentration was widest between two seasons since very low levels were observed in summer, but very high levels in winter. Generally in the ambient air, the PM concentration in Korea is highest during the winter heating season, but lowest during the summer rainy season. Thus the subway Line-2 might be easily influenced by the ambient air when comparing other lines since the Line-2 has 11 above-ground sections out of total 44 sections as shown in Table 1. On the other hands, seasonal differences in terms of PM levels were very small since other lines have a few or none ground sections.

The Korean MOE has established the PM$_{10}$ indoor air quality (IAQ) standard of 150 μg/m$^3$ for subway platform, concourse, and passage way, while the standard for tunnel air does not exist yet (Ministry of Environment, 2014). According to the IAQ recommenda-

### Table 2. Specifications of the Dust monitor.

| Measurement mode       | Continuous                  |
|------------------------|-----------------------------|
| Size range (μm)        | 0.3-20                      |
| Display resolution     | 15 channels                 |
|                       | (0.3/0.4/0.5/0.65/0.8/1.0/1.6/2.5/3.0/4.0/5.0/7.5/10/15/20 μm) |
| Concentration range (p/L) | 1 to 2,000,000              |
| Measurement intervals  | 6 sec, 1 min, 5 min         |
| Sampling flow rate (L/min) | 1.2                     |
| Reproducibility (%)    | ± 2                         |
| Sensitivity (particle/liter) | 1                       |

Reference: Grimm aerosol Technik.
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Fig. 2. Photos for a sampling location (left) and an inlet tube (right) in a subway passenger cabin.

Table 3. Average concentrations of PM$_{10}$, PM$_{2.5}$, and PM$_{1}$ in Seoul subway tunnels each lines during sampling periods.

| Line No. | Total No. of station | PM$_{10}$ | | | | PM$_{2.5}$ | | | | PM$_{1}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Max. | Min. | Average | STD* | Max. | Min. | Average | STD* | Max. | Min. | Average | STD* |
| Winter | 1 | 12 | 369 | 30.9 | 136.0 | 55.5 | 273.3 | 22.8 | 101.7 | 39.7 | 151.2 | 19.7 | 67.3 | 20.9 |
| | 2 | 43 | 348.5 | 30.5 | 128.1 | 58.2 | 262.7 | 27.3 | 103.8 | 45.3 | 183.7 | 25.2 | 77.1 | 27.8 |
| | 3 | 44 | 330.1 | 21.4 | 83.9 | 37.5 | 247.4 | 41.3 | 63.1 | 37.0 | 114.2 | 11.0 | 43.2 | 16.0 |
| | | 4 | 35 | - | - | - | - | - | - | - | - | - | - |
| | | 5 | 46 | - | - | - | - | - | - | - | - | - |
| | 6 | 39 | 270.4 | 34.4 | 96.7 | 31 | 222.4 | 27.9 | 83.2 | 25.9 | 149.6 | 22.5 | 60.5 | 18.7 |
| | 7 | 42 | - | - | - | - | - | - | - | - | - | - |
| | 8 | 17 | 192.3 | 45.4 | 106.2 | 27.5 | 133.6 | 41.5 | 85.4 | 15.8 | 106.2 | 37.9 | 71.0 | 14.0 |
| | 9 | 25 | 308.3 | 33.0 | 118.4 | 46.1 | 254.1 | 28.0 | 97.3 | 39.2 | 175.0 | 23.4 | 69 | 28.2 |

| Summer | 1 | 12 | 30.9 | 136.0 | 55.5 | 273.3 | 22.8 | 101.7 | 39.7 | 151.2 | 19.7 | 67.3 | 20.9 |
| | 2 | 43 | 348.5 | 30.5 | 128.1 | 58.2 | 262.7 | 27.3 | 103.8 | 45.3 | 183.7 | 25.2 | 77.1 | 27.8 |
| | 3 | 44 | 330.1 | 21.4 | 83.9 | 37.5 | 247.4 | 41.3 | 63.1 | 37.0 | 114.2 | 11.0 | 43.2 | 16.0 |
| | | 4 | 35 | - | - | - | - | - | - | - | - | - | - |
| | | 5 | 46 | - | - | - | - | - | - | - | - | - |
| | 6 | 39 | 270.4 | 34.4 | 96.7 | 31 | 222.4 | 27.9 | 83.2 | 25.9 | 149.6 | 22.5 | 60.5 | 18.7 |
| | 7 | 42 | - | - | - | - | - | - | - | - | - | - |
| | 8 | 17 | 192.3 | 45.4 | 106.2 | 27.5 | 133.6 | 41.5 | 85.4 | 15.8 | 106.2 | 37.9 | 71.0 | 14.0 |
| | 9 | 25 | 308.3 | 33.0 | 118.4 | 46.1 | 254.1 | 28.0 | 97.3 | 39.2 | 175.0 | 23.4 | 69 | 28.2 |

Overall mean | 282.8 | 29.5 | 101.3 | 38.4 | 214.5 | 24.4 | 81.5 | 30.2 | 141.2 | 18.9 | 59.7 | 19.9 |

*Standard deviation

For urban transit units, PM$_{10}$ concentration in train cabins should not be exceeded 200μg/m$^3$. Furthermore, the Korean ambient air quality standards (AAQS) of 24-hr basis PM$_{10}$ and PM$_{2.5}$ were set by 100μg/m$^3$ and 50μg/m$^3$, respectively.

Fig. 3 showed seasonal cumulative distributions of PM concentrations monitored on the Line-2, 3, 6, 8 and 9. The distributions were obtained by integrating total concentration range with respect to the frequency distribution of the PM concentration in a certain section. The cumulative distribution analysis was performed using an Excel program. The respective median concentrations of PM$_{10}$ on the Line-2, 3, 6, 8 and 9 were 122.6, 76.7, 91.1, 89.6, and 109.7μg/m$^3$ in winter [see Fig. 3(a)] and 66.2, 76.3, 72.6, 82.5, and 110.0μg/m$^3$ in summer [see Fig. 3(b)]. In addition, the respective median concentrations of PM$_{2.5}$ on the Line-2, 3, 6, 8 and 9 were 99.1, 58.3, 78.4, 85.2, and 87.8μg/m$^3$ in winter [see Fig. 3(c)] and 57.6, 61.1, 61.3, 73.9, and 97.0μg/m$^3$ in summer [see Fig. 3(d)].

The PM$_{10}$ distribution in Fig. 3(a) and (b) showed that 36% of Line-2 did not meet the IAQ standard of...
150 μg/m³ in winter, while 30% of Line-6 did not meet the standard in summer. In addition, the PM_{2.5} distributions in Fig. 3(c) and (d) showed that 99% of Line-8 did not meet the Korean AAQS of 50 μg/m³ in winter, while 95% of Line-2 as well as Line-8 did not meet the standard in summer.

3. 2 PM Mass Ratios on the Seoul Subway Lines

Particle size as one of physical parameters is important to determine the properties, effects, and fate of airborne particles. Also aerosol deposition rate as well as residence time directly affecting human health and wealth are strongly related with aerodynamic diameter (EPA, 1999). To examine the aerosol behaviors and its possible sources in the subway environment, we initially calculated the size-oriented PM mass ratios. Table 4 shows the average PM mass ratios for PM_{2.5}/PM_{10}, PM_{1}/PM_{10}, and PM_{1}/PM_{2.5} which were monitored on all the ground and underground sections on the selected Seoul subway lines.

When comparing results among subway sections, the average mass ratio of PM_{2.5}/PM_{10} was calculated by 0.78 on ground and 0.82 on underground sections.
in winter and that was also calculated by 0.84 on
ground and 0.86 on underground sections in summer.
The range of mass ratios for PM$_{2.5}$/PM$_{10}$ was 0.67-
0.78 in Taipei subway stations (Cheng et al., 2008),
0.79 in Guangzhou (Chan et al., 2002a), 0.72-0.78 in
Hong Kong subway stations (Chan et al., 2002b) and
0.76 on the ground stations and 0.73 on underground
stations in Los Angeles (Kam et al., 2011). Further the
respective mass ratios of PM$_{1}$/PM$_{10}$ and PM$_{2.5}$/PM$_{10}$
were 0.49-1.00 and 0.56-1.00 in a Shanghai subway
tunnel (Qiao et al., 2015a). The result of LA was rela-
tively close to our results obtained on the Line-4 dur-
ing summer survey. It might be natural that the mass
ratios of PM$_{1}$/PM$_{10}$ and/or PM$_{2.5}$/PM$_{10}$ were observed
to be somewhat different in every subway environ-
ment due to various control facilities, power and brake
systems, ventilation systems, and operation conditions.
Above all things, the in/out air quality near each sta-
tion should be a significant influence factor on the PM
mass ratios.

There are many internal and external PM sources
worsen the subway air quality. Internal PM is mainly
produced from mechanical wear during the period of
trains running or braking, maintenance activities as
well as construction works in tunnels, etc. (Kim et al.,
2008). It is also noted that most of the internal PM is
considered as coarse particles. According to a research
paper (Qiao et al., 2015a), the mass ratios of PM$_{1}$/
PM$_{10}$ and PM$_{2.5}$/PM$_{10}$ were higher when subway trains
went out of service since the emission activities gener-
ating coarse particles were completely ceased. On the
other hands, external PM is penetrated from various
outdoor sources like traffic emissions surrounding the
subway (Qiao et al., 2015b), where the PM penetration
into the subway is significantly assisted by mechanical
and natural type ventilations. It seems that the amount
of ventilation presumably affects the PM mass ratios
on the Seoul subway lines. During our study period,
the amount of subway ventilation was usually decreased
to keep warm air temperature from inflowing cold
ground air during winter time; however, that was
increased to reduce hot air temperature and to enhance
air quality by inflowing fresh outdoor air during the
summer time. Thus it seems that internal emissions
tend to be accumulated in subway tunnels during win-
ter, while external emissions tend to easily flow into
the tunnels during the other seasons.

In our study, it was observed that the fine propor-
tions (i.e. the mass ratios of PM$_{1}$/PM$_{10}$ and PM$_{2.5}$/
PM$_{10}$) were generally higher in summer than those in
winter and also each fine proportion was elevated on
ground sections in summer as well as on underground
sections in winter. For example, the respective PM$_{1}$/
PM$_{10}$ ratios on underground and ground sections were
0.61 and 0.62 in winter and 0.67 and 0.70 in summer.
It is presumably because the fine secondary aerosols,
mostly PM$_{1}$, are generated by photochemical reaction
during summer. It is also worth noting in this study
that the PM$_{1}$/PM$_{2.5}$ ratio was always higher on ground
sections; however, the PM$_{2.5}$/PM$_{10}$ ratio was always
higher on underground sections. It is partly because a
proportion of fine particles including PM$_{1}$ and PM$_{2.5}$
was increased on ground sections due to various anthro-
pogenic emissions such as on-road mobile source, foss-
il fuel combustion source, secondary aerosol source,
and so on. In an earlier study, the mass ratio of PM$_{2.5}$/
PM$_{10}$ for on-road vehicles was almost 1 (Jin et al.,
2012).

Fig. 4. Proportions of PM mass concentration observed during winter and summer on the Seoul subway lines.
It is necessary to figure out the behaviors of internal and external emission sources in order to improve subway air quality. According to a result from PMF (positive matrix factorization) receptor modeling study in Seoul subway tunnels, a total of 3 sources was identified and then average contribution to PM$_{10}$ mass was determined by 56.9% from brake wear-related source, 13.8% from iron-related source, and 17.9% from secondary aerosol sources (Park, 2013). Since a mass proportion of fine particle is considered to be significant in subway tunnels, it is needed to extend receptor modeling study to determine quantitative contribution to each PM$_1$ and PM$_{2.5}$ mass from various emission sources.

### 3.3 PM Size Distribution in Subway Tunnels and Outdoor

Fig. 4 shows mass concentrations of PM$_1$, PM$_{2.5}$, and PM$_{10}$ measured on the subway Line-2, 3, 6, 8, and 9 during the study periods. On the basis of PM$_{10}$ mass concentration, the sum of fine mass proportions including PM$_1$ and PM$_{2.5}$ occupied a minimum of 0.75 in winter on the Line-3 and a maximum of 0.88 in summer on the Line-8, while the range of PM$_1$ mass proportion occupied 0.51-0.71 in PM$_{10}$.

The MOE has been operating automatic monitoring networks to monitor criteria air pollutants including PM$_{2.5}$ and PM$_{10}$ on 259 monitoring sites nationwide including 27 sites in Seoul City (NIER, 2016). For our study on comparing between subway tunnel air and outdoor air, we obtained ambient PM$_{2.5}$ as well as PM$_{10}$ hour-data from the MOE. Initially we had to select each MOE monitoring site locating near the subway lines, and then we synchronized ambient MOE data with our subway data one by one basis. Fig. 5 shows a comparative result studied on both tunnel air and outdoor air for each subway line. The mass ratio range for PM$_{2.5}$/PM$_{10}$ in tunnel air was 0.76-0.89, while that in outdoor air was 0.48-0.68. In general, the ratio of PM$_{2.5}$/PM$_{10}$ was much higher in tunnel air than that in outdoor air. Especially the ratio of PM$_{2.5}$/PM$_{10}$ in outdoor air was always higher in summer than that in winter.

Fig. 6 shows the average proportions of PM$_1$, PM$_{2.5}$, and PM$_{10}$.
and PM$_{10}$ mass observed in tunnel sections, passenger cabins and outdoors on the Line-8. The outdoor PM$_{2.5}$ and PM$_{10}$ data were obtained from the MOE as mentioned earlier. The PM$_{2.5}$/PM$_{10}$ ratio in cabin air was observed to be slightly higher than that in tunnel, but the ratio was much higher than in outdoor air. It seemed from the result that fine particles generated in tunnels intruded into cabins after PSD installation more significantly than before so that tunnel air directly affected cabin air. Thus it is necessary to improve ventilation systems to block fine particle inflows from tunnels or to enhance tunnel air quality by proper controls.

4. CONCLUSION

In this study, PM$_{1}$, PM$_{2.5}$, and PM$_{10}$ concentrations had been measured by a real-time dust monitor to investigate the physical characteristics of PM on 5 lines among the 9 Seoul subway lines during winter and summer periods. The subway lines were initially separated into ground and underground sections and then size-oriented PM mass ratios were calculated to figure out the behaviors of internal and external particle sources. We calculated extensively PM mass ratios in tunnel air, passenger cabin air, and in the ambient air. The results showed that the average PM concentration was about 1.2 times higher in winter than in summer and about 1.5 times higher in underground tunnel sections than in ground sections. Since PM concentration in Korea is generally highest during the winter but lowest during the summer in the ambient air, the underground tunnel air might be seasonally influenced by the ambient air. Further, when comparing among subway sections, the average mass ratio of PM$_{2.5}$/PM$_{10}$ was calculated by 0.78 on ground and 0.82 on underground sections in winter and that was also calculated by 0.84 on ground and 0.86 on underground sections in summer. Even though the PM mass ratios in subway tunnels were mainly affected by various internal emission activities, the in/out air quality near each station was consider to a significant influence factor on the ratios. In addition, the PM$_{2.5}$/PM$_{10}$ ratio in passenger cabin air was almost similar to tunnel air, but much higher in outdoor air. It seemed that fine particles in tunnels intruded more into cabins after PSD installation. Thus a proper amount of ventilation in each subway station should be a key factor to control the subway air quality. To improve ventilation systems or to enhance tunnel air quality by proper controls, it is necessary to preferentially consider extended receptor modeling studies to determine quantitative contribution to each PM$_{1}$ and PM$_{2.5}$ mass emitted from various sources since the fine PM proportions are huge in subway environment.

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REFERENCES

Chan, C.Y., Chan, L.Y., Lau, W.L., Lee, S.C. (2002b) Commuter Exposure to Particulate Matter in Public Transportation Modes in Hong Kong. Atmospheric Environment 36(21), 3363-3373.
Chan, L.Y., Lau, W.L., Zou, S.C., Cao, Z.X., Lai, S.C. (2002a) Exposure Level of Carbon Monoxide and Respirable Suspended Particulate in Public Transportation Modes While Commuting in Urban Area of Guangzhou, China. Atmospheric Environment 36(38), 5831-5840.
Cheng, Y.H., Lin, Y.L., Liu, C.C. (2008) Levels of PM$_{10}$ and PM$_{2.5}$ in Taipei Rapid Transit System. Atmospheric Environment 42(31), 7242-7249.
Colls, J.J., Micallef, A. (1999) Measured and Modelled Concentrations and Vertical Profiles of Airborne Particulate Matter within the Boundary Layer of a Street Canyon. Science of the Total Environment 235(1), 221-233.
EPA (1999) Air Quality Criteria for Particulate Matter, Vol. 1, EPA600/P-99/002a.
Grimm Aerosol Technik (2010) Aerosol Spectrometer and Dust Monitor series 1.108 and 1.109, http://www.wmo-gaw-wcc-aerosol-physics.org/files/OPC-Grimm-model-1.108-and-1.109.pdf
Jin, H.A., Lee, J.H., Lee, K.M., Lee, H.K., Kim, B.E., Lee, D.W., Hong, Y.D. (2012) The Estimation of PM$_{2.5}$ Emissions and Their Contribution Analysis by Source Categories in Korea. Journal of Korean Society for Atmospheric Environment 28(2), 211-221.
Kam, W., Cheung, K., Daher, N., Sioutas, C. (2011) Particulate Matter (PM) Concentrations in Underground and Ground-Level Rail Systems of the Los Angeles Metro. Atmospheric Environment 45(8), 1506-1516.
Kim, K.H., Kim, J.C., Ho, D.X., Jeon, J.S. (2012) a Noticeable Shift in Particulate Matter Levels after Platform Screen-Door Installation in a Korean Subway Station. Atmospheric Environment 49, 219-223.
Kim, Y.S., Kim, C.N., Kim, K.Y., Roh, Y.M., Lee, C.M. (2008) Spatial Distribution of Particulate Matter (PM$_{10}$ and PM$_{2.5}$) in Seoul Metropolitan Subway Stations. Journal of Hazardous Materials 154(1), 440-443.
Lee, T.J., Jeon, J.S., Kim, S.D., Kim, D.S. (2010) A Comparative Study on PM$_{10}$ Source Contributions in a Seoul
The Characteristics on the Seoul Metropolitan Subway Lines

Metropolitan Subway Station before/after Installing Platform Screen Doors. Journal of Korean Society for Atmospheric Environment 26(5), 543-553.

Lee, T.J., Lim, H.J., Kim, S.D., Park, D.S., Kim, D.S. (2015) Concentration and Properties of Particulate Matter (PM$_{10}$ and PM$_{2.5}$) in the Seoul Metropolitan. Journal of Korean Society for Atmospheric Environment 31(2), 164-172.

Ministry of Environment (2014) http://www.me.go.kr

NIER (2016) National Institute of Environmental Research, Annual Report of Air Quality in Korea 2015.

Park, S.B.S.N. (2013) Chemical Characteristics of PM$_{10}$ and Identification of its Sources in a Seoul Metropolitan Subway Station, Kyung Hee University Master Thesis.

Qiao, T., Xiu, G., Zheng, Y., Yang, J., Wang, L. (2015a) Preliminary Investigation of PM$_{1}$, PM$_{2.5}$, PM$_{10}$ and its Metal Elemental Composition in Tunnels at a Subway Station in Shanghai, China. Transportation Research Part D 41, 136-146.

Seoul Metropolitan Government (2015) Transportation allotment rate, http://traffic.seoul.go.kr/archives/289

Seoul Metropolitan Government (2016) Subway statistics, http://traffic.seoul.go.kr/archives/296

Son, Y.S., Salama, A., Jeong, H.S., Kim, S.H., Jeong, J.H., Lee, J.H., Sunwoo, Y., Kim, J.C. (2013) The Effect of Platform Screen Doors on PM$_{10}$ Levels in a Subway Station and a Trial to Reduce PM$_{10}$ in Tunnels. Asian Journal of Atmospheric Environment 7(1), 38-47.

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