Generation Characteristics of Nanoparticles Emitted from Subways in Operation

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ABSTRACT

In this study, measurements were carried out to identify the generation characteristics of wear particles emitted under a subway cabin during operation. Along with a fast mobility particle sizer, probes were installed under a subway cabin and in a subway tunnel to measure the size distributions of nanoparticles at 1-s intervals. Based on the particle density measured under the cabin minus that measured in the tunnel, the size distribution of wear particles generated under the cabin during deceleration was estimated to be bimodal at 165.5 nm and 6.98 nm. These particles were most likely generated from wheel-rail contact, as the train utilized electric braking (no mechanical force applied). In addition, a change in the wear mechanism appears to have arisen due to the increased temperature of the wheel-rail contact while nanoparticles were being emitted, leading to an initial generation of 165.5-nm particles followed by 6.98-nm particles 1 s later.

Keywords: Nanoparticle size distribution; Urban railway; Wear particle; Wheel-rail contact.

INTRODUCTION

Metropolitan areas around the world continue to build new subway systems or expand existing ones as a primary transportation system to address traffic congestion. Subway vehicles, however, are enclosed and are structurally prone to the ingestion, generation, and accumulation of dirt and fine dust. Passengers and operators are constantly exposed to contaminants from the inside and outside of the vehicle. Platform screen doors installed in every station in Korea have helped to reduce fine dust in station buildings (Kim et al., 2012). Despite this improvement, air quality in subway tunnels is problematic, with a mass concentration of particles 10 µm in diameter almost twice as high as on underground platforms (Park et al., 2009). Recently, the WHO concluded that fine particulate matter (PM₂.₅) is carcinogenic to humans (Group 1). Other studies have found that small dust particles are more likely to penetrate deep into lung tissue and induce disease than larger particles containing the same elements (von Klot et al., 2005). Bigert looked at the effects of fine subway dust on underground platform workers in Stockholm, Sweden, and found that those with greater exposure to subway particulate matter were more likely to have cardiovascular diseases (Bigert et al., 2008). Grass determined the level of toxicity for humans posed by metal particulate matter by looking at New York City subway workers (Grass et al., 2010). Karlsson compared sampled particles released from roadside trees and car tires as well as particulate matter from Stockholm streets and subway platforms in terms of genotoxicity and inflammatory response, finding that every particle type induced DNA damage, and those particles from subway stations did the greatest damage (Karlsson et al., 2006). Active iron (Fe)-induced damage primarily caused an oxidation-reduction reaction (Karlsson et al., 2005). A study on the toxicity level of a metallic oxide using particles of different diameters found that nanoparticles were much more toxic than larger classes (Karlsson et al., 2009). Other studies found that fine dust from tunnels mainly consisted of metal components, accounting for 64.7 wt% of PM₁₀ emissions (Guo et al., 2014; Park et al., 2014; Jung et al., 2010; Midander et al., 2012; Moreno et al., 2015). In another study, Park (2014) used a technology acceptance model and found that wear particles arising from subway vehicle brakes accounted for 67.7% of the PM₁₀ emissions in subway tunnels, with wear particles from brake-wheel-rail contact accounting for 59.6% of pollution under subway cabins. Thus, these were the major pollutants in subway tunnels. Midander (2012) divided the distribution of particles from 14–32,000 nm in subway tunnels into four peaks (30 nm, 90 nm, 3.3 µm, 8 µm). In general, nanoparticles were released at high temperatures due to combustion and melting,
whereas coarse particles were emitted from mechanical wear. However, nanoparticles were also produced from wear during wheel-rail contact in another study (Sundh et al., 2009).

In addition, Fe was found in particles 100 nm or smaller, which could affect the air quality in subway tunnels (Reche et al., 2017). The generation processes and characteristics of wear particles were studied with different disk materials using a pin-on-disk machine (Olofsson, 2011), which showed a peak that varied from 70 to 80 nm made up of particles emitted from cast iron while another peak was found at 0.3 µm, similar to the generation characteristics of wear particles reported by Sundh (2009) in wheel-rail contact.

Namgung et al. (2016) studied differences in wear particles depending on train speed and braking force using a dynamometer. They found that higher braking mechanical force and initial speed led to the generation of more particles in the 7–100 nm range. Their results showed that 200-nm particles were common, regardless of the two factors noted above. They also reported mechanism of generation of nanoparticle that evaporation occurred with increasing contact surface temperature after mechanical friction emitted first.

Abbasi et al. (2011) measured wear particles from brake pads and disks to determine the wear particle characteristics, using a detection device installed on vehicles during operation. This study found that the emission of wear dust increased as mechanical braking force increased. With electric braking, no wear particles were emitted from brakes or disks. In other words, many studies have found that nanoparticles infiltrate into subway cabins from the outside and are simultaneously generated from vehicle operation.

Prior to our study, measurement of the nanoparticle size distribution had not been carried out on running vehicles. In this study, we analyzed nanoparticle size distribution as measured by sampling devices at 1-s intervals under a subway cabin and in a tunnel. In addition, the size distribution characteristics of nano-sized wear particles arising from under the cabin were compared with those collected in the tunnel.

METHODS OF MEASUREMENT AND ANALYSIS

Measurement Subjects and Methodologies

Fig. 1 shows the three lines of the Daegu Metro. Line 1 has a higher passenger load than the other two lines, transporting 191,433 people per day. It spans 31.02 km and consists of only concrete tracks. Each train has six cars and runs at an average speed of 40.1 km h⁻¹. An end-to-end one-way trip takes about 55 min, and this line runs from 5:30 a.m. to midnight at 5-min intervals during rush hour and 8-min intervals at other times. For the purpose of this study, measurements were carried out on a train heading east at 2:05 p.m. on November 5, 2016.

One probe was installed on the window near the courtesy seats (designated for senior citizens, the disabled, and pregnant women) at first cabin and another on the rear side of a wheel under the second cabin of the train, measuring the baseline concentrations in subway tunnels and the concentration of nanoparticles generated under the cabin body during deceleration, respectively (Fig. 2). The probes were connected to a measurement device with

Fig. 1. Map showing the subway line in Daegu.
conductivity tubes of the same length, avoiding any errors caused by a difference in length. And, we don’t consider isokinetic sampling because of Brownian motion in nanoscale (Arouca et al., 2010). As the use of electricity on the subway vehicle was prohibited, an uninterruptible power supply (UPS) was utilized. A fast mobility particle sizer (FMPS; TSI Model 3091) measured particles ranging from 5 to 560 nm in size that were generated at 1-s intervals using electrical mobility by corona discharge in 32 channels. Before measurement, we conduct calibration of two FMPS and comparison two FMPS (Fig. 3). Operating information, including subway stops and starts, was recorded by hand in the train to ensure that the FMPS was synchronized with the Automatic Train Control (ATC) system.

Information Regarding the Operation of Daegu Metro and the Automatic Train Control System

Modern subway trains are operated automatically. However, when entering a platform area, they are controlled manually to ensure that they stop at the correct location. All information is recorded in an ATC system embedded in the train, which records train speed, whether the brake was engaged, opening and closing of doors, and other information. Daegu Metro also uses this ATC system to record operational information. For this study, ATC information on train speed and braking provided by Daegu Metro was used to identify the operational patterns of the train. Daegu Metro used this ATC system to record operational information. Daegu Metro recorded these data while the train made five round trips. Fig. 4 (Up) shows the overlapping speed distribution curves of the train measured over five trips while it ran from Seolhwa-Myeonggok Station (one end of the line) to Ansim Station (the other end).

The operational pattern was constant except for the [a] period, as shown in Fig. 4. This indicates that the operating environment for this train did not change during the measurement process, and the train ran in a slightly different manner when a new factor was encountered. Indeed, large-scale street-level construction was ongoing in the area of [a] on that day. These data show that the time to travel between stations varied from 70 to 100 s, depending on the shape of the tunnel and the distance between stations. Fig. 4 (Down) shows train speed and whether the brake was engaged during the measurement process. When the train speed exceeds a set limit, Daegu Metro’s braking system automatically engages. There are generally two braking systems: electric and mechanical. Electric braking is designed to reduce the motor-speed (without mechanical force) if the train speed is 20 km h⁻¹ or greater, while mechanical and electric braking are both available once the speed falls below 20 km h⁻¹. ATC records only whether the braking system was engaged, not braking type. As can be seen in Fig. 4 (Down), braking was applied whenever the train decelerated. Also, the braking system was operated intermittently when the train exceeded the set speed in some constant velocity sections. This figure also shows that the brake was engaged constantly when the train passed through the [a] section, in contrast to other areas.

In Fig. 5, curves show four operational patterns of Daegu Metro Line 1 trains. In Case 1, the tunnels are straight, and the train passes through acceleration–constant velocity–deceleration–stopped sections for approximately 80 s. Case 2 includes relatively short distances between stations, and the train goes through acceleration–deceleration–stopped sections in 70 s. Case 3 involves curved tunnels, in which the train speed is 60 km h⁻¹ or less, with an operating pattern of acceleration–constant velocity–deceleration–stopped. Case 4 contains both straight and curved tunnels in an acceleration–constant velocity–acceleration–constant velocity–deceleration–stopped pattern. In every case, speed did not exceed 78 km h⁻¹ and the train accelerated for 36 s after starting. It also took 36 s for the train to stop after deceleration began. The train’s acceleration and deceleration speed was ± 0.6 m s⁻², with similar speeds recorded in other sections. As can be seen in the results, the key factors that affect train operational conditions are the distance between stations and curvature of the track and tunnel. These operational patterns are assumed to be similar to those in other subway systems.
RESULTS AND DISCUSSION

Particle Number Concentrations in Subway Tunnels and under the Cabin

Fig. 6 shows the total number concentration of particles in Daegu Metro Line 1 tunnels and under the train cabin, the ratio of tunnel to under cabin concentrations, and train speed. The solid line represents the total number concentration and ratio, while the dotted line represents train speed. The average total number concentration in tunnels was 295,043.1.
The number concentration was found to be nearly constant, except in some sections where the number varied. Several factors (e.g., vent system and tunnel shape) are assumed to drive this variation (Moreno et al., 2017). The number concentration under the cabin was 341,209.5 \((\pm 188,027.4) \, \text{# m}^{-3}\). When the train traveled between stations, the number concentration surged instantly, reaching a maximum concentration of 5,055,740 \(\text{# m}^{-3}\). These peaks were noted during deceleration in most cases, as well as in a few constant velocity sections. These results indicate that trains in operation emit nanoparticles. The bottom image shows the tunnel to under cabin concentration ratio. When peaks were present under the cabin, the concentration was generally higher by 2- to 4-fold, and 19-fold at most (Fig. 6). The tunnel to under cabin ratio was nearly 1 with these peaks excluded, which was assumed to be the baseline concentration.

Fig. 7 shows Cases 1 to 4, described above for Fig. 6, to clarify why the number concentration of nanoparticles spiked under the cabin. Cases 1 and 2, which involved straight tunnels, showed similar patterns. In Cases 3 and 4, nanoparticles at the sampling port under the cabin were emitted even when the train was running at a constant velocity. We assume that the tunnels may cause increased particle generation in these cases, rather than the operational patterns of the train. In all cases, nanoparticles were emitted during deceleration when the train was running at 20 km h\(^{-1}\) or more. This means that electric braking was applied. According to Abbasi et al. (2011), electric braking does not generate wear particles, while mechanical braking does. Therefore, the nanoparticle peak shown in Fig. 7 is assumed to be attributable to wheel-rail contact. We suggest that the resulting constant wear from wheel-rail contact has an impact on the volume of nanoparticles generated (Sundh and Olofsson, 2011).

**Size Distribution of Nanoparticles from Subway Tunnels and under the Cabin**

Fig. 8 shows the average concentration and size distribution from subway tunnels and under the cabin in Cases 2 and 3. In all cases, similar size distributions were obtained. The concentration of particles ranging from 29.4–80.6 nm in size was high in tunnels; other sizes were more concentrated under the cabin, where nanoparticles 165.5 nm in size were particularly concentrated. The average concentration of nano-sized particles with diameter under 10 nm was similar in tunnels and under the cabin, but their standard deviations were markedly different, showing that single-digit nano-sized particles were being generated. To analyze this phenomenon, Case 2 was expressed in contour graphs as shown in Fig. 9. Fig. 9 shows the number concentration of nanoparticles by
color. Particles generated under the cabin 8 s after the train started braking were 165.5 nm in diameter, whereas those generated 9 s later were 6.98 nm in diameter. Sundh and Olofsson (2011) found that wear conditions changed as the temperature of the contact surface increased, which, in turn, generated nanoparticles. Namgung et al. (2016, 2017) found that 200-nm-sized particles were generated when 12 kN of braking force was applied to a train running at 50 km h⁻¹, and 7- to 20-nm particles were generated 2 s later. Therefore, we assume that, a size change of particles was induced within 1 s; 165.5-nm-sized nanoparticles were generated by heat warming the wheel, and then 6.98-nm-sized nanoparticles were generated later. A slip in wheel-rail contact is similar to the friction between the pad and disk during braking. As a result, all cases showed the same size distributions and different total nanoparticle number concentration emitted at the wheel-rail contact.

Size Distribution Characteristics of Nanoparticles from under the Cabin

Fig. 10 shows the average concentration difference between the tunnel and under the cabin in each case. With zero as the starting point, the average concentrations in all cases were found to be similar. As mentioned above, 165.5-nm and 6.98-nm particles were emitted at wheel-rail surface due to wear. And the standard deviations at Case 1 and 2 (straight) higher than at the Case 3 and 4 (curved section).

The average concentration ratio of 45.3-nm particles was negative, which means that the concentration was higher in the tunnels by at least 2,137 # cm⁻³. This is not a large concentration difference, but provides reasonable suspicion that pollutants in the upper portions of subway tunnels due to vent systems hanging from the ceiling, pantographs, contact surfaces with trolley lines, and train wind may cause the observed negative figures.

In this study, we looked at the size distribution of nanoparticles and found that they were emitted due to wheel-rail contact. It was difficult to install measurement devices on trains in operation. We could not analyze the elements making up the wear particles or their shapes, or measure the temperature of the contact, and thus it was not possible to determine whether wheel-rail and wheel flange-gauge corner wear and the resulting temperature increase induces evaporation of the lubricants applied to the rail resulting in nanoparticle emission. In future studies, it would be useful to look at a wider size distribution of particles from 6 to 10,000 nm, and to sample the various sizes and analyze their shapes, with the aim of identifying characteristics of the nanoparticles emitted during wheel-rail contact and the mechanism of wear particle generation.

CONCLUSIONS

We conducted measurements outside a train running on
Daegu Metro Line 1, travelling from one end of the line to the other, to figure out the generation characteristics of wear particles emitted from wheel-rail-brake contact during operation. First, we analyzed ATC recordings and divided them into four operational condition types and noted whether braking was engaged. Next, an FMPS recorded the size distribution of nanoparticles at 1-s intervals. We assumed that the difference in particle concentration between tunnels and under the cabin arose from wear particles. We confirmed through measurement that 165.5-nm and 6.98-nm particles were emitted under the cabin. As the train is controlled by electric braking (no mechanical force), nanoparticles were emitted due to wheel-rail contact. The increase in temperature during contact resulted in the generation of 165.5-nm wear particles and, 1 s later, 6.98-nm wear particles. The assumption here was that the generation mechanism for
Fig. 9. Contour plot of the nanoparticle concentration in the tunnel and under the train in Case 2.

Fig. 10. Size distribution difference between the tunnel and under the train in each case.
nanoparticles from wheel-rail contact was due to mechanical friction, which generates heat, resulting in nanoparticles. The number concentrations and size distributions of wear particles generated during wheel-rail contact vary, depending on the slip speed, contact surface pressure, and state and materials of the rails and wheel surfaces. Lubricants used to prevent the wear of wheels and rails also affect particle generation (Olofsson et al., 2009; Arias Cuevas et al., 2010; Abbasi et al., 2013). In addition, increases in temperature caused by contact wear induce a change in the size distribution of nanoparticles (Sundh and Olofsson, 2011; Namgung et al., 2017). The higher the slip speed during wheel-rail contact, the more drastic the temperature increase (Sundh and Olofsson, 2011).

As described above, wear may vary according to numerous factors. In this study, it was difficult to measure all of these factors, as a limited number of measurement devices could be installed on a train in operation. However, we can assume that temperature is also a very important factor in changing the mechanism by which nanoparticles are generated. As shown in other studies, wheel-rail contact generates high temperatures that can emit single-digit nanoparticles. Future studies should focus on determining the mechanism of generating wear particles and the contribution of emissions under the cabin through analyzing the elemental compositions and shapes of particles sampled under the cabin.

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