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Modeling Study on Dispersion and Scavenging of Traffic Pollutants at the Location Near a Busy Road

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ABSTRACT

The information about the dispersion and scavenging of traffic-related pollutants at the locations near busy expressways is very helpful to highway planners for developing better plans to reduce exposures to air pollution for people living as well as children attending schools and child care centers near roadways. The objective of the current study was to give information in the dispersion and scavenging of vehicle-derived pollutants at the region near a busy urban expressway by a combination of two different model calculations. The modified Gaussian dispersion model and the Lagrange type below-cloud scavenging model were applied to evaluate NO_x dispersion and DEP (Diesel exhaust particles) wet removal, respectively. The highest NO_x was marked 53.17 ppb within 20-30 meters from the target urban expressway during the heaviest traffic hours (08:00AM-09:00AM) and it was 2.8 times higher than that of really measured at a nearby ambient measuring station. The calculated DEP concentration in size-resolved raindrops showed a continuous decreasing with increasing raindrop size. Especially, a noticeable decrease was found between 0.2 mm and 1.0 mm raindrop diameter.

Key words: Vehicle exhaust, Nitrous oxide, DEP scavenging, Gaussian model, Health effect

1. INTRODUCTION

Living close to a major highway will save a lot of time for commuting to work (or school) and be very convenient for daily life. For these reasons, there were already many people living near major highways all across the globe. In the case of U.S., with more than 45 million people living within 100 meters of a major transportation facility or infrastructure, notably busy roads (Boehmer *et al.*, 2013).

However, living and working near heavily traveled roadways can lead to higher exposures to elevated levels of ultrafine particulates, black carbon (BC), oxides of nitrogen (NO_x), and carbon monoxide (CO). There is growing evidence that people living or otherwise spending substantial time within the contaminated downwind region of major highways are exposed to pollutants more so than persons living at a greater distance (Nordling *et al.*, 2008). Children, older adults, and people with preexisting cardiopulmonary disease are among those at higher risk for health impacts associated with living close to major roads or in areas of high traffic density (Morgenstern *et al.*, 2007).

Numerous epidemiologic studies have consistently demonstrated that the exposure to pollutants emitted from motor vehicles contributes to adverse health effects including asthma, chronic obstructive pulmonary disease, and other respiratory symptoms (McEntee *et al.*, 2008; Morgenstern *et al.*, 2007; McConnell *et al.*, 2006; Gauderman *et al.*, 2004). In some previous studies, truck traffic has been more strongly associated with these adverse outcomes than total vehicular traffic (Janssen *et al.*, 2003; Brunekreef *et al.*, 1997).

For estimation and prospect of the health effects derived from heavy traffic as well as the impacts of future road construction projects, it is important to evaluate pollutants dispersion to downwind. The results of roadway pollutants dispersion modeling were being applied to real world cases of highway planning and airport projects even including some controversial court cases (Benson, 1982).

The study of pollutants scavenging, especially rainfall scavenging, is as much important as that of pollutants dispersion. This is because the wash-out of a large amount of automobile derived pollutants by rain falling in the neighborhood road is expected. If ambient particles are soluble, most of them may enter human body by dissolution, and then release potentially harmful material to the body (Morrow, 1992). Moreover, if the water-soluble components pass through the skin into the bloodstream, this can lead to more harmful health risk (Garrod *et al.*, 1998).

Fig. 1 illustrates the dispersion and scavenging of pollutants exhausted from vehicles running on an urban expressway.

In this study, in order to fully estimate the residents' exposure to the traffic-contaminated air at the downwind region from major highways, a combined modeling study on pollutant dispersion and scavenging was carried out.

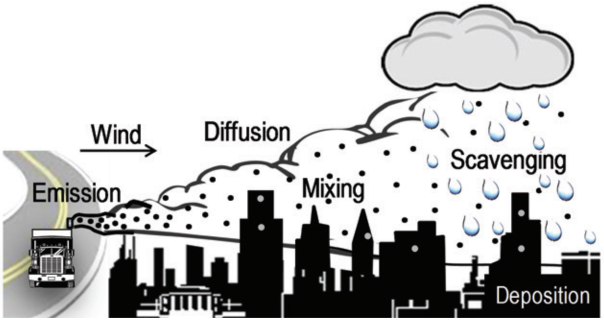


Fig. 1. Illustration explaining the diffusion and scavenging of pollutants exhausted from vehicle running on an urban expressway.

2. EXPERIMENTAL METHODS

2.1 Description of the Target Area of Modeling Study

Kashiihama in Fukuoka, Japan was selected to conduct the combined modeling study. Fig. 2 shows this target area (upper) and the road conditions (bottom). As shown in Fig. 2, an elementary school, a child-care center, a middle school, and many residential mansions are located within a few hundred meters of an urban expressway. Urban expressway is intra-city expressway which was found in many of Japan's other largest urban areas. Due to lack of space, many of expressways were constructed as viaducts running above local road. The Fukuoka urban expressway is nearly all entirely two lanes in each direction. In most places the speed limit is either 100 kmph or 80 kmph. Its average daily traffic volume is exceeding 163,000 vehicles (General affairs bureau of Fukuoka, 2012).

2.2 Schematic Representation of Modified Gaussian Plume Coordinate

In this study, in order to evaluate NO_x dispersion from an urban expressway to downwind, the modified

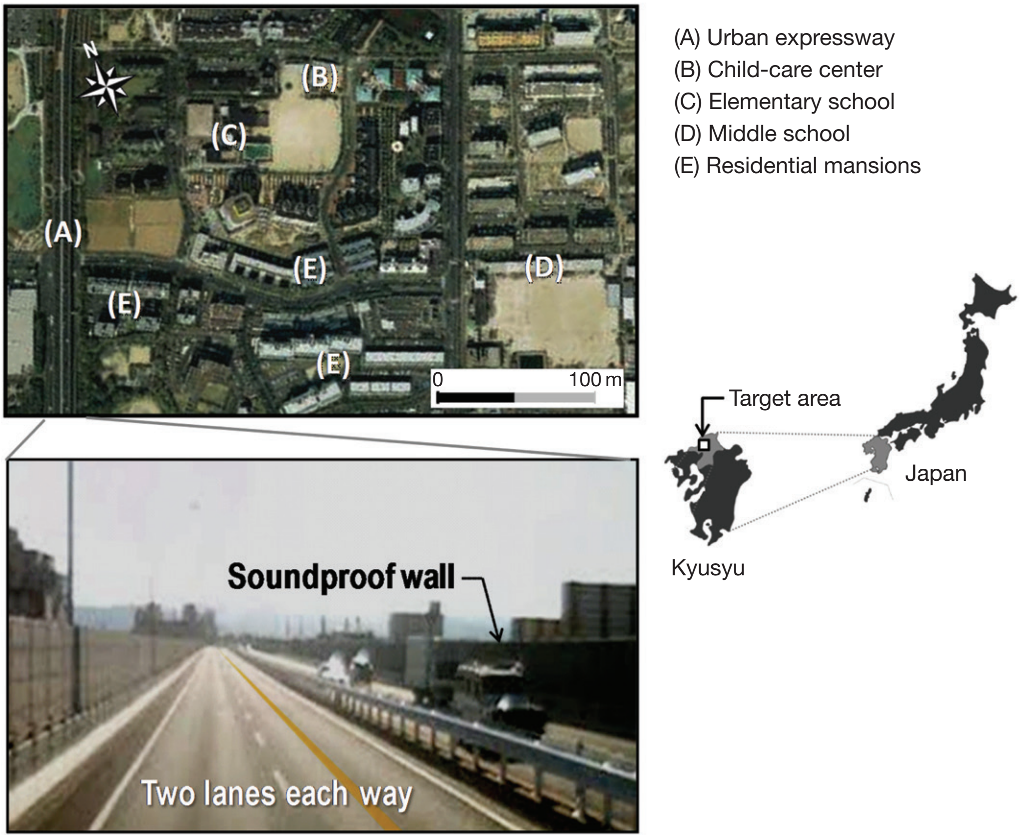
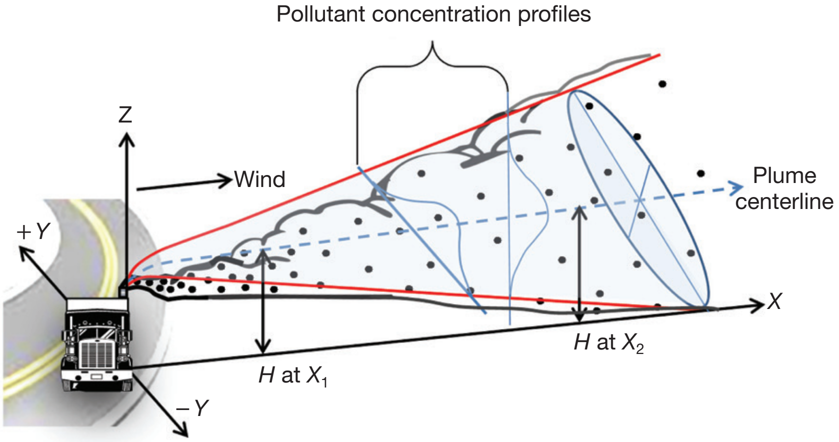


Fig. 2. Target area of modeling study (Kashiihama, Fukuoka, Japan) (upper) and the road conditions (bottom).



where:
X = downwind distance from plume source (m)
$X_{1,2}$ = downwind distance from plume source to $X_{1,2}$ points (m)
Y = horizontal plume distribution
Z = vertical plume distribution
H = effective height of plume rise (m)

Fig. 3. Schematic representation of plume coordinate system for the Gaussian plume equation.

Gaussian model (Benson, 1982) was applied. The basic concept of this dispersion model is to calculate air pollutant concentration in the vicinity of a roadway.

Though the Japan's ambient air quality standards is based on NO_2 concentration, the majority of NO_x emissions are in the form of NO rather than NO_2. The resultant NO_2 concentration in the vicinity of roadways is largely driven by the chemical reaction of NO with ambient ozone to form NO_2, photodissociation of NO_2, O_3 formation, hydroperoxyl radical (HO_2), organic peroxyl radical (RO_2), and the initial NO_2/NO_x ratio of the emissions.

Since the modified Gaussian model employed the vertical dispersion parameter, σ_z, near roadways estimated from data obtained in the General Motors sulfate dispersion experiment, it is therefore potentially more accurate than conventional Gaussian plume model.

Fig. 3 schematically illustrates the representation of plume (in here, plume of motor vehicle exhaust gases) coordinate system for the Gaussian plume equation.

The model formulation applied to the estimation of downwind dispersion of NO_x from the target region (i.e., an urban expressway running at Kashiihama, Fukuoka) of this study is as follows:

$$C_{NO_x}(x,y,z)=\frac{Q}{2\pi u\sigma_y\sigma_z}e^{\frac{-y^2}{2\sigma_y^2}}\left[e^{\frac{-(z-H)^2}{2\sigma_z^2}}+e^{\frac{-(z+H)^2}{2\sigma_z^2}}\right]$$

where:
C_{NO_x} = NO_x concentration as a function of downwind x, y, z position (ppb)
Q = average vehicle emission rate of NO_x (mL s^{-1})
u = average wind speed (m s^{-1}, in this study: 2.90 m s^{-1})
σ_z = dispersion width in the z direction ($\sigma_{zo}+0.31\ L^{0.83}$) (m)
σ_{zo} = initial dispersion width in the z direction (m)
without soundproof wall, $\sigma_{zo}=1.5$
with soundproof wall taller than 3 m, $\sigma_{zo}=4.0$
L = distance from the edge of roadway ($L=x-W/2$) (m)
W = width of roadway (m)
if, $x<W/2$, $\sigma_z=\sigma_{zo}$
σ_y = dispersion width in the y direction ($W/2+0.46\ L^{0.81}$) (m)
if, $x<W/2$, $\sigma_y=W/2$

The roadway source Q, average vehicle emission rate of NO_x (mL s^{-1}), is the average vehicle emissions rate.

The initial NO_x emission from roadways is generally presumed to consist of 95% NO and 5% NO_2 by volume in the vicinity of roadways. However, because of the implementation of oxidation catalytic converters or diesel particular filters (DPF) in diesel vehicles, the NO_2/NO_x ratio by volume of 5% increased markedly from a mean of about 5-6% in 1997 to about 17%, especially those with a high fraction of heavy-duty truck traffic (Carslaw, 2005).

In this study, Q (mL s^{-1}) was finally calculated by the light- and heavy-duty vehicle's NO_x emission rates (g km^{-1} · $vehicle^{-1}$), source characteristics such as the ratio of traffic (light- and heavy-duty) volume, number of vehicle per second, and vehicle speed. The $\sigma_{zo}=4.0$ was accepted because the soundproof wall taller than 3 m was installed at the target urban expressway. In order to estimate the time series variation of NO_x concentration including rush hours, in this study, the time classification for model calculation was one hour from 7 AM to 7 PM.

2. 3 Calculation of DEP's Wash-out by Falling Raindrops

As mention earlier, in addition to dispersion of pollutants from a line source, the wash-out of massive quantities of automobile derived pollutants such as DEP by rain falling in the neighborhood road is also seriously concerned. Previous studies (McConnell *et al*., 2006; Gauderman *et al*., 2004) have provided an evidence of long-term effects of DEP exposure including deficits in lung development or development of asthma. The wet scavenging of DEP in the atmosphere is a crucial factor in determining its atmospheric lifetime and thereby its health effects. Moreover, in recent, Vierkötter *et al*. (2010) unexpectedly pointed out that DEP exposure was significantly correlated to extrinsic skin aging signs, in particular to pigment spots and less pronounced to wrinkles.

Under these circumstances, in this study a further attempt was made to determine the scavenged DEP amount as a function of raindrop size by a model calculation. Fig. 4 shows the schematic of the wash-out model used for calculating concentration of DEP scavenged in the size-resolved raindrops falling through the vertical plume distribution. The model introduced in Fig. 4 is a Lagrange type model that set the special coordinates as the one-dimensional vertical direction from below cloud base to ground. For model calculation, several parameters were assumed as followings: the uniform distribution of DEP existing in a volume swept by falling raindrops, stable atmosphere, no dispersion by a rising air current, and non evaporation and coalescence of raindrops. When the raindrop with diameter d_R falls for one second, the volume V_{DROP} swept by a falling raindrop is described as following equation.

$$V_{DROP}=\frac{\pi d_R^{\,2}}{4}v_t$$

where v_t is the terminal velocity.

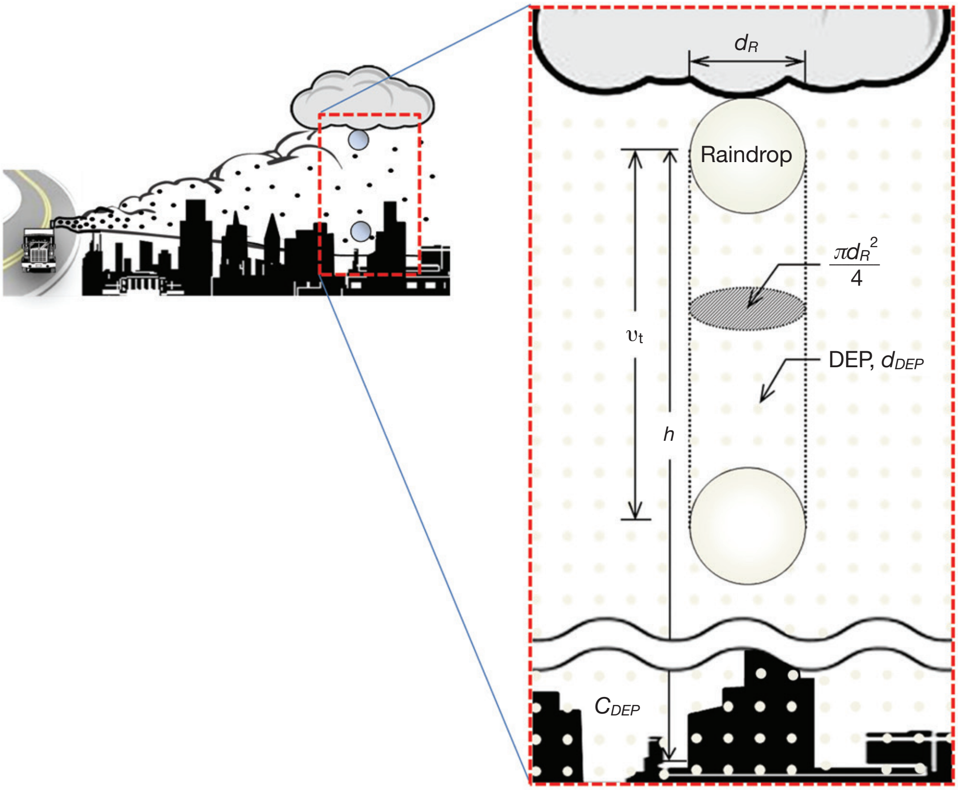


Fig. 4. Schematic of the model used for the calculating concentration of DEP scavenged in the size-resolved raindrops falling through the vertical plume distribution.

When the mass concentration of DEP with diameter d_R at ground is defined as $C_{DEP,0}(d_{DEP})$, and the collection efficiency of raindrop with d_R for DEP with diameter d_{DEP} is defined as $E_0(d_R, d_{DEP})$, the mass (m_V) of DEP (d_{DEP}) in a raindrop (d_R), which falls through V_{DROP} for one second, can be written as following.

$$m_V = \frac{\pi d_R^2}{4} \upsilon_t \cdot C_{DEP,0}(d_{DEP}) \cdot E_0(d_R, d_{DEP})$$

Therefore, the total mass (M_{TOTAL}) of DEP (d_{DEP}) in a raindrop (d_R), which falls through from below cloud base to ground, can be rearranged as following equation.

$$M_{TOTAL} = \int_0^t \frac{\pi d_R^2}{4} \upsilon_t(h,d_R) \cdot C_{DEP}(h,d_{DEP}) \cdot E(h,d_R,d_{DEP})dt$$

where $\upsilon_t(h,d_R)$ is the terminal velocity of a raindrop (d_R) at height (h), $C_{DEP}(h,d_{DEP})$ is the mass concentration of DEP existing at height (h), and $E(h,d_R,d_{DEP})$ is the collection efficiency of raindrop (d_R) for particle (d_{DEP}) at height (h).

Although ambient particles can be mainly removed through the processes of Brownian diffusion, interception, and impaction, in the present study the DEP scavenging efficiency (E) of raindrops was considered only Brownian diffusion (E_{dif}). In this work, the following E_{dif} proposed by Slinn and Hales (1971) was applied.

$$E_{dif} = \frac{4}{Re \cdot Sc}\left(1 + 0.4 Re^{1/2} Sc^{1/3}\right)$$

where Re is the Reynolds number of raindrop based on its radius ($(r_R \cdot \upsilon_t \cdot \rho_a)/\mu_a$), Sc is the Schmidt number of collected particle ($\mu_a/\rho_a \cdot D_p$), r_R is raindrop radius (μm), ρ_a is density of air (kg m^{-3}), μ_a is dynamic viscosity of air (Pa·s), and D_p is particle diffusivity (cm s^{-2}).

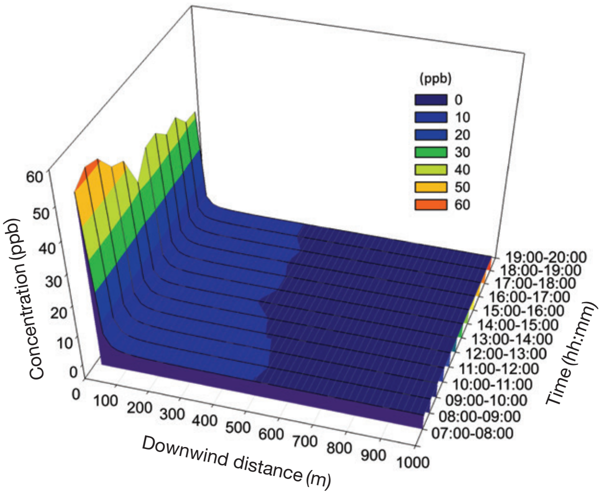


Fig. 5. Modeling result showing NO_x distribution within 1 km downwind distance.

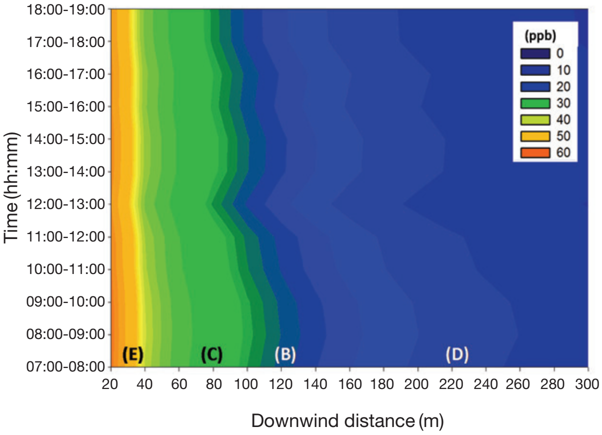


Fig. 6. Timely variation of calculated NO_x distribution at adjacent areas (0 to 300 m on the X-axis) of a line source.

3. RESULTS AND DISCUSSION

3.1 Dispersion of NO_x Exhausted from Vehicle Running on an Urban Expressway

Fig. 5 shows the timely variation of calculated NO_x distribution within 1 km downwind distance of a line source. According to the modeling result, the traffic-emitted NO_x was highest at the close area of urban expressway and diminished to near background levels within 300 to 500 meters from a roadway. Although, the NO_x concentration around road can vary considerably depending on meteorological conditions (especially wind direction), traffic kind and volume, emitted NO_x concentrations, land surface characteristic at downwind, and topography, the highest NO_x was marked 53.17 ppb within 20-30 meters from a line source from 08:00AM to 09:00AM. The maximum NO_x concentration calculated in this study was 2.8 times higher than that of a nearby ambient measuring station (19 ppb).

Additionally, from Fig. 5 it was possible to find out the hourly variation of calculated NO_x from the morning rush hour to evening. The theologically estimated NO_x concentration in the present study showed a severe temporal fluctuation. As might be expected, the maximum level of modeled NO_x was marked during the morning rush-hour from 07:00AM to 09:00AM. Meanwhile, during lunch break (i.e., from 12:00 to 13:00), NO_x concentration was significantly degraded, and then, it fluctuated slightly with relatively similar level to that of ambient till evening without an evening rush-hour peak. However, in the study on motorists' exposure to traffic-related air pollution carried out by Bigazzi *et al.* (2011), the peaks of NO_x inhaled were clearly appeared both morning and evening rush hours. One of the reasons for the peak of NO_x in the evening busy time did not appear is likely to be real differences in the close of the office hours in the world.

Fig. 6 shows the two-dimensional modeled NO_x distribution within a more adjacent area (0 to 300 m on the X-axis) of a line source. Horizontal gradient of NO_x concentration still illustrates that NO_x concentrations declined exponentially with increasing distance from the roadway due to the dilution process.

To investigate the influence of vehicle emissions on air pollutants at 9 heavy traffic sites in Fukuoka Prefecture, Japan, Itagaki *et al.* (2000) measured NO_x concentrations at several downwind portions (20 m, 100 m, and 200 m) of heavily traveled roadway by means of a mobile monitoring system. The theologically estimated NO_x values in the present study are comparable with those of real measured reported by Itagaki *et al.* (2000). Among their measured NO_x values from 9 sites, the data at a site having matched conditions specified in the model calculation of this study was compared to the theologically estimated NO_x values in the present study. Their measured NO_x at downwind portions of 20 m, 100 m, and 200 m from heavy trunk road were 47 ppb, 32 ppb, and 11 ppb, respectively. Meanwhile, in this study, the average modeled NO_x concentrations at each downwind area of a line source were 42 ppb, 29 ppb, and 8 ppb, respectively. Although their variations do not match perfectly, there is a close correspondent between the real measured data (Itagaki *et al.*, 2000) and the theoretically calculated NO_x concentrations.

This result indicates that the profiles applied to modified Gaussian plume coordinate in this study were very appropriate. In this regard, the model results, although they were acquired from simple line source Gaussian plume dispersion, can be helpful for the prediction of gaseous pollutants impacts near roadways.

As previously stated, in the neighborhood of target area of modeling study (see Fig. 1) many residential mansions, two schools, and a child-care center are located. Exposure to NO_x during the first year of life was associated with increased sensitization to inhalant allergens in addition to increased risk of wheeze and lower lung function at an age of 4 years (Nordling *et al.*, 2008). In addition, it was turned out that people live near busy roads (< 50 m) have come to be exposed to the risk of wheezing and asthmatic bronchitis. It is therefore urgent to take more comprehensive measures to solve the potential health threats to people live nearby roads where there is much traffic.

3. 2 Theoretical Estimation of DEP's Rain Scavenging

Fig. 7 shows the calculated DEP concentrations as the functions of raindrop size and mixing height. In this study, raindrops were fractionated into size class 0.2, 1.0, and 2.0 mm diameter. According to Fig. 7, the theoretically calculated DEP concentrations in three kinds of rain drops varied from 0.2 to 62.1 $\mu g\ L^{-1}$ depending on three categories of mixing heights. Although it is readily conclude that DEP cannot be easily scavenged by rainfall, this result clearly proved that wet scavenging is one of most effective natural removal mechanisms of DEP from ambient air.

Even though the fresh BC which is mostly hydrophobic, once it become sufficiently hydrophilic, it can act as the nuclei for cloud condensation nuclei (CCN) (Posfai *et al.*, 1999). This nucleation scavenging (i.e., rainout) of BC was clearly proven through the laboratorial scale model experiment (Ma and Kim, 2014).

As the peculiar phenomenon, a continuous decreasing of DEP mass concentration with increasing raindrop size was shown in Fig. 7. Especially, a noticeable decrease was found between 0.2 mm and 1.0 mm raindrop diameter.

Through a number of field experiments, Bächmann *et al.* (1993) suggested that a continuous decrease in the concentration with increasing drop radius near and at the ground was found. They also reported that, during a precipitation event, the salt concentration across the raindrop spectrum evolves in time, and often develops the maximum concentration in drops of 0.5 to 0.6 mm diameter. More recently, this raindrop size dependence

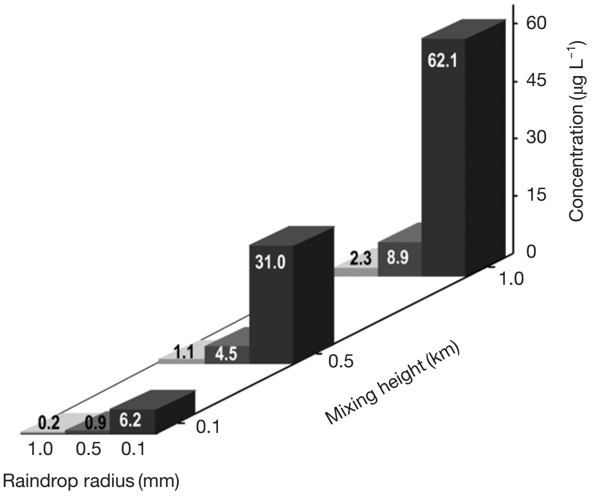


Fig. 7. Theoretically estimated DEP concentrations in the size-resolved raindrops.

of pollutant concentration has been proved by Ma *et al*. (2001) through a field measurement performed at a height of 20 m above ground level.

Even though little is known on the reasons for the dissimilar scavenging efficiency among raindrops with different sizes, the higher DEP concentration in smaller raindrops was probably caused because smaller raindrops have lower falling velocities and consequently have longer lifetimes than larger ones. This phenomenon might also be caused by the effect of evaporation, i.e. small raindrops show a much higher degree of evaporation than larger ones which leads to an increase of the mass concentration.

During rainfall the raindrops can take up a large amount of other traffic derived pollutants such as gaseous NO_x and VOCs. The water soluble fraction of DEP can also be dissolved into raindrops. And then, the released potentially harmful material may enter through the skin into our body (Morrow, 1992). It can therefore be said that people live or stay in the neighborhood road must pay particular attention to these points.

4. CONCLUSIONS

This study aims at giving information in the dispersion and scavenging of vehicle derived pollutants at the locations near busy urban expressways by a combination of two different model calculations. The modeling result pointed out that NO_x was highest at the close area of urban expressway. The highest calculated level of NO_x was 2.8 times higher than that of a nearby ambient measuring station during the heaviest traffic hours. In addition, the theoretical calculation of DEP's wet-scavenging at the downwind region of a busy urban expressway suggested DEP was more effectively washed out by smaller raindrops. This result indicates that during a rainfall event, especially drizzle event, the high concentration of some dissolved harmful ingredients from DEP as well as noxious gases have an adverse effect on people's health. Even though in this study a combined model study was practiced under a limited circumstance, the results of our model calculation suggest that it is urgent to take more comprehensive measures for come to understanding the potential health threats to children and dwellers living or staying nearby urban express ways. Additionally, the results of this study provide transportation planner with information about the traffic-related health effects when evaluating alternative transportation infrastructures.

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