Correction Method for Resuspended Road Dust Emission Factors
According to Vehicle Speed Using a Mobile Monitoring Vehicle

Sang-Hee Woo\textsuperscript{1}, Hyoungjoon Jang\textsuperscript{1}, Seung-Bok Lee\textsuperscript{2}, Juyoung Jeong\textsuperscript{3},
Choonghwan Lee\textsuperscript{3}, SeokHwan Lee\textsuperscript{1}\textsuperscript{*}

\textsuperscript{1} Department of Mobility Research, Korea Institute of Machinery and Materials, 156, Gajeongbuk-ro, Yusong-gu, Daejeon, 34103, Republic of Korea

\textsuperscript{2} Center for Sustainable Environment Research, Korea Institute of Science and Technology, 14-gil 5 Hwanrang-ro, Seoungbuk-gu, Seoul 02792, Republic of Korea

\textsuperscript{3} Department of Atmospheric Environment, Korea Environment Corporation, 42 Hwangyeong-ro, Seo-gu, Incheon 22689, Republic of Korea

\* Corresponding author. Tel: +82-(0)42-868-7050

E-mail address: shlee@kimm.re.kr
Abstract

A mobile monitoring vehicle was used to measure road dust concentrations and determine resuspended road dust emission factors (EFs). By comparing the dust signal from the mobile monitoring vehicle and the EF calculated from a PM flux measurement using a flux tower, it was possible to convert the dust concentration detected by the mobile monitoring vehicle into resuspended road dust EF. On-road driving studies were conducted at various vehicle speeds on six different roads to determine the relationship between vehicle speed and resuspended road dust EF. The resuspended road dust EF exponentially increased with vehicle speed. A speed-related correction approach was established to reduce the variability in resuspended road dust EF caused by variations in vehicle speed. A mobile monitoring vehicle was used to determine the EFs of resuspended road dust from motorways and urban and rural roads in the Daejeon metropolitan of Korea. Local hot spots with high silt loading were identified by adjusting the EF according to vehicle speed. Additionally, three repeated measurements taken along the same route confirmed that EF deviation between measurements could be decreased by ≥ 50% after adjustment. In this study, we devised a vehicle speed-related correction method to obtain accurate and reliable EFs of resuspended road dust using a mobile monitoring vehicle, even based on a single on-road driving measurement.

Keywords: Non-exhaust particulate matter, re-suspended road dust, mobile sampling vehicle.
INTRODUCTION

The majority of (80-90%) of particulate matter (PM) released by the road transport sector in the early 1990s was emitted as exhaust emissions (Denier van der Gon et al., 2013). Because of strict emission regulations during the past 10 years, air pollutant emissions from vehicle exhausts have been significantly reduced; however, PM$_{10}$ concentrations in European cities have decreased more slowly than anticipated (Rienda and Alves, 2021). According to Amato et al., (2014a, 2014b), this slow decrease is likely related to non-exhaust emissions, a key pollution source that is typically disregarded or underestimated in national emission inventories. Recent studies have shown that the relative contribution of non-exhaust PM emissions, generated by brake wear, tire wear, road wear, and resuspended road dust, in the road transport sector, is similar to or greater than the contribution of exhaust PM emissions (Amato et al., 2014a, 2014b; Denier van der Gon et al., 2018; Monks et al., 2019).

Among the various non-exhaust emission sources, resuspended road dust is a generic term for any form of solid particles distributed on the road surface that can be suspended in the air through traffic or windblown resuspension (Amato et al., 2014a). Additionally, among the typical suspended road dust deposited on roads, resuspended road dust has a size that allows it to be dispersed and airborne. Road dust can consist of brake, tire and road wear particles that have been deposited on the road, as well as particles that have migrated to the road from other sources, including construction and other dusty sites. The relative contribution of different sources and the
overall chemical composition of road dust likely varies from one site to another, so individual
findings in one environment may not be applicable to others. Hence, the source apportionment of
road dust, separating from the non-exhaust emission sources of tire wear particles, brake wear
particles, and road wear particles, is a difficult task due to the chemical affinity of these sources.

The European Commission has reported that resuspended road dust contributes 28-59% of
all non-exhaust PM$_{10}$ emissions, while brake wear contributes 16-55%, and tire wear contributes
5-30% (EEA 2019). Salameh et al. (2018) investigated the background PM$_{2.5}$ in Marseille, France;
they discovered that resuspended road dust, which constituted 0-13% of total PM$_{2.5}$ emissions,
was responsible for a background concentration of 4-9 $\mu$g/m³. According to Chen et al. (2019),
resuspended road dust in Lanzhou, an urban region of China, is responsible for 24.6% of total
PM$_{2.5}$ emissions. Although resuspended road dust has been identified by numerous researchers as
a key source of atmospheric PM emissions, it is difficult to estimate its contribution to urban air
quality because resuspension depends on several variables, including weather, road infrastructure,
traffic volume, vehicle weight, and vehicle speed (Candeias et al., 2020; Rienda and Alves, 2021).

Three different procedures are frequently used to calculate the emission factor (EF) of
resuspended road dust. The first procedure utilizes an empirical expression linking the PM EF
with vehicle weight and the silt loading of the road. It is expressed as:

\[ EF (g/v.km) = k (sL)^{0.91} (W)^{1.021} \]  (1)
where EF is the PM emission factor (g/v.km), k is a constant dependent on the aerodynamic size range of PM (0.62 for PM\(_{10}\) and 0.15 for PM\(_{2.5}\)), sL is the road surface silt loading of material \(\leq 75\ \mu m\) (g/m\(^2\)), and W is the mean vehicle weight (tons) (US EPA, 2011). This procedure was included in document AP-42 (Compilation of Air Pollution Emissions Factors) from the US Environmental Protection Agency (EPA), and has been frequently used to determine the fraction of PM\(_{10}\) originating from roadways. However, the EF significantly changes depending on silt loading of the collecting area, lane, and traffic patterns of the road, which is a disadvantage of this empirical approach (Bogacki et al., 2018). Additionally, because the AP-42 approach does not consider the vehicle speed, it is difficult to evaluate the impact of vehicle speed on the resuspended road dust EF (Langston et al., 2008). Furthermore, it is time-consuming and unsafe for humans to collect silt samples from the road surface (Fitz 2020; Kuhns et al., 2001).

The second procedure used to determine the resuspended road dust EF is based on PM flux measurements performed with a flux tower. To assess the distribution of road dust downstream of a car and calculate the EF, several particle measurement devices are placed in the flux tower at various heights in the downwind direction of passing vehicles (Gillies et al. 2005). However, the installation of a flux tower is resource-intensive, the tower is greatly affected by the background wind direction, and the road dust concentration detected in PM measuring instruments alongside paved roads is typically sufficiently low that it results in poor accuracy and reliability.
The final procedure, a mobile platform measurement, was used in this study to assess the resuspended road dust EF for a diverse range of road types in real time. This technique involves mounting a sampling plenum, line, and PM measurement equipment on a mobile monitoring vehicle, which enables the real-time determination of resuspended road dust concentrations at a specific location. The testing re-entered aerosol kinetic emission form roads (TRAKER) and system of continuous aerosol monitoring of partial emission from roads (SCAMPER) are two real-time mobile platform that have been used to measure road dust. SCAMPER was used by Fitz et al. (2020) to calculate the resuspended road dust EF in real time. By multiplying the area of the target vehicle’s rear flow by the road dust PM flux recorded in a trailer, they were able to determine the EF. SCAMPER does not require modification of the target vehicle for assessments of the resuspended road dust EF. Kuhns et al. (2001) measured the resuspended road dust EF by mounting sampling inlets on the back and front of the TRAKER vehicle wheels. They discovered that the relationship between the silt loading and PM concentration of road dust recorded by TRAKER was linear, allowing measurements of the silt loading distribution on the road while driving. Etyemezian et al. (2003) used comparative measurements between TRAKER and a flux tower for unpaved roads to derive a correlation between the TRAKER dust signal and the EF estimated by the PM flux measurement. The following power function between vehicle speed (V) and the TRAKER dust concentration (C) was observed.
where $a$ and $b$ are coefficients. Although the power functional correlation in Equation (2) between vehicle speed and dust concentration was obtained from unpaved roads, other studies have indicated that it could also be applied to paved roads (Gertler et al. 2006; Etyemezian et al. 2006; Zhang et al. 2017; Li et al. 2021).

Etyemezian et al. (2006) reported that the TRAKER dust signal was related to the cube power of the vehicle speed. Many measurements of road dust at the same location showed that PM$_{10}$ emissions were reproducible. Repeated measurements revealed that the variance ranged from 10% to 70% depending on the target road; the deviation decreased with increasing vehicle speed.

The silt loading distribution of paved roads in Tianjin, China, was measured by Zhang et al. (2017) using the TRAKER. The TRAKER signal was corrected by comparing it with direct slit loading measurement from the target road surface. By adjusting the TRAKER dust signal measured at various speeds to the signal at the average speed on the road (40 km/h), they were able to determine the speed-corrected TRAKER dust signal. Then speed-corrected TRAKER signal was compared to the direct silt loading measurement. According to Zhang et al. (2017), the average vehicle speed and silt loading on the same road were inversely proportional, and there was a substantial difference in silt loading depending on the lane.
In a side-by-side comparison study by Langston et al. (2008) and Fitz et al. (2021), the resuspended road dust EF was measured on the same road simultaneously using the AP-42 method, flux tower, SCAMPER, and TRAKER. According to Langston et al. (2008), the EFs calculated by SCAMPER and TRAKER were correlated with the EF calculated by the flux tower, with R squared values of 0.45-0.75. Additionally, the EF calculated using the AP-42 method based on measured silt loading was lower than the values determined by SCAMPER and TRAKER, which were corrected by a flux tower. However, a reasonable agreement was observed between the widely varying approaches.

A method for calculating the resuspended road dust EF using a mobile platform measurement in real time has been successfully developed, but the coefficients in Equation (2) must be changed for use in different regions and other TRAKERs, because several other regional studies suggested different coefficients. Li et al. (2021) compared the coefficient of b (from Equation (2) of the TRAKER method) with their own experimental results for different vehicle speeds on paved road. Zhang et al. (2017) and Li et al. (2021) reported that the coefficient b values for a paved road were 2.57 in Tianjin, China and 2.19 in Haoding, China, respectively. Etyemezian et al. (2003) reported differences in the coefficient b on unpaved road, with values of 2.96 in Treasure Valley, USA and 2.75 in Fort Bliss, USA. Additionally, they reported that the coefficient b decreased as the percentage of coarse particles in the particle size distribution
increased. Studies of resuspended road dust using mobile platform measurements have also been conducted in Korea. On the same road, Noh et al. (2022) compared the EFs of resuspended road dust measured by a flux tower with EFs measured by mobile monitoring vehicles; these latter EFs were approximately the same magnitude as EFs determined by TRAKER. The power function relationship between the EF estimated by the flux tower and the dust signal recorded by the mobile monitoring vehicle was proportionate.

In the present study, a TRAKER-based mobile monitoring vehicle was used to determine the resuspended road dust EFs in motorways and urban and rural roads in the metropolitan area of Daejeon, Korea. First, comparative experiments on the same route were conducted to assess the correlation between the dust signal from the mobile monitoring vehicle and the EF calculated by the flux tower. The resuspended road dust EF was corrected using a speed-related correction algorithm that considered the average speed of the mobile monitoring vehicle, then checked whether variance in the data decreased after repeated measurements of the EF for the same road.

2 METHODS

External factors, such as weather (humidity, temperature, wind speed, rain, snow, etc.), traffic volume, vehicle weight and speed, road infrastructure, and so on, can all have a substantial impact on road dust resuspension. In this study, a mobile sample vehicle, a conventional passenger car, was employed in all experiments to eliminate the effect of vehicle type.
Furthermore, flux tower experiments and public road driving experiments were carried out in May and September, respectively, on sunny days with temperatures ranging from 20 to 30°C and humidity levels of 40 to 60% to minimize the weather effect on road dust resuspension.

2.1 Mobile Monitoring Vehicle and Flux Tower

The relationship between the resuspended road dust EF estimated by the flux tower and the dust signal detected by a mobile monitoring vehicle was investigated by a simultaneous measurement; a schematic diagram of the experimental setup is shown in Fig. 1 (a). A passenger car with a 2000 cc gasoline engine and unloaded weight of 1560 kg served as the mobile monitoring vehicle. This vehicle was equipped with two aerosol monitors (DustTrak DRX 8533; TSI, USA) to measure the particle mass concentrations of the background and resuspended road dust. Because DustTrak is an optical instrument which relies on the refractive index of choice for conversion to mass, it should be calibrated by comparing with gravimetric method. In this study, DustTrak was compared with the gravimetric method and calibrated, using the specific road dust sampled from the test site as indicated in Fig. 1 (b). Resuspended road dust had no effect on the aerosol monitor that measured the background PM concentration because a background sampling inlet was installed in front of the vehicle. As shown in Fig. 1 (a), a sampling probe for resuspended road dust was mounted close to the front-right tire. Diluter was not used, because the concentration of resuspended road dust did not exceed aerosol monitor’s acceptable range. In this
study, it is possible to neglect the direct tire and brake wear particles from the test vehicle itself while it was being driven. When braking events occurred, the PM values at the moment could be filtered to exclude brake wear particles. Furthermore, there was very little direct tire wear particle generation from the test vehicle. In our previous study (Woo et al. (2022a), it was shown that the proportion of direct tire wear particles among the PMs collected using a mobile sampling vehicle was calculated to be 2–4%.

Resuspended road dust was sampled behind the front-right tire and collected on Teflon filters (Teflo 2 μm pore filter, PALL, USA), where it was classified as PM$_{10}$ or PM$_{2.5}$ using PM$_{10}$ (URG-2000-30ENB, URG, USA) and PM$_{2.5}$ cyclones (URG-2000-30EH, URG, USA), respectively. To determine the PM$_{10}$ and PM$_{2.5}$ ratio of resuspended road dust, the collected PM$_{10}$ and PM$_{2.5}$ were weighed using a A&D model BM-22 analytical balance. To facilitate mobile air pollution monitoring, the measurement probe must successfully sample particles at different velocities (Heo et al., 2018). In this study, a shrouded sampling probe was used that offered precise isokinetic fine particle sampling for moving vehicles travelling up to 120 km/h (Lim et al. 2021). A shrouded sampling probe was installed in both the background and road dust sampling inlets, as shown in Fig. 1 (a). To guarantee thorough mixing of the sample air flow, the sampling probe was connected to a sampling plenum with an inner diameter of 48 mm. To reduce the electrostatic loss of nanoparticles, conductive tubing with an inner diameter of 10 mm was
attached from the sampling plenum to the particle measurement equipment. The mobile monitoring vehicle’s measurement of PM concentration of resuspended road dust (C) was calculated as follows.

\[ C = C_{RD} - C_{BG} \]  

Where \( C_{BG} \) is the background dust concentration, and \( C_{RD} \) is the dust signal detected at or near the front-right tire of the mobile monitoring vehicle.

A rural road in the Yeongjong-do suburb of Incheon, Korea, with a low vehicle traffic volume (≤ 10 vehicles per hour) and a high silt loading was chosen as the target road to prevent interference from other cars. Therefore, the flux tower was placed in the middle of the rural road. The ideal height of a flux tower and optimal distance from the target vehicle for measuring all PM fluxes are given in Noh et al. (2021). Based on this study, the flux tower’s height was 4.5 m, as shown in Fig.1 (b). At intervals of approximately 0.9 m, five aerosol monitors (DustTrak 8530; TSI, USA), which could measure only PM\textsubscript{10} fractions of road dust, were positioned to a height of 4.5 m. Anemometers were installed at the second and fourth stages to measure the wind speed and direction.

Four different vehicle speeds of 20, 50, 80, and 110 km/h were used in this study; the vehicles passed a position 4 m from the flux tower. The horizontal PM\textsubscript{10} flux for the mobile monitoring vehicle was estimated using data from the flux tower and Equation (4)
where $EF$ is the total flux of PM$_{10}$ (mg/m) perpendicular to the road, $\theta$ is the angle between the wind direction and a line perpendicular to the road, $i$ corresponds to a data point for a given time, $n$ is the number of data points in the sampling period, $u$ is the measured wind speed (m/s), $C_i$ is the $i$th PM$_{10}$ concentration (mg/m$^3$) measured using an aerosol monitor, $C_0$ is the background concentration (mg/m$^3$), $\Delta z_i$ is the height (m) of the section of the flux plane represented by the $i$th position, and $\Delta t_i$ is the time (s) between data points (Gillies et al., 2004). The flux tower data were only used when the wind was within ±45° of the direction perpendicular to vehicle movement.

2.2 Dust Signal of the Mobile Monitoring Vehicle According to Vehicle Speed

Road dust is a generic description for any form of solid particle deposited on the road surface that can be suspended in the air through traffic-induced turbulence. When the air moving over the vehicle is separated at the rear end, it leaves a large low-pressure turbulent region behind the vehicle known as the vehicle wake turbulence. Fine dust particles are lifted from the ground surface because of the pressure gradient underneath and behind the vehicle. The pressure gradient will, according to the energy conservation law, raise the dust particles from the ground. A car that is moving swiftly sweeps out a volume where the flow is extremely turbulent and the air pressure
is lower than in the surrounding areas. The dust particles are raised by vehicle wake turbulence, which exerts a pressure gradient force proportionate to the vehicle's speed (Chen et al., 2000). According to Etyemezian et al. (2003), Zhang et al. (2017), and Fitz et al. (2021), even when travelling on the same road, the dust signal measured by a mobile monitoring vehicle increases in direct proportion to the vehicle speed. The resuspended road dust concentration at various vehicle speeds (20, 50, 80, and 110 km/h) was determined for six different routes on suburban roads in Daejeon, Korea, to obtain a value for the coefficient b (Equation (2)) that was compatible with Korean road characteristics. The six routes chosen as test roads were the left and right lanes in the Daecheong tunnel, the left and right lanes in the Bugang tunnel, and the left and right lanes outside the Bugang tunnel. The roads inside the tunnel were targeted to minimize the influence of the wind, whereas the road outside the tunnel was included because a sample road with a low silt loading was needed. The vehicle speed was kept constant using the cruise control system mounted on the vehicle, and was found to have a variance of less than ±5%. Each speed was driven five times consecutively for each test speed.

2.3 The Resuspended Road Dust EF for Motorways, and Urban and Rural Roads

Motorway, and urban and rural roads near Daejeon were identified as indicated in Fig. 2, and the resuspended road dust EF was determined by driving the mobile monitoring vehicle along each road three times. The corresponding lengths of the motorways, urban roads, and rural roads
were 24 km, 18 km, and 28 km. Every measurement had different driving speeds because it was a public road. The travel times were as follows: for urban roads, the travel times were approximately 1 hour 13 minutes, 1 hour 7 minutes, and 1 hour 17 minutes; for rural roads, they were 26, 21, and 28 minutes; and for motorway routes, they were 14, 18, and 19 minutes. Therefore, using the speed-related correction equation, the resuspended road dust EF was adjusted to match the average road speed of each target road; these data were used to explore whether the EF deviation decreased between measurements.

3 RESULTS AND DISCUSSION

3.1 Relationship Between the Dust Signal of the Mobile Monitoring Vehicle and the Resuspended Road Dust EF Determined by the Flux Tower

A mobile monitoring vehicle was used to estimate the horizontal PM$_{2.5}$ flux because a flux tower measured only the horizontal PM$_{10}$ flux. A gravimetric method using filter sampling was used to evaluate the PM$_{10}$/PM$_{2.5}$ ratio of resuspended road dust on the rural road in Yeongjong-do; the ratio was 0.487. Thus, the PM$_{2.5}$ resuspended road dust EF measured at the flux tower was assumed to be about 50% of the PM$_{10}$ EF.

Fig. 3 shows the relationship between the PM$_{10}$ concentration measured by the aerosol monitor installed in the mobile monitoring vehicle and the PM$_{10}$ resuspended road dust EF calculated using a flux tower. Nine data points derived from each single experiment are represented in Fig. 3.
The experimental results supported the earlier results of Etyemezian et al. (2003) and Noh et al. (2022) by demonstrating that the resuspended road dust EF calculated using the flux tower was linearly proportional to the dust signal of the mobile monitoring vehicle. The slope between the dust signal of the mobile monitoring vehicle and PM$_{2.5}$ resuspended road dust EF was calculated using the gravimetrically measured PM$_{2.5}$/PM$_{10}$ ratio of 0.487.

3.2 Correlation Between the Dust Signal of the Mobile Monitoring Vehicle and Vehicle Speed at Different Sites

Fig. 4 shows the correlation between the PM$_{10}$ dust signal of the mobile monitoring vehicle and vehicle speed at each of the six test sites. Each data point was derived using the methodology described in section 2.2. The dust signal and the vehicle speed have a power function relationship. The dust signal of the mobile monitoring vehicle was also proportional to vehicle speed according to Etyemezian et al. (2003), Zhang et al. (2017) and Fitz et al. 2021; in those works, the power index ranged from 2 to 3. In this study, there were also power function relationships between the PM$_{10}$ and PM$_{2.5}$ concentrations measured by the mobile monitoring vehicle and the vehicle speed, with power variables of 1.9 and 2.3, respectively. Compared with the power variables (b) of 2.75 (Etyemezian et al. (2003)), 2.57 (Zhang et al. (2017)), and 2.19 (Li et al. (2021)) reported in previous studies, the power variable (b) of 1.9 for PM$_{10}$ determined in this study was relatively low. Etyemezian et al. (2003) measured the road dust concentration in arid,
sandy regions of the western United States. Li et al. (2021) and Zhang et al. (2017) conducted studies in the cities of Baoding and Tianjin, which are both adjacent to the Gobi Desert and can experience substantial yellow dust exposure. Accordingly, on the Korean road surfaces examined in this study, it was expected that the fraction of coarse particles would be lower than the fraction on roads used in previous investigations. As shown in Fig. 4, the power regression curve demonstrated good fit when the vehicle was moving at speeds $\geq 50$ km/h, but the experimental error was large when the vehicle was moving at 20 km/h. These results arose from the low PM concentration measured by the mobile monitoring vehicle at low speeds, which hindered separation from the background concentration, and the considerable variability of the measured values.

Using the dust signal ($C: \mu g/m^3$) and vehicle speed ($V: km/h$) of the mobile monitoring vehicle, the PM$_{10}$ and PM$_{2.5}$ resuspended road dust EFs for the target road ($EF_R: mg/km$), while driving at the target vehicle speed ($V_R: km/h$), were calculated using the equations below.

$$EF(PM_{10})_R = 525C \left(\frac{V_R}{V}\right)^{1.9}$$  \hspace{1cm} (5)  

$$EF(PM_{2.5})_R = 256C \left(\frac{V_R}{V}\right)^{2.3}$$  \hspace{1cm} (6)

In this study, target vehicle speed is defined as average vehicle speed during traveling each urban, rural and motorways region. Coefficients 525, and 256 in Equations (5) and (6) was derived from the correlation between the flux tower EF and dust signal of mobile sampling.
vehicle, as shown in Fig. 3. The association between the dust signal of the mobile sampling vehicle and the vehicle speed, as illustrated in Fig. 4, is what generates exponents 1.9 and 2.3. These coefficients were determined by the vehicle's parameters, which included the weight of the vehicle, its shape-induced turbulence, and its position at the sampling point.

3.3 The Resuspended Road Dust EF from Motorways, and Urban and Rural Roads in Daejeon Metropolitan Area

The PM$_{10}$ dust signal was measured by driving three times along the test roads at each speed using a mobile monitoring vehicle. Then, using Equations (5) and (6), the dust signals obtained when the mobile monitoring vehicle was moving at irregular speeds distinct from the average speed for the road were converted into the EFs of resuspended road dust during movement at the average vehicle speed. When the correlations in Equation (5) and (6) were applied, there was considerable deviation in the resuspended road dust EF, especially for the urban road, because the dust concentrations were very low and variable when the vehicle was moving below 10 km/h. Furthermore, even at moderate speeds, the dust concentration substantially increased when harsh braking applied. Data collected under these conditions were removed from the analysis to reduce the EF deviation under low-speed conditions.

Fig. 5 shows the average EFs of resuspended road dust from motorways, and urban and rural roads of Daejeon metropolitan area after three separate test drives. The PM$_{10}$ EFs of resuspended road dust were 20.78±2.12, 14.31±2.87, and 9.80±1.84 mg/km, respectively, for urban roads,
rural roads, and motorways. The PM$_{2.5}$ EFs of resuspended road dust were 7.41±0.76, 4.91±0.89, and 3.56±0.87 mg/km, respectively, for urban roads, rural roads, and motorways. Woo et al. (2022b) reported PM$_{10}$ EFs of resuspended road dust in the Seoul metropolitan area of 28.5 mg/km for urban roads, 21.0 mg/km for rural roads, and 9.3 mg/km for motorways. Mathissen et al. (2012) reported a PM$_{10}$ resuspended road dust EF of 26±19 mg/km on paved roads. In urban areas of Zurich and Reiden, Switzerland, Bukowiecki et al. (2009) reported PM$_{10}$ EFs of resuspended road dust of 27 and 48 mg/km, respectively. In metropolitan areas of Barcelona (Spain) and Turin (Italy), Padoan et al. (2018) reported the PM$_{10}$ EFs of resuspended road dust of 13-34 and 10-85 mg/km, respectively. According to Fitz and Bumiller (2021), the PM$_{10}$ EFs of paved roads resuspended road dust ranged from 70 to 130 mg/km depending on the season in the Phoenix, Arizona metropolitan area. The PM$_{10}$ EFs of resuspended road dust measured in this study (9.80-20.78 mg/km) were similar to the findings in previous studies.

Equations of (5) and (6) were used to reduce deviation in the resuspended road EFs that resulted from different driving speed of repeated measurements. Based on the average vehicle speed for each road type, variations in vehicle speed were adjusted for the different road type. For urban, rural, and motorways regions, the mobile monitoring vehicle was being driven along the traffic flow and its averaged speeds were 40, 75, and 103 km/h, respectively. The correlation equations were used to confirm reductions in the deviation of PM$_{10}$ and PM$_{2.5}$ EFs of resuspended
road dust before and after vehicle speed correction, as shown in Fig. 5. For the urban roads, the PM$_{2.5}$ EF deviation decreased from 0.76 mg/km before correction to 0.27 mg/km after correction. The PM$_{10}$ EF deviation (2.12 mg/km prior to speed adjustment) was reduced by $\geq 50\%$ (to 1.01 mg/km) after correction. For the rural roads, the deviations of the PM$_{10}$ and PM$_{2.5}$ EFs were adjusted from 2.87 and 0.89 mg/km to 1.61 and 0.29 mg/km, respectively, after correction. Finally, the deviations of PM$_{10}$ and PM$_{2.5}$ resuspended road dust EFs from the motorways decreased from 1.84 and 0.87 mg/km to 0.98 and 0.49 mg/km, respectively. The resuspended road dust EF deviation caused by three repetitive measurements substantially decreased with the speed correction, but the average EF was almost unchanged. It is not possible to guarantee accuracy and dependability if the resuspended road dust EF is calculated from a single measurement made by a mobile monitoring vehicle without speed correction. However, the resuspended road dust EF can be calculated reasonably accurately and consistently with single measurement if that measurement is corrected based on the average vehicle speed.

Contour maps of resuspended road dust PM$_{10}$ EFs for motorways, and urban and rural roads, before and after speed correction, are shown in Figs. 6-8. Fig. 6 demonstrates that PM$_{10}$ hot spots were discovered near intersections in urban roads. As shown in Fig. 6 (a), two additional measurements revealed that the EFs differed in areas A and B, even when traveling on the same road, because of the different vehicle speeds. As shown in Fig. 6 (b), the EFs became identical in
areas A and B for all three repeated tests if the EF was corrected according to average vehicle speed using Equations (5) and (6). Although it was not possible to equally measure the EFs in three repetitive measurements, the speed correction made EFs comparable for most route points. Similarly, for rural roads, the speed correction caused the PM$_{10}$ EFs of resuspended road dust for most routes to become equivalent, as shown in Fig. 7. Prior to the speed correction, there were low EFs in area A's first and third measurements of PM$_{10}$ EF because of the low actual vehicle speeds; after the speed correction, these areas became PM$_{10}$ hot spots. Compared with the urban and rural roads, the effect of the speed correction was comparatively minimal for motorways because the speed differences were not substantial across the three repeat measurements. However, some routes were eliminated through the data filtering process because of the potential impact of heavy traffic-related brake wear PM emissions on resuspended road dust (Woo et al., 2021).

The contour maps in Figs 6-8 show that the PM$_{10}$ EF deviation of the three repeated experiments partially persisted despite EF adjustment according to average vehicle speed. There were three plausible explanations for this. First, braking may have had a substantial impact on the mobile monitoring vehicle's dust signal. Although the mobile monitoring vehicle's sampling inlet position was behind the tire and some distance from the brake, hard braking caused a considerable amount of brake wear PM to be generated and transmitted to the sampling inlet,
resulting in an abnormally high PM concentration. The very high peaks in PM$_{10}$ concentration when the driving speed decreased, such as the three peaks at 14:27–14:31 in Fig. 9(a), were influenced by brake wear PM and therefore removed from the analysis. In several instances, such as the peak at 14:33, the peak was limited high although it was presumably caused by braking. Because it was impossible to determine whether the dust was caused by brake wear or the resuspension of road dust, data screening was not possible.

The second possible explanation is a sudden increase in the background PM concentration. The background and resuspended road dust PM concentrations were simultaneously assessed using two aerosol monitors mounted in a mobile monitoring vehicle. A high PM concentration was only observed in the aerosol monitor used to measure the background PM concentration because of numerous environmental interferences; this concentration had no effect on the other monitor. The background PM concentration abruptly increased and exceeded the dust signal of the mobile monitoring vehicle, as shown in the data collected at 10:32:30 in Fig. 9(b). This increase led to a resuspended road dust EF of zero. In such cases, the resuspended road dust EF could be underestimated and the deviation of the three repeat measurements may be impacted.

The third possible explanation is that, even at the same location on the target road, the resuspended road dust EF could fluctuate when the vehicle was driven in a different lane in different experiments because of variations in traffic conditions. Although the vehicle traveled an
identical route three times, traffic conditions and unforeseen factors, particularly in the urban road, prevented consistent travel in the same lane. Zhang et al. (2017) reported that there may be variations in the resuspended road dust EF due to variations in the silt loading deposited on the different driving lanes of a road. Because the mobile monitoring vehicle detected a different dust signal when traveling in a different lane, the deviation could not be corrected by the average vehicle speed, even if the measurement had been conducted three times along the same route at the same speed.

4 CONCLUSIONS

Using the dust signal from a mobile monitoring vehicle, a vehicle speed-related correction method was developed to determine the resuspended road dust EF in real time. To develop this, the relationship between the EFs of resuspended road dust based on a flux tower measurement and the dust signal of a mobile monitoring vehicle was determined. Furthermore, at six sites with various silt loadings, power function correlations were determined between the dust signal of the mobile monitoring vehicle and vehicle speed.

A mobile monitoring vehicle was used to determine the EFs of resuspended road dust from motorways, and urban and rural roads in the Daejeon metropolitan area. By correcting the EF based on the average vehicle speed, local hot spots with high silt loadings were identified. Furthermore, the results showed that application of the correction method could reduce the EF
measurement deviation by more than 50% when a mobile monitoring vehicle repeatedly traveled
the same route three times. The greatest decrease in EF deviation was observed for urban roads,
whereas the smallest decrease was observed for motorways.

Urban roads had the highest resuspended road dust EF, and motorways had the lowest EF. This
difference was caused by high traffic flow and high vehicle speed on the motorways, which
resulted in less deposition of silt on the road. Locations that were not previously identified as hot
spots of resuspended road dust could become hot spots after application of the EF correction
according to average vehicle speed. However, due to error inducing factors including hard
braking, high background PM concentration, and lane changes, the EF deviation calculated by the
repeated measurements could not be entirely eliminated using the correction method alone. A
new sampling technique is required to prevent brake wear PM from being transmitted to the road
dust sampling inlet, enabling more precise and consistent measurement of the resuspended road
dust EF using a mobile monitoring vehicle.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) granted by
Ministry of Science and ICT, Korea (No.RS-2023-00282244).

DISCLAIMER
REFERENCES


road dust re-entrainment. Atmos. Environ. 40, 5976-5985.


30

Fig. 1 Experimental setup to examine the relationship between the resuspended road dust EF determined by a flux tower and the dust signal measured by a mobile monitoring vehicle; (a) schematic of PM measurement utilizing the flux tower and mobile monitoring vehicle, and (b) test location
Fig. 2 Routes (motorways, and urban and rural roads) in the Daejeon metropolitan area used to calculate the resuspended road dust EF
Fig. 3 Relationships between the PM$_{10}$ concentration measured by the mobile monitoring vehicle and the PM$_{10}$ and PM$_{2.5}$ EFs of resuspended road dust determined by the flux tower.

\[ y = 0.525 \, x \]
\[ R^2 = 0.71 \]

\[ y = 0.256 \, x \]
Fig. 4 Power function correlation between the dust signal and vehicle speed at six different test sites (a) PM$_{10}$ and (b) PM$_{2.5}$
Fig. 5 Average EFs of resuspended road dust from motorways, and urban and rural roads, and their deviations determined from three repeat measurements before and after speed correction: (a) PM$_{10}$ and (b) PM$_{2.5}$
Fig. 6 Contour maps of resuspended road dust PM$_{10}$ EFs based on measurements made by a mobile monitoring vehicle during three passes on the same urban road: (a) before correction and (b) after correction.
Fig. 7 Contour maps of resuspended road dust PM$_{10}$ EFs based on measurements made by a mobile monitoring vehicle during three passes on the same rural road: (a) before correction and (b) after correction.
Fig. 8 Contour maps of resuspended road dust PM$_{10}$ EFs based on measurements made by a mobile monitoring vehicle during three passes on the same motorway: (a) before correction and (b) after correction.
Fig. 9 Factors leading to abnormally high PM concentrations due to resuspended road dust: (a) hard braking and (b) high background (BG) PM concentration