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Investigation of Diurnal Pattern of Generation and Resuspension of Particles Induced by Moving Subway Trains in an Underground Tunnel

Sang-Hee Woo[1,2], Jong Bum Kim[2], Gwi-Nam Bae[2,3*], Moon Se Hwang[4], Gil Hun Tahk[4], Hwa Hyun Yoon[4], Se-Jin Yook[1*]

[1] *School of Mechanical Engineering, Hanyang University, Seoul 04763, Korea*
[2] *Center for Environment, Health and Welfare Research, Korea Institute of Science and Technology, Seoul 02792, Korea*
[3] *Energy and Environmental Engineering, University of Science and Technology, Daejeon 34113, Korea*
[4] *Technology Research Center, Seoul Metropolitan Rapid Transit Corporation, Seoul 04806, Korea*
[5] *Transportation Environmental Research Team, Korea Railway Research Institute, Uiwang 16105, Korea*

ABSTRACT

To protect the health of subway users, it is essential to investigate the generation, resuspension, and decay of particles in underground tunnels. In this paper, we analyzed the diurnal pattern of variation in particle concentration in a subway tunnel. The mass concentration of particles was measured in a shelter located midway in the underground tunnel connecting Janghanpyeong station and Gunja station on Seoul Subway Line 5 by using an aerodynamic particle sizer, a dust monitor, and a fast mobility particle sizer. The particle mass concentration increased uniformly as a train passed through the tunnel, which was followed by an exponential decay. The particle concentration in the tunnel decreased when the decrease in the number of particles between train operations exceeded the number of particles generated and resuspended by a passing train, and increased in the opposite case. The diurnal variation in particle concentration in the tunnel according to train operations can be predicted by applying such a pattern of variation to the mass concentration of particles.

Keywords: Aerosol; Particle concentration; Subway; Underground tunnel; Train operation.

INTRODUCTION

Particulate matter is a representative airborne pollutant and carcinogen that increases the risks of heart disease and lung cancer (Pope *et al.*, 2002, 2004). In a big city, many types of sources including dust scattering on roads and smoke emit particulate matter. Especially, subway trains also generate very toxic particulate matter, which should be effectively controlled. In Seoul, the annual subway ridership is more than 2.6 billion people (www.seoulmetro.co.kr), which is equivalent to 260 times the population of this city. This means that quite a large number of people are exposed to particulate matter in the subway system. The airborne particles in underground tunnels consist mostly of metals such as Fe, Mn, Ni, Cr, and Cu (Aarnio *et al.*, 2005; Salma *et al.*, 2007). These subway particles are 8 times more genotoxic and 4 times more likely to cause oxidative stress of lung cells than urban roads particles (Karlsson *et al.*, 2005). Besides, the particle concentration of an underground tunnel is usually higher than the concentration of urban road particles (Johansson and Johansson 2003; Aarnio *et al.*, 2005).

As the subway particulate matter has a great effect on the health of people in a big city, there have already been many studies on this matter internationally (Pfeifer *et al.*, 1999; Furuya *et al.*, 2001; Johansson and Johansson 2003; Chillrud *et al.*, 2004; Aarnio *et al.*, 2005; Seaton *et al.*, 2005; Branis 2006; Ripanucci *et al.*, 2006; Salma *et al.*, 2007; Cheng *et al.*, 2008; Kim *et al.*, 2008; Park and Ha; 2008; Jung *et al.*, 2010; Midander *et al.*, 2012; Fan *et al.*, 2017; Zhang *et al.*, 2017). Although the measurements of PM_{10} and $PM_{2.5}$, which were obtained from subway platforms and trains around the world, showed a wide range of 41–469 µg m^{-3} and 21–258 µg m^{-3} respectively, almost every case exceeded the WHO guideline for average 24-hour PM levels, which are 50 and 25 µg m^{-3} respectively. Jung *et al.* (2010) and Kim *et al.* (2010) collected particle samples from Seoul Metro stations and analyzed that the more distant from an underground tunnel the less the particle concentration and Fe content. It was also reported that other subway station platforms in other countries showed a high level of Fe content. Based on these measurements, the friction of train wheels and rails has been picked out as a main cause of subway particulate matter (Birenzige *et al.*, 2003; Chillrud, 2004; Aarnio *et al.*, 2005; Salma *et al.*, 2007).

* Corresponding author.
E-mail address: gnbae@kist.re.kr (G.N. Bae);
ysjnuri@hanyang.ac.kr (S.J. Yook)

However, although the subway operation is clearly a cause of high particle concentrations in an underground tunnel, only a few studies have addressed the effect of subway operation on particle concentrations in an underground tunnel. These studies presented a correlation between the train interval and the particle concentration (Johansson and Johansson, 2003; Salma *et al.*, 2007). In these papers, the PM concentrations were in a linear proportion to the train interval. Especially, Salma *et al.* (2007) showed that the train-induced wind increased steeply the particle concentration on a subway platform and the concentration decreased steeply after the train left the platform. The particles flowing into a platform along with an approaching train obviously came from an underground tunnel connecting stations. However, few studies have been done on how the particle concentration varies in an underground tunnel. Thus, if the generation, resuspension, and decay of particles in an underground tunnel could be identified in terms of subway train operation, we would be able to predict the diurnal variation of particle concentration only from train interval. Moreover, if the variation of particle concentration in an underground tunnel could be successfully predicted, such predictions will be useful data for preparing a method of reducing particulate matter in a subway system (Chen *et al.*, 2017; Sim *et al.*, 2017).

In this paper, we measured the variation of particle concentration in an underground tunnel according to train operation, and analyzed the characteristics of particle generation, resuspension, and decay in terms of train interval. To minimize the influence of other factors like the operation of train brakes and the movements of passengers getting on or out of a train, the measurement was conducted at a shelter located midway in a tunnel connecting stations, where a train runs at a constant velocity. From the analysis, it was found that the particle concentration had a unique pattern of increase and decrease according to train operation. We also used the pattern to predict the diurnal variation of particle concentration in the tunnel only from the information of train operation.

EXPERIMENTAL

Monitoring Location

The measurement was performed at a shelter located in an underground tunnel between Janghanpyeong station and Gunja station on Seoul Subway Line 5 (See Fig. 1(a)). The tunnel length was 1400 m. The measurement point was 586 m distant from the center of Janghanpyeong station platform in order to exclude the influence of events like the passenger movements or the operation of screen doors on the platform. A train consisted of 8 cars. Each car was 20 m in length, and the total length of a train was 160 m. As shown in Fig. 1(b), two horseshoe tunnels were separated by a shelter. A sliding door was installed at the shelter, but it was closed during the measurement in order to exclude the effect of the opposite track. Although the sampling instrument needed to be installed as close as possible to a passing train, it was set up 3.4 m away from the rail due to safety. As shown in Fig. 1(c), the sampling inlet was installed 1.5 m above the ground, and the measuring instruments were arranged to face an approaching train to minimize the influence of air recirculation in the shelter.

Fig. 2 shows the velocities of trains in the section between two stations. Every train ran at the constant velocity of 72 km h^{-1} at the measurement point. We conducted the measurement from January 27 to February 2, 2016. January 30 and 31 were weekend days. The first and last trains passed the measurement point at 6:00 a.m. and 1:00 a.m, respectively. The outside atmospheric temperature ranged from –6.5°C to 6.3°C and the weather was fine for the 7 days. During the period, the temperature and humidity of the tunnel were maintained constantly at 12–15°C and 25–50% respectively.

Monitoring Instruments

A closed-circuit television was used to check the time

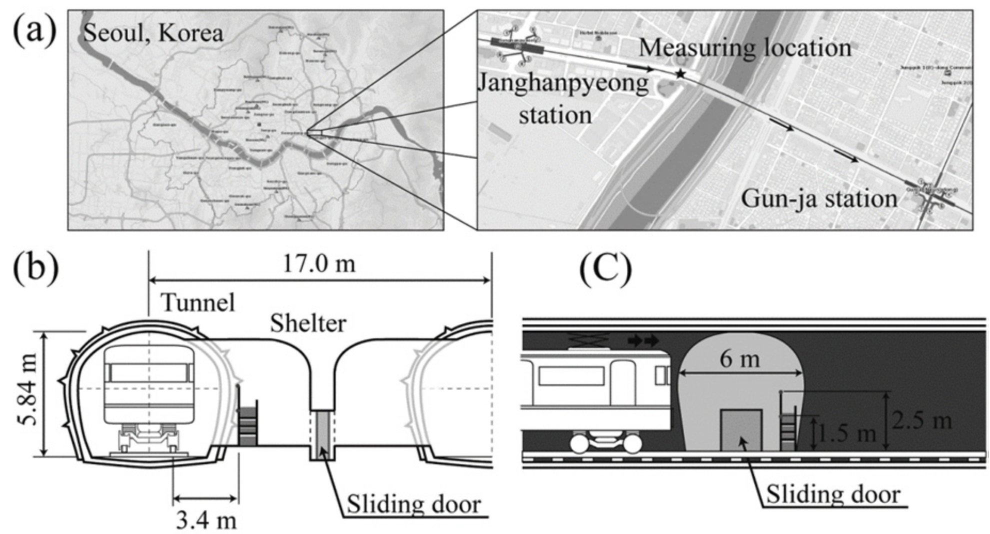

Fig. 1. Measurement site information: (a) location of the measurement site, (b) cross-sectional view of the tunnel at measurement site, and (c) side view of tunnel at measurement site.

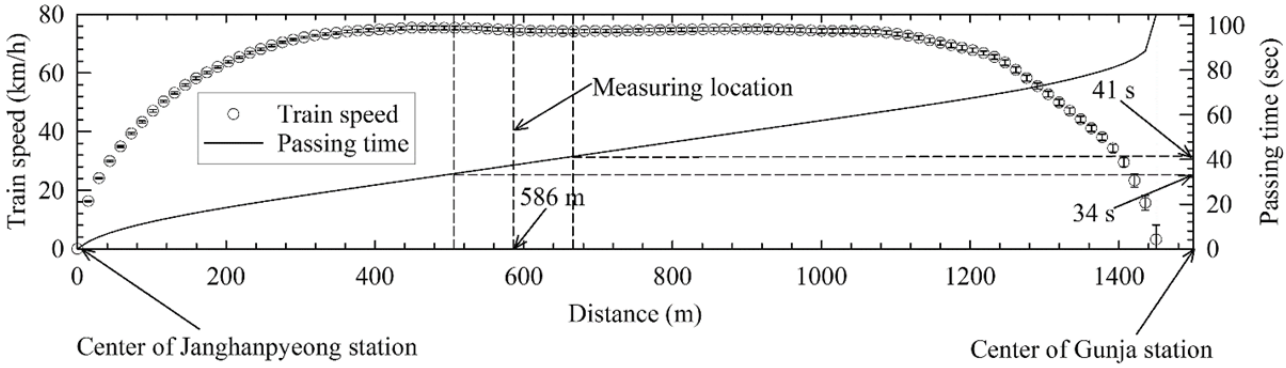

Fig. 2. Speed and passing time of a subway train.

when a train passed. The most accurate method of measuring the mass concentration of aerosol is to directly measure the weight of particles, as in a gravimetric method. However, the gravimetric method is not available for real-time measurement, since it needs collecting particles on a filter for a sufficient time to achieve a measurable weight. On the other hand, the DustTrak uses an optical method and can measure particles in real-time. For this reason, it has been adopted in many studies to measure particle concentrations on subway platforms and in trains (Chan *et al.*, 2002a, b; Branis, 2006; Cheng *et al.*, 2008). In this study, it took about 8 seconds for an 8-car train to pass the measurement point completely. However, the resolution time of DustTrak was 6 seconds. Accordingly, it was concluded that the DustTrak was inadequate to measure a momentary change of particle concentration due to a running train in the tunnel. We used an aerodynamic particle sizer (APS 3321, TSI, USA) and a fast mobility particle size spectrometer (FMPS 2091, TSI, USA), which had a much shorter resolution time. The DustTrak, APS, and FMPS all collected samples by using flow splitter in a single inlet.

APS accelerates aerosol through a nozzle, measures the time for a particle to pass the distance between two lasers, and converts the time to an aerodynamic size of particle. As the minimum resolution time of APS was 1 second, which enabled quick measurement, APS was utilized to measure airborne particles in many studies (Brand *et al.*, 1991; Shi *et al.*, 2001; Shen *et al.*, 2002; Yanosky *et al.*, 2002). However, since APS measures a number concentration of particles, if the measured density and shape of particles are different from those of particles used for calibration, the converted mass concentration becomes erroneous (Peters and Leith, 2003). Hence, in order to know a mass concentration through APS, the effective density and the dynamic shape factor should be given (Peters, 2006). It is known that subway particles have a relatively constant Fe content of 60–70% (Aarnio *et al.*, 2005; Salma *et al.*, 2007) and the subway particle samples collected from each site do not have quite a different shape (Ripanucci *et al.*, 2006; Jung *et al.*, 2012). Consequently, referring to the existing studies (Salma *et al.*, 2007; Martins *et al.*, 2015), we assumed the effective density and the dynamic shape factor of subway particles to be 4 g cm^{-3} and 1.4, respectively. The aerodynamic diameter (d_{ae}) of particles, which was measured by APS, was converted to a volume equivalent diameter (d_{ve}) by the following equation (Peters, 2006).

$$d_{ve} = d_{ae}\sqrt{\frac{\rho_0 C_{ae}\chi}{\rho_p C_{ve}}} \quad (1)$$

here, ρ_0 is the unit density of 1 g cm^{-3}, ρ_p is the density of measured particles, C_{ae} and C_{ve} are the slip correction factors for the aerodynamic diameter and the volume equivalent diameter, respectively, and χ is the dynamic shape factor of particles. The particle mass concentration (dM_i) for the *i*th size bin was calculated from the calculated volume equivalent diameter, as follows.

$$dM_i = \frac{\pi\rho_p d_{ve}^3}{6} \times dN_i \quad (2)$$

here, dN_i is the number concentration measured at the *i*th size bin of APS.

Since APS could measure particles with the size of 0.5 µm or above, FMPS was additionally used to measure nanoparticles. FMPS measured particles of 6–523 nm in size. FMPS measures particle mass concentration by classifying the size of charged particles according to their electrical mobility diameter (d_e) and measuring the charge of aerosol. Here, d_e was converted to d_{ve} as follows (DeCarlo *et al.*, 2004).

$$d_{ve} = \frac{C_{ve} d_e}{C_e \chi_t} \quad (3)$$

here, C_e is the slip correction factor based on the electrical mobility diameter, and χ_t is the shape factor of transmission regime. According to DeCarlo *et al.* (2004), if the dynamic shape factor is 1.4, χ is equal to χ_t. The particle mass concentration measured by FMPS was also obtained from Eq. (2).

RESULTS AND DISCUSSION

Fig. 3 presents the diurnal variation of mass concentration of tunnel particles. The mass concentrations measured by

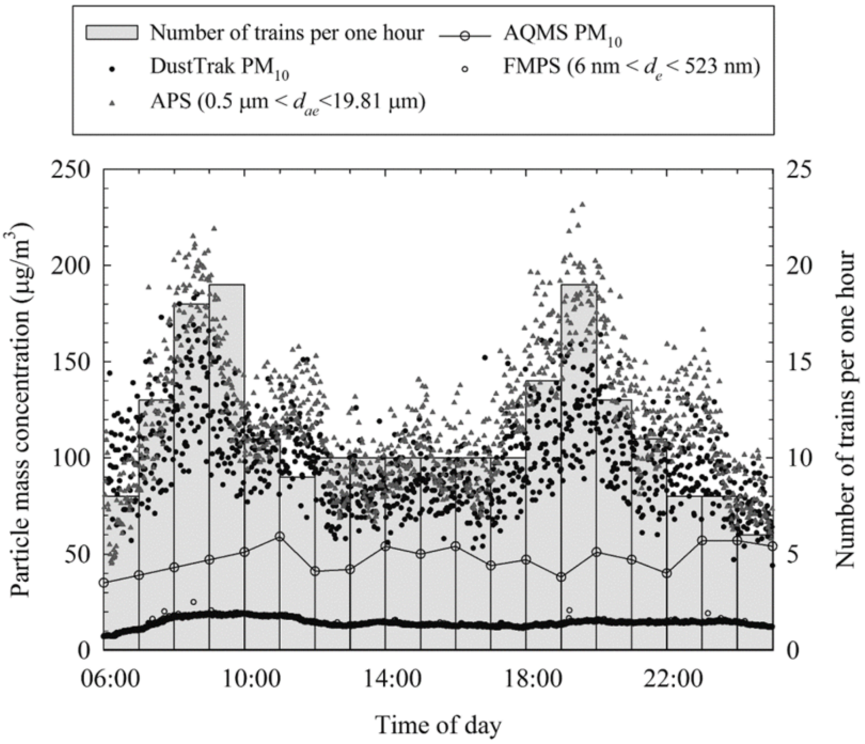

Fig. 3. Diurnal variation of particle mass concentration measured by APS, FMPS, and DustTrak, according to the number of trains per one hour.

DustTrak and APS during the subway operating hours were 50–180 µg m^{-3} and 50–240 µg m^{-3}, respectively. The measurements of FMPS for nanoparticles ranged between 6 and 20 µg m^{-3}. The measurements of FMPS were converted by applying 4 g cm^{-3}, which was the effective density of subway particles, and added to those of APS. The result was the mass concentration of subway particles covering both sub-micron and micron particles, and turned out to be about 1.4 times that of DustTrak. The DustTrak is usually calibrated by using Arizona test dust (ISO 12013-1), of which density is 2.65 g cm^{-3}. If this density is multiplied by 1.5 times, the result becomes almost equal to 4 g cm^{-3} that is the effective density of subway particles. For this reason, it was estimated that the mass concentration converted through the effective density of 4 g cm^{-3} was about 1.4 times higher than the measurement of DustTrak. The mass concentration of tunnel particles tended to increase linearly during the morning rush hour from 6:00 a.m., when the first train was passing, to 9:00 a.m. Then, as the number of trains per one hour (NTH) decreased steeply, the mass concentration marked a sharp drop. From 11:00 a.m. to 6:00 p.m., where the subway trains were operated at a constant interval, the mass concentration of tunnel particles was maintained at a generally constant level. After that, from 6:00 p.m. to 8:00 p.m., which corresponds to the evening rush hour, the mass concentration increased linearly again, and then decreased until 1:00 a.m., when the last train passed. The peak of mass concentration during morning and evening rush hours was already observed in the existing studies (Johansson and Johansson, 2003; Salma *et al.*, 2007). Fig. 3 also shows the average mass concentrations measured at 5 ground observatories located within 4 km radius of the tunnel by using the air quality monitoring system (AQMS). As the AQMS measurements showed a constant level of 30–50 µg m^{-3} from morning to night, they had little effect on the diurnal variation of mass concentration of tunnel particles.

As shown in Fig. 4, along with the existing studies, this study shows that the mass concentration of tunnel particles was generally in a linear proportion to NTH. Thus, it is estimated that the diurnal variation of mass concentration of subway particles is much affected by train operation. Since each of the studies shown in Fig. 4 was conducted in a different measurement environment, the gradient of mass concentration proportional to NTH appeared to be different in each case. In previous studies of Johansson and Johansson (2003) and Salma *et al.* (2007), particle mass concentrations were measured at the subway station platforms where the particle concentration might be influenced by many factors. In the present study, particle mass concentrations were monitored in a more controlled environment, i.e., in the middle of the subway tunnel where the particle concentration was mostly affected by the passing of subway trains. As a result, the standard deviation (σ) of the present study's data was estimated to be lower than those of Johansson and Johansson (2003) and Salma *et al.* (2007).

Fig. 5 shows the comparison of particle number concentrations measured before and after a subway train passed by. Particle number concentrations were much higher for sub-micron particles than for micron particles, and peak appeared at around 0.1 µm. The change of particle number concentration due to the passing of a subway train was almost negligible for sub-micron particles, whereas particle

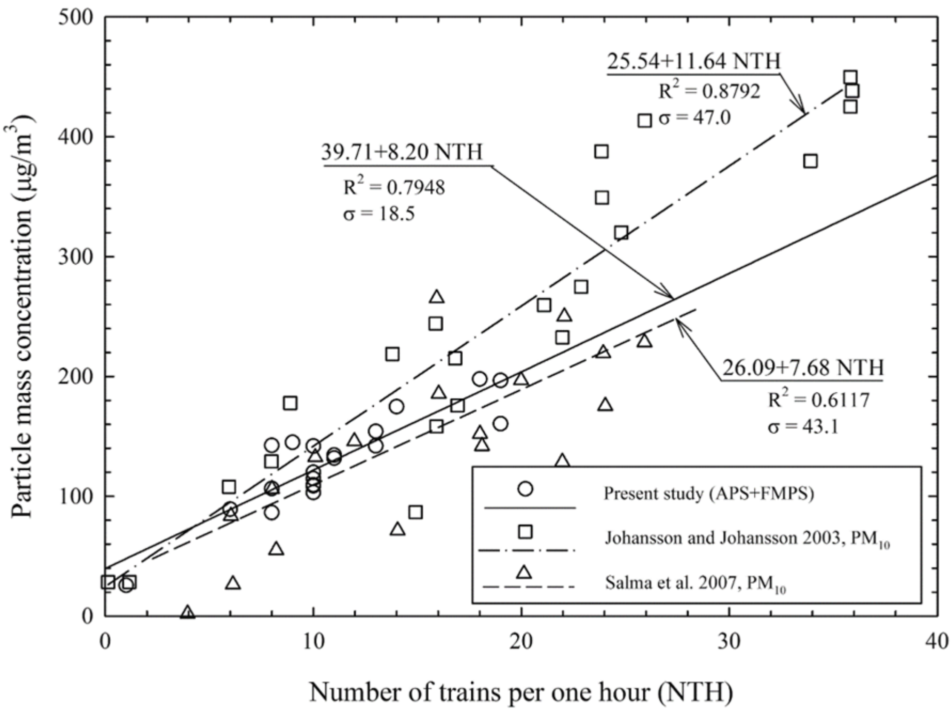

Fig. 4. Correlation between number of trains per one hour and particle mass concentration.

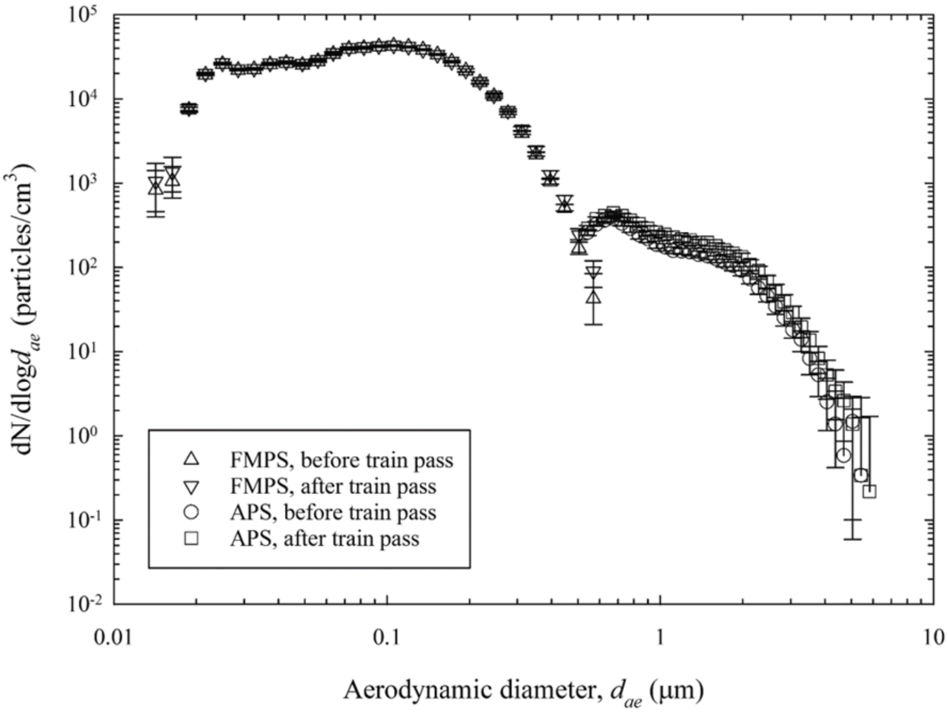

Fig. 5. Particle number concentration distribution measured by FMPS and APS.

number concentration slightly increased for micron particles after the subway train passed by. This implies that the particles generated and/or resuspended by the passing of a subway train in an underground tunnel are mostly in micron size range. However, as displayed in Fig. 5, the influence of a passing subway train on the change of particle number concentration looked unnoticeable, implying that diurnal pattern of generation and resuspension of particles induced by moving subway trains in an underground tunnel cannot be effectively analyzed in terms of particle number concentration.

Fig. 6 illustrates particle mass concentrations measured before and after a train passed by using FMPS and APS. Those particles smaller than 0.5 μm, which were measured by FMPS, showed little variation in mass concentration.

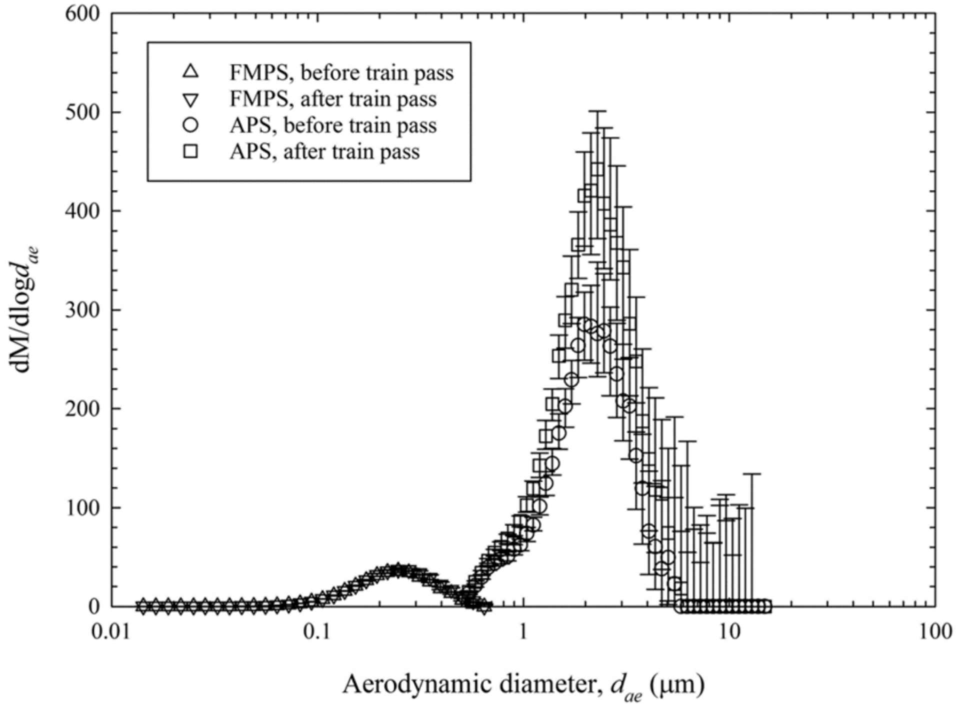

Fig. 6. Particle mass concentration distribution measured by FMPS and APS.

On the other hand, the remaining particles larger than 0.5 µm, which were measured by APS, increased their mass concentration steeply after a train passed. It turned out that micrometer-sized particles mostly decreased or increased their mass concentration due to train operation. For this reason, the particle mass concentrations measured by APS and DustTrak were analyzed. Moreover, as APS had a shorter resolution time than DustTrak and thus was easier to identify a trend, we analyzed the APS measurements first and then extended the result to the DustTrak measurements.

Since the proportion between NTH and mass concentration of tunnel particles indicates that the influence of a single train is repeated with high reproducibility, we considered train intervals to analyze the pattern of variation in particle concentration shown while a train passed. As the train interval is the time difference between trains passing the measurement point, it is proportional to the inverse of NTH. Fig. 7 shows variations of mass concentration for the passing of a single train with the intervals of 2–3 min, 5–7 min, and 10 min or longer. The measurements were obtained by APS. The *x*-axis indicates the distance between the measurement point and the head of a train. Negative values mean that a train has not passed the measurement location yet, while positive values indicate that the train has passed. In Figs. 7(a), 7(b) and 7(c), the mass concentrations according to train interval are 152–199 µg m^{-3}, 96–148 µg m^{-3}, and 61–107 µg m^{-3}, respectively. Accordingly, it turns out that the shorter the train interval the higher the mass concentration of tunnel particles.

Fig. 8(a) shows the variation of mass concentration of tunnel particles according to train operation by setting the initial mass concentration, at the measurement point and the moment when a train started the station, to 0 g cm^{-3}. The result is a pattern obtained from the measurements of APS. As the train-induced wind was a turbulent flow with a large kinetic energy, the measurement result had a large spread. However, the variation pattern of mass concentration in the tunnel tended to be constant irrespective of train interval. This means that the mass concentration of tunnel particles increased at a relatively constant rate when particles were generated and resuspended by a running train.

As illustrated in Fig. 8(a), the generalized pattern of variation in the mass concentration of particles could be divided into 4 sections. The mass concentration was maintained almost constantly while a train stated from Janghanpyeong station and arrived at a point where it became about 200 m distant from the measurement point (P_{stable} section). From this point, the mass concentration began to increase and kept rising linearly until the tail of the train passed the measurement point ($P_{inc,1}$ section). According to Lee *et al.* (2016), the particles generated by the friction of wheels and track cannot move ahead of the running train. Accordingly, the increment of particle concentration at the measurement point before the train passed is mainly due to the particle resuspension caused by train-induced wind. Then, the mass concentration of particles increased with a lower gradient than in $P_{inc.1}$ section until the head of the train was about 480 m distant from the measurement point ($P_{inc,2}$ section). This seems to be because particles were resuspended or new particles were generated to the extent that the wake of the passing train increased the turbulence intensity. As the train was moving further away, the mass concentration decreased gradually (P_{dec} section). It is estimated that, as the influence of train-induced wind disappeared from the measurement point, particles were deposited by gravitational settling. Moreover, as shown in Fig. 8(b), the measurements of DustTrak showed a similar trend to those of APS. The mass concentration at the measurement point before a train started from Janghanpyeong station was again set as the initial concentration, i.e., 0 µg m^{-3}. As is clear from Fig. 8(b), the mass concentration of particles at the measurement point in the tunnel began to increase and the increasing gradient changed at similar points to those of APS measurements. However, the mass concentration began to

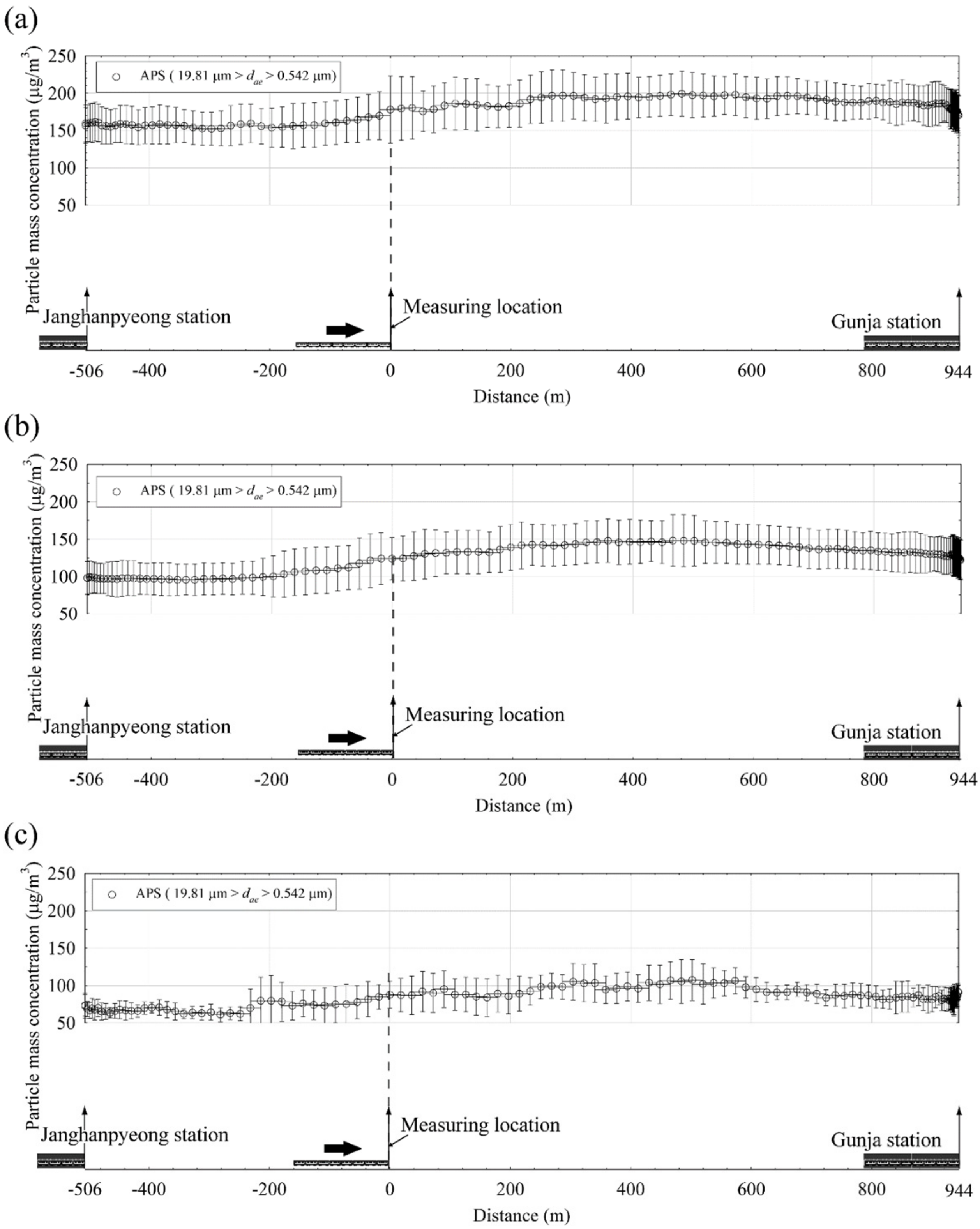

Fig. 7. Change of particle mass concentration at measurement site according to train position in the tunnel: (a) train interval of 2–3 min, (b) train interval of 5–7 min, and (c) train interval of 10 min or longer.

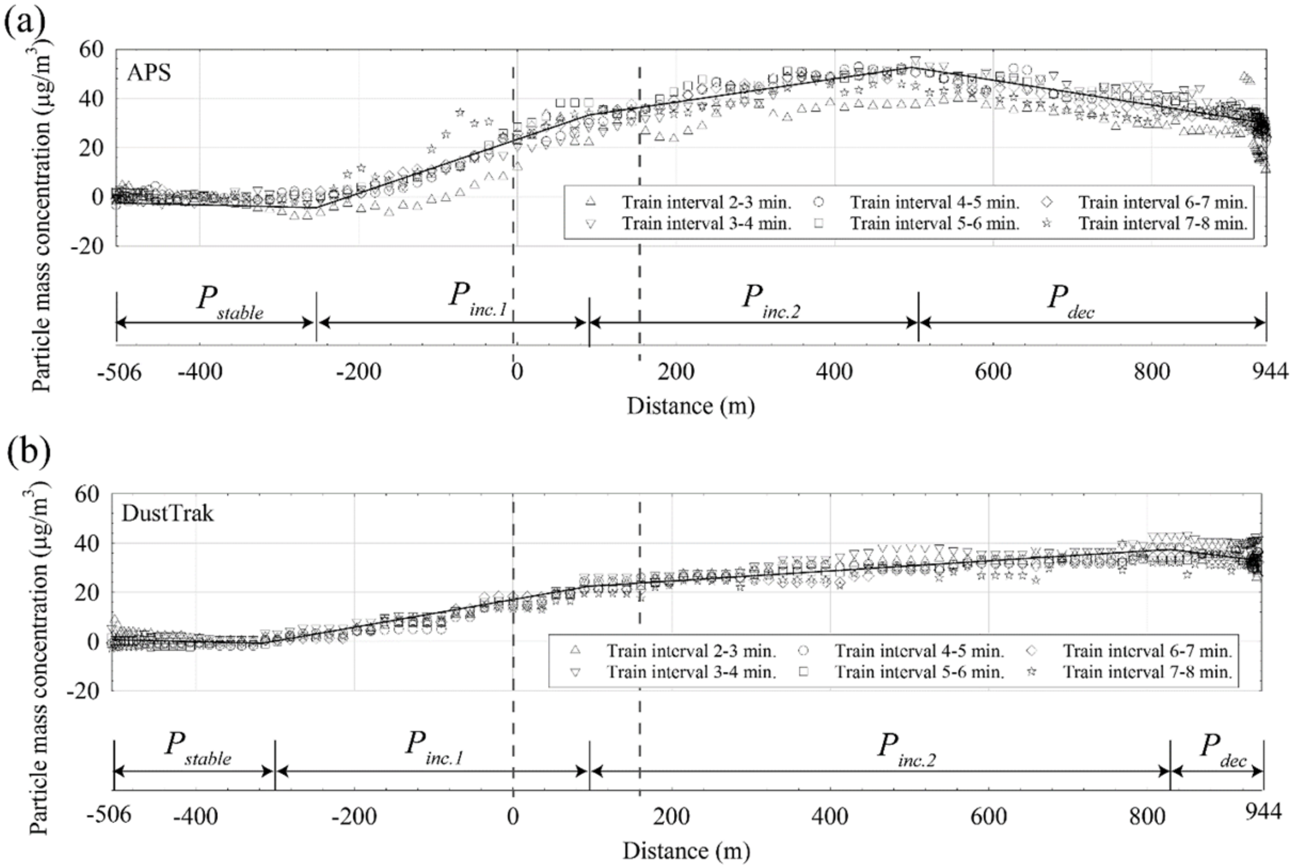

Fig. 8. Variation of particle mass concentration in reference to particle mass concentration at the measurement site and the moment when a train started the station, measured by: (a) APS and (b) DustTrak.

decrease at a later time in DustTrak than in APS.

In the case of stirred settling, the particle concentration usually decreases exponentially (Hinds, 1999). During weekdays, 220 trains on average were operated every day. Eq. (4) below was used to obtain an exponential regression curve representing the trend where the particle concentration in the tunnel increased due to the passing of each train and then decreased until being affected by the next train. Fig. 9 shows the fitting constants of each case.

$$m(\tau) = m_i \exp(-\alpha\tau) \qquad (4)$$

here, τ is the time elapsed (min) after the increase in particle concentration caused by each train reaches its peak, in other words, the time elapsed from 0 min, which is the moment where $P_{inc.2}$ section ends; m is the mass concentration of particles; and m_i is the peak value of the mass concentration after each train passed, in other words, the mass concentration at the point where $P_{inc.2}$ section ends. The exponent α is the reduction coefficient. As shown in Fig. 9(a), m_i was 1.0312 times the maximum measurement of mass concentration, which indicates almost the same level. As shown in Fig. 9(b), the data of α showed an increasing trend. In other words, as the NTH increased or the time interval between the trains decreased, the particle concentration level in the underground tunnel became higher and the particle mass concentration decayed more rapidly, resulting in the increase of α. A linear regression line to represent the increasing trend of α is displayed in Fig. 9(b).

The above analysis result showed that the mass concentration had a relatively constant trend of increase or decrease during the operation of each train. In other words, as the increment or decrement of mass concentration could be identified according to train operation, it was possible to predict the diurnal variation of mass concentration of tunnel particles. As illustrated in Fig. 10, the mass concentration varies in a constant pattern whenever a train passes the measurement point. Before the first train starts running, all the particles, which were generated or resuspended the previous day, are settled so that the particle concentration in the tunnel becomes m_0. From the time t_i, which corresponds to 18 seconds before the passing of the ith train, the particle concentration in the tunnel begins to increase due to train-induced wind. According to Fig. 10, the mass concentration increases steadily by m_G for 40 seconds from t_i so that it becomes $m_{I,i}$. Based on the result of Fig. 9(a), as for the increase of mass concentration of particles in the tunnel due to each passing train, the experimental measurements were almost equal to the calculations from curve fitting. For this reason, we could set m_i to be $m_{I,i}$. Then, the mass concentration decreases until the time t_{i+1}, which corresponds to 18 seconds before the passing of the next train. Here, if the train interval between t_i and t_{i+1} is τ_i, the mass concentration decreases during τ_i by $D_i(= m_{I,i} \cdot \exp(-\alpha\tau_i))$ on the basis of

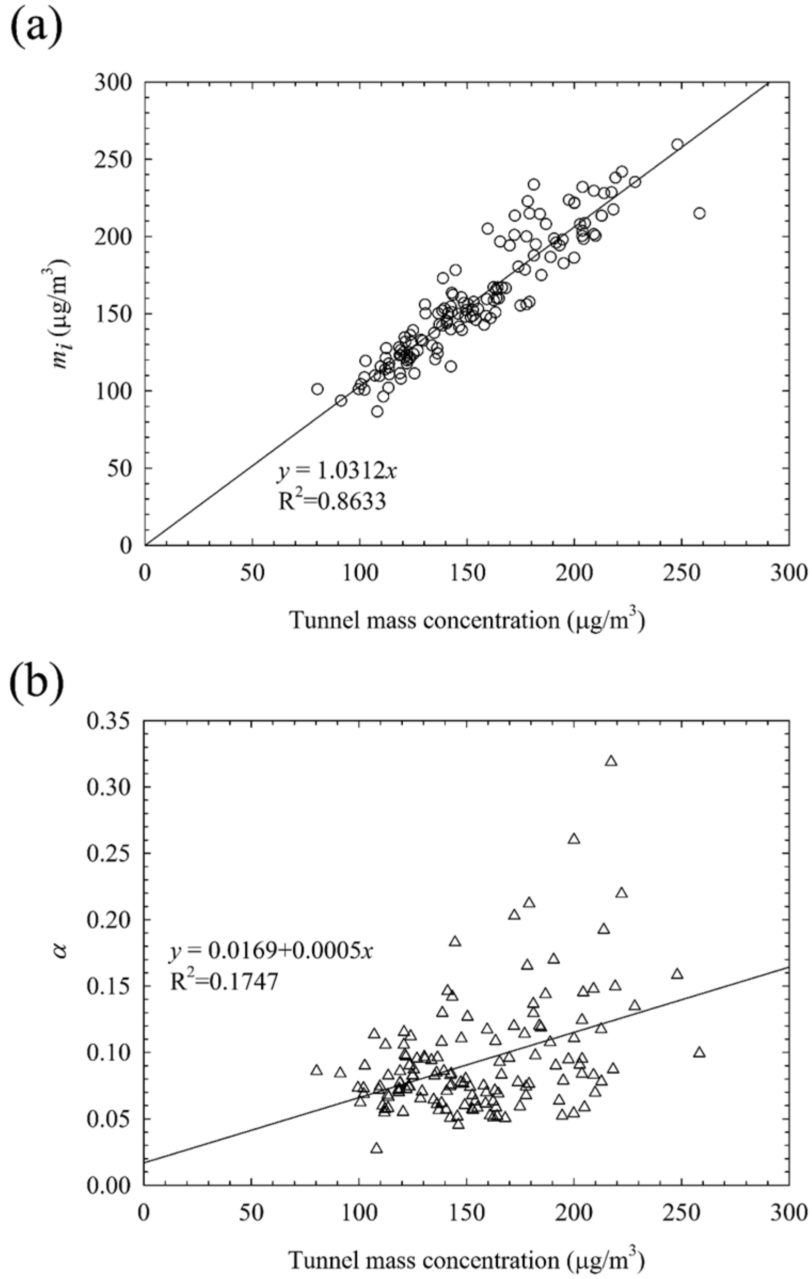

Fig. 9. Correlation between tunnel particle mass concentration and fitting constants of Eq. (4): (a) m_i and (b) α.

Eq. (4). If the increase and decrease of mass concentration caused by each subsequent train is considered, it is possible to predict the diurnal variation of particles in the tunnel. This approach seems to be applicable to other tunnels on the condition that the increment m_G of mass concentration and the reduction coefficient α for the section where a train runs at a constant velocity are obtained from measurement.

Fig. 11 compares the diurnal variation of mass concentration between APS measurements and the predictions acquired by using Eq. (4) and the concepts of Fig. 10. From the analysis results of APS measurements in Figs. 8(a) and 9(b), m_G was set to 48 g m^{-3} and α was assumed to increase linearly with the particle mass concentration level in the underground tunnel. The predictions and the measurements matched well both in the overall trend and the mass concentration.

The measurement using APS was conducted only on one day during the week, while the measurement using DustTrak was carried out for 7 days including weekdays and weekend days. Fig. 12 makes a comparison between the predictions of the proposed model and the measurements of DustTrak. The reduction coefficient of the model, α, was assumed to increase linearly with the tunnel mass concentration, which had been obtained from the analysis of DustTrak data as in Fig. 9. The increment of mass concentration m_G caused by the particle generation and resuspension, which is attributable to train operation, was set to 36 g m^{-3}, on the basis of the DustTrak measurements in Fig. 8(b). The comparison with the DustTrak measurements also clarified that the variation pattern of mass concentration during weekdays and weekend days can be satisfactorily predicted. From the results so far, it follows that the proposed model of this study can predict well the diurnal variation of mass concentration of particles in an underground tunnel.

CONCLUSION

In this study, we measured mass concentrations of particles in a shelter located midway in an underground subway tunnel in order to see the generation and the decay of particles due to train operations. APS, FMPS, and DustTrak

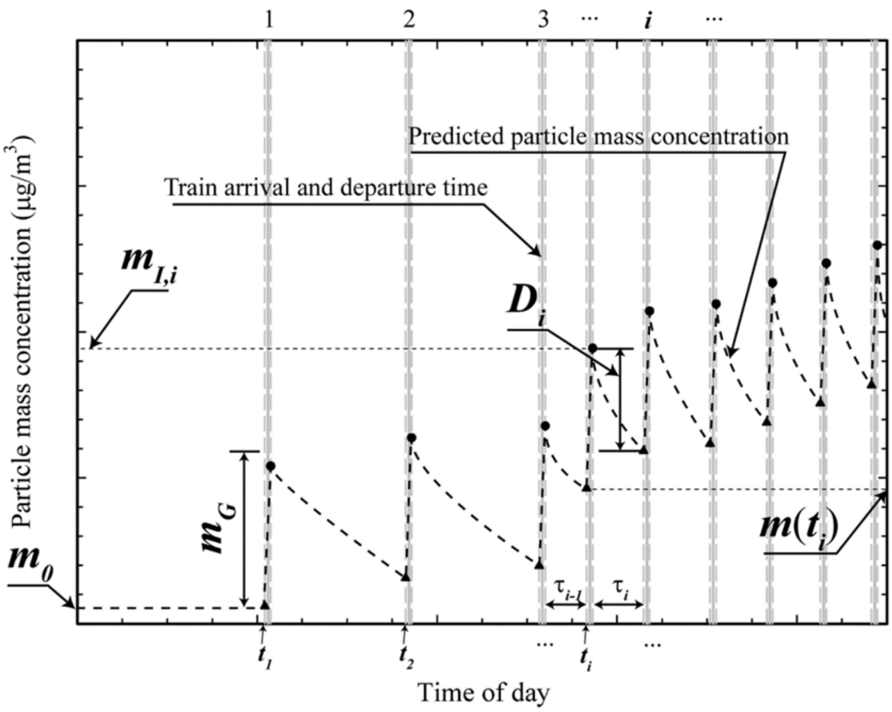

Fig. 10. Concept of the proposed model to predict tunnel particle mass concentration.

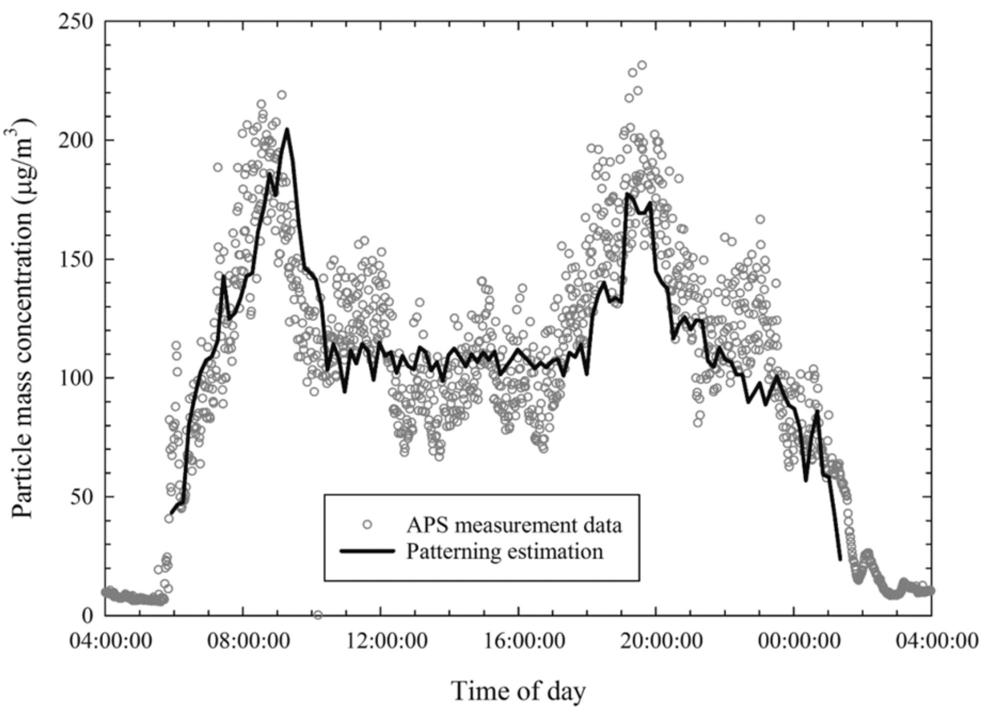

Fig. 11. Comparison of diurnal variation of particle mass concentration between APS measurements and the predictions acquired by Eq. (4) and the concepts of Fig. 9.

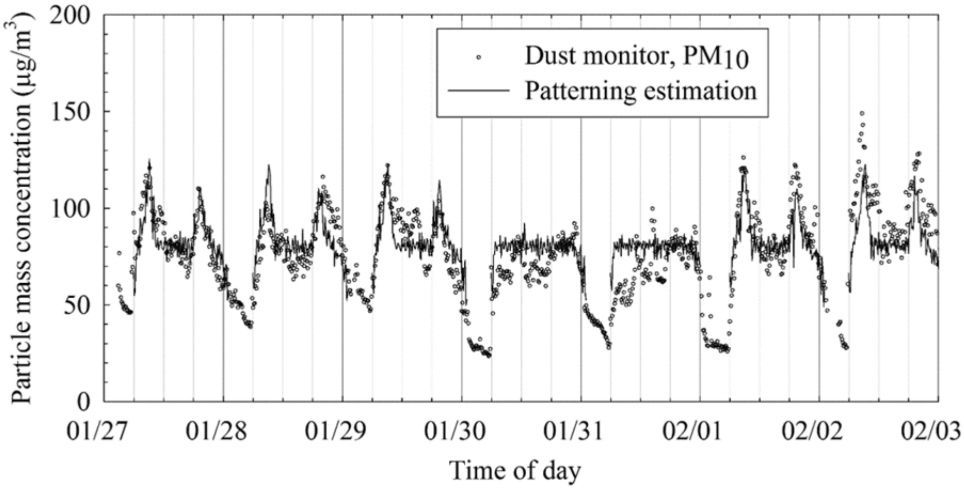

Fig. 12. Comparison of diurnal variation of particle mass concentration between DustTrak measurements and the predictions acquired by Eq. (4) and the concepts of Fig. 9.

were used for the measurement. A total of 220 trains passed the measurement point at a constant velocity of 72 km h^{-1} during weekdays. The mass concentration varied in proportion to the number of trains per one hour (NTH). When a train passed the tunnel connecting the two stations, the absolute value of the variation in mass concentration varied according to the train interval. However, if the mass concentration before the passing of a train was set to 0 μg m^{-3}, the increment of the concentration was constant, irrespective of the train interval, and the patterns of increase and decrease were almost identical. Based on this result, we proposed a model that predicts the increment and decrement of the mass concentration of particles in a tunnel according to the train operation and that considers the train intervals during a day, thereby predicting the diurnal variation in mass concentration. The predictions of the diurnal variation obtained from this model agreed well with the measurements acquired by using APS for a day and DustTrak for 7 days. This result verified the accuracy and excellence of the proposed model.

The particles generated and resuspended in a tunnel flow into a running train and onto the platform. For this reason, if the proposed model is utilized to predict the diurnal variation in mass concentration in a tunnel, the predictions will be very useful data for preparing a method of reducing the level of particulate contamination in a subway environment. It is also expected that the proposed model will be applied to other tunnels. However, the increment m_G of mass concentration due to the passing of a single train and the reduction coefficient α may vary depending on the shape and cleanliness of a tunnel; the shape, length and velocity of a train; and the seasonal temperature and humidity. Therefore, further studies need to address the effect of such factors concerning train operations and tunnel environment on m_G and α.

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CONFLICT OF INTEREST

The author states that there are no conflicts of interest.

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