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\textsubscript{x} dispersion and DEP (Diesel exhaust particles) wet removal, respectively. The highest NO\textsubscript{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\textsubscript{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
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 NOx dispersion from an urban expressway to downwind, the modified
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 NO2 concentration, the majority of NOx emissions are in the form of NO rather than NO2. The resultant NO2 concentration in the vicinity of roadways is largely driven by the chemical reaction of NO with ambient ozone to form NO2, photodissociation of NO2, O3 formation, hydroperoxyl radical (HO2), organic peroxy radical (RO2), and the initial NO2/NOx ratio of the emissions.

Since the modified Gaussian model employed the vertical dispersion parameter, $\sigma_z$, 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 NOx from the target region (i.e., an urban expressway running at Kashiihama, Fukuoka) of this study is as follows:

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

where:

- $C_{NOx}$ = NOx concentration as a function of downwind $x$, $y$, $z$ position (ppb)
- $Q$ = average vehicle emission rate of NOx (mL s\(^{-1}\))
- $u$ = average wind speed (m s\(^{-1}\), in this study: 2.90 m s\(^{-1}\))
- $\sigma_z$ = dispersion width in the $z$ direction ($\sigma_{zo} + 0.31 L^{0.83}$) (m)
- $\sigma_{zo}$ = 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, $x < W/2$, $\sigma_z = \sigma_{zo}$
  - $\sigma_y$ = dispersion width in the $y$ direction ($W/2 + 0.46 L^{0.83}$) (m)
  - if, $x < W/2$, $\sigma_y = W/2$

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

The initial NOx emission from roadways is generally presumed to consist of 95% NO and 5% NO2 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 NO2/NOx 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 NOx 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 $a_{\text{to}} = 4.0$ 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 $V_{\text{DROP}}$ swept by a falling raindrop is described as following equation.

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

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.](image)
When the mass concentration of DEP with diameter \( d_R \) at ground is defined as \( C_{DEP_0} \), and the collection efficiency of raindrop with \( d_R \) for DEP with diameter \( d_{DEP} \) is defined as \( E_0 \), 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.

\[
m_v = \frac{\pi d_R^2}{4} v_t \cdot C_{DEP_0}(d_{DEP}) \cdot E_0(d_R, d_{DEP})
\]

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.

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

where \( v_t(h, d_R) \) 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.

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

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

### 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 NOx inhaled were clearly appeared both morning and evening rush hours. One of the reasons for the peak of NOx 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 NOx distribution within a more adjacent area (0 to 300 m on the X-axis) of a line source. Horizontal gradient of NOx concentration still illustrates that NOx 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 NOx concentrations at several downwind portions (20 m, 100 m, and 200 m) of heavily traveled roadway by means of a mobile monitoring system. The theoretically estimated NOx values in the present study are comparable with those of real measured reported by Itagaki et al. (2000). Among their measured NOx values from 9 sites, the data at a site having matched conditions specified in the model calculation of this study was compared to the theoretically estimated NOx values in the present study. Their measured NOx 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 NOx 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 NOx 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 NOx 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 μg 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 laboratory 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...
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\textsubscript{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\textsubscript{x} was highest at the close area of urban expressway. The highest calculated level of NO\textsubscript{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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