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Predicting particle number concentrations near a highway based on vertical concentration profile

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Abstract

This paper presents vertical profiles of particle number concentration and size distribution near the Interstate 405 Freeway. Based on vertical concentration data, averaged emission factor for total particle number concentration was determined to be 8.3e14 particle^{-1} vehicle^{-1} mile^{-1}. A simple analytical solution was obtained by solving the atmospheric diffusion equation and used to predict horizontal profiles of total particle number concentrations. Good agreement was achieved when model results were compared with previously published experimental data (J.Air Waste Manage. Assoc. 52 (2002b) 174–185). Model inputs are traffic, wind, and locations. With the particle emission factors, traffic compositions, and meteorological data, particle number concentrations near freeways can be quantitatively determined using the simple equation achieved in this study.

Keywords: Ultrafine particles; Atmospheric dispersion; Emission factor; Vertical concentration profile

1. Introduction

Epidemiological studies all over the world have consistently linked increases in particulate matter (PM) exposure to increases in mortality and morbidity (Dockery et al., 1993; Vedal, 1997). Improvement in particle measurement technologies has allowed exposure to smaller particle sizes to be evaluated. The link between PM and adverse health effects has been suggested to be stronger as smaller particle sizes are considered (Wichmann and Peters, 2000). Recent epidemiological studies, dealing with short-term effects in adults and children with asthma and daily mortality, have addressed the role of ultrafine particles (diameter <100 nm) (Penttinen et al., 2001; Peters et al., 1997; Wichmann et al., 2000a, b). These studies suggested that health effects might be more associated with the number of ultrafine particles than with the mass of the fine particles.

Health effects have been related to traffic volume. Children living near high traffic streets are more likely to have more medical care visits per year for asthma (English et al., 1999) and a higher prevalence of most respiratory symptoms (Ciccone, 1998; Oosterlee et al., 1996) than those living near lower traffic streets. Although it is not clear which traffic related pollutant contributes to the observed adverse health effect, traffic is the major source of ultrafine particles in an urban environment (Hitchins et al., 2000; Schauer et al., 1996; Shi et al., 1999; Zhu et al., 2002a, b, 2004). Both diesel and gasoline engines generate a significant number of particles in the ultrafine size range (Morawska et al.,

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1998; Ristovski et al., 1998). Increases in particle number concentration have been observed during the rush hours (Wichmann and Peters, 2000). With increasing concern about ultrafine particle exposure near traffic sources, Zhu and co-workers conducted measurements of particle number concentration and size distribution near two major freeways in Los Angeles, CA, in two seasons (Zhu et al., 2002a, b, 2004). Measurements showed ultrafine particle concentration immediately downwind near both freeways were approximately 25 to 30 times greater than the concentrations upwind and decreased rapidly with increasing distance downwind from the freeway.

Although a number of line source models have been developed by US Environmental Protection Agency and many other research institutes for estimating vehicular pollutant concentrations, these models have focused primarily on gas-phase pollutants. Some of them have the capacity to predict PM_{10} and sometimes $PM_{2.5}$. However, little attention has been given to particle number concentrations. Nagendra and Khare presented a thorough review on line source models (Nagendra and Khare, 2002). More recently, Jamriska and Morawska developed a box model to assess the traffic-related emission rates of fine and ultrafine particles to local areas in Queensland, Australia (Jamriska and Morawska, 2001). Johnson and Ferreira developed a statistical model to predict submicrometer particle concentration (diameter less than 1 μm) contributed by traffic flows in Brisbane, Australia (Johnson and Ferreira, 2001). CALINE4 software package was recently adapted to determine the average emission factors for ultrafine particles based on their number concentration (Gramotnev et al., 2003).

Predicting particle size distributions as a function of distance from an emission source is apparently much more challenging and controversial. Based on data published in the series of papers from Zhu et al. (2002a, b, 2004), Jacobson and Seinfeld argued that enhanced Brownian coagulation due to van der Waals forces and fractal geometry may account for observed particle size evolution (Jacobson and Seinfeld, 2004); while Zhang et al. (2004) hypothesized that condensation/evaporation was the dominant mechanisms in altering particle size distributions. Although discrepancies exist in the literature, they seem to agree that atmospheric dispersion/dilution is the most important process in decreasing particle number concentrations near the source.

The present research focuses on determining particle number emission factors based on vertical concentration profiles near the Interstate 405 freeway and developing a simple atmospheric dispersion models that predict ultrafine particle number concentration as these particles are transported away from a major emission source—a freeway. The goal of this research is to quantitatively predict particle number concentration at any specified distance from a freeway based on traffic and atmospheric conditions.

2. Experiment

Previously, we have reported horizontal concentration profiles of ultrafine particles and co-pollutants near the Interstate 405 Freeway in summer 2001 (Zhu et al., 2002b). During our 2001 summer field campaign, vertical concentration profiles were obtained on 17th and 18th July 2001. These data were used to determine average particle number emission factors from the traffic, which was later used as an input parameter for the atmospheric dispersion model developed in this study.

Near the sampling site, Freeway 405 runs generally north and south. Average traffic density was 230 vehicles min^{-1} passing the sampling site in both directions with approximately 5% being heavy-duty diesel trucks. During the sampling period, a consistent sea breeze (eastward from the ocean) developed in mid-morning, reached its maximum early to mid-afternoon, and died out in the early evening. The region upwind of the freeway is a residential area without any industrial or other obvious PM sources. A 12 m scissors lift with a 6 m extension mast was used to sample carbon monoxide (CO) and particle number concentrations at different heights at a fixed location, 50 m downwind from the center of Freeway 405. A detailed description of the sampling site, can be found in Zhu et al. (2002a).

A video recorder (camcorder) was located on top of a 10-m tower near the sampling site and operated continuously throughout the measurement. The camcorder was high enough to capture all nine lanes on the 405 Freeway. After sampling session, the videotapes were replayed and traffic density, defined as number of vehicles passing per minute, was determined manually.

Total particle number concentration was measured every minute by a condensation particle counter (CPC 3022A; TSI Inc., St. Paul, MN). Data reduction and analysis were done by the Aerosol Instrument Manager software (version 4.0, TSI Inc., St. Paul, MN). In addition to total particle number concentration, CO concentration was measured every minute by a near-continuous CO monitor (Dasibi Model 3008, Environmental Corporation, Glendale, CA). The CO monitor was calibrated by standard CO gas (RAE systems Inc., Sunnyvale, CA) in the laboratory and automatically zeroed each time the power was turned on. Before each measurement, all instruments were synchronized. Vertical concentration profiles for CO, and total particle number concentrations measured by the CPC were obtained near the freeway. Measurements were taken at 50 m downwind from the center of Freeway 405 at 0.6, 3.0, 5.5, 8.0, 10.4, 12.8, 15.3, and 17.7 m above the ground.

Meteorological parameters including ambient temperature, wind speed and directions were measured on site by a computerized weather station (Wizard III, Weather Systems Company, San Jose, CA) and logged at 1-min. intervals. The weather station was placed on top of the scissors lift to achieve a vertical wind profile. It takes about 10 min to complete sampling at each height and 2 h to complete a set, all eight heights. Two sets were performed on each sampling date.

3. Theory

Atmospheric dispersion, coagulation and condensation/evaporation have been reported to cause a rapid decrease in particle number concentration and changes in particle size distribution with increasing distance from freeways (Jacobson and Seinfeld, 2004; Zhang et al., 2004). Atmospheric dispersion will decrease particle number concentrations but would not change particle size distribution. Coagulation will cause a decrease in particle number concentration and an increase in particle size. Condensation will not change particle number concentration but will cause particles to grow and shift particle size distribution to larger sizes. The relative contribution of coagulation and condensation/evaporation in causing the observed size distribution changes is an area of on-going research (Jacobson and Seinfeld, 2004; Zhang et al., 2004). Published studies seem to agree that atmospheric dispersion is the dominant mechanism in determining particle number concentration near sources. In this study, we focus on developing an easy to use atmospheric dispersion model to predict particle number concentration near a freeway as a function of traffic conditions and wind speed.

Vehicular exhaust emission from the freeways can be represented as a line source. The most commonly used line source models are based on the Gaussian Plume model, for example, CALINE4, developed by the California Department of Transportation. CALINE4 employs a mixing zone concept to characterize the concentration of CO near roadways (Benson, 1989). Recently, CALINE4 has been successfully adapted to estimate the average emission factor for number-based particle concentrations and has been validated against data collected near a road in Brisbane, Australia (Gramotnev et al., 2003). The calculated average emission factor for vehicles on this road is about 4.5×10^{14} particles vehicle^{-1} mile^{-1} in that study.

While the Gaussian model has been widely used to simulate atmospheric dispersion, it does not represent well the pollutant concentration distribution under strong convective condition, under ground-level release, and near sources (Seinfeld and Pandis, 1998; Sharan et al., 1996a; Turner, 1994). Instead, the atmospheric diffusion equation was found to provide a more general approach than the Gaussian models. Assuming incompressible flow and the absence of chemical reaction, atmospheric diffusion equation based on the Gradient-transport theory (K-theory) is (Seinfeld and Pandis, 1998)

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}+w\frac{\partial C}{\partial z}=\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial C}{\partial z}\right), \tag{1}$$

where C is the mean concentration of a pollutant; (u, v, w) and (K_{xx}, K_{yy}, K_{zz}) are the components of wind and eddy diffusivity vectors in x, y and z direction, respectively, in an Eulerian frame of reference.

For a continuous, crosswind line source ($\partial C/\partial y=0$), at a height h emitting at a rate q_l (particle m^{-1} s^{-1}), with the following assumptions:

(a) Steady state conditions, i.e. $\partial C/\partial t=0$.
(b) The vertical velocity is much smaller than the horizontal velocity so the term $w(\partial C/\partial z)$ can be neglected.
(c) The x-axis is oriented in the direction of the mean wind, i.e. $u=U$ and $v=0$, where U is the wind velocity ($U>0$).
(d) The diffusion in the direction of the mean wind can be neglected, i.e. $K_{xx}=0$.

Eq. (1) reduces to

$$U\frac{\partial C}{\partial x}=\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial C}{\partial z}\right). \tag{2}$$

The source term q_l is introduced through the following boundary conditions

$$C(0,z)=(q_l/U(h))\delta(z-h), \tag{3}$$

where $\delta(z-h)$ is Dirac's delta function.

Far away from the line source, the concentration decreases to zero after subtracting the background concentration, i.e.

$$C(x,z)=0 \quad x,z\to\infty. \tag{4}$$

Ground surface is assumed impermeable to the pollutants, i.e.

$$\frac{\partial C}{\partial z}=0 \quad \text{at } z=0. \tag{5}$$

For near source diffusion, Sharan et al. (1996a, b) showed that K_{zz}, the vertical eddy diffusivity, can be specified as linear functions of downwind distance based on Taylor's statistical theory of diffusion for small travel times (Taylor, 1921). Thus,

$$K_{zz} = \gamma U x, \tag{6}$$

where γ represents the turbulence parameter in the z direction. This is based on the fact that near a point source, the surface containing the standard deviations of the pollutants from a horizontal straight line to leeward of the source is a cone, not a paraboloid as the classical Gaussian model assumes. Now Eq. (2) becomes

$$\frac{\partial C}{\partial x} = \gamma x \frac{\partial^2 C}{\partial z^2}. \tag{7}$$

Eq. (7) with boundary conditions (3)–(5) can be solved analytically using Fourier's transforms or similarity method (Kevorkian, 1990) to obtain

$$C(x,z) = \frac{q_1}{Ux\sqrt{2\gamma\pi}}\left\{\exp\left(-\frac{(z-h)^2}{2\gamma x^2}\right) + \exp\left(-\frac{(z+h)^2}{2\gamma x^2}\right)\right\}. \tag{8}$$

A similar approach has been used previously by Sutton (1947) for an elevated point source and analyzed in detail in the book by Csanady (1980). For practical application, the turbulence parameter γ, can be identified as the square of turbulence intensity using Taylor's statistical theory of diffusion, i.e.

$$\gamma = \left(\frac{\sigma_{\mathrm{w}}}{U}\right)^2. \tag{9}$$

When measurements of turbulence intensities are available, γ should be computed directly by Eq. (9). In the absence of direct measurement, mixed-layer similarity scaling and empirical turbulence data suggest that $\sigma_{\mathrm{w}} = bw_*$, where w_* is the convective velocity scale. This scale is the magnitude of the vertical velocity fluctuations in thermals and is usually on the order of 1.0–2.0 m/s (Stull, 1988). Depending on the dimensionless height z/z_i, where z_i is the convective mixing height, the constant b can be from 0.4 to 0.6. It is a good approximation to take $b = 0.4$ for modeling dispersion in the surface layer and $b = 0.6$ in the mixed layer (Sharan et al., 1996a, b). Thus, turbulence parameter can be expressed as

$$\gamma = 0.16(w_*/U)^2. \tag{10}$$

4. Results and discussion

4.1. Vertical profile

Fig. 1 showed the vertical concentration profile of CO measured at 50 m downwind from the 405 Freeway. A maximum concentration of CO was observed at a height around 5 m above the ground. As mentioned before, at the sampling site, Freeway 405 is elevated ~4.5 m above the surrounding terrain. The observed maximum concentration, plume centerline concentration, is approximately at the freeway height indicating that the road does not result in any effects of the thermal rise of the plume. CO concentration decreased to about 50% of its central line concentration at ground level and 30% at 18 m above the ground. A dimple was observed at 10 m, which may be due to a secondary mixing above the central line of emission. In general, the shape of the curve corresponds to classical picture of the plume with its lower part reflected from the ground (Csanady, 1980), and seemed to indicate that we have captured most of the plume.

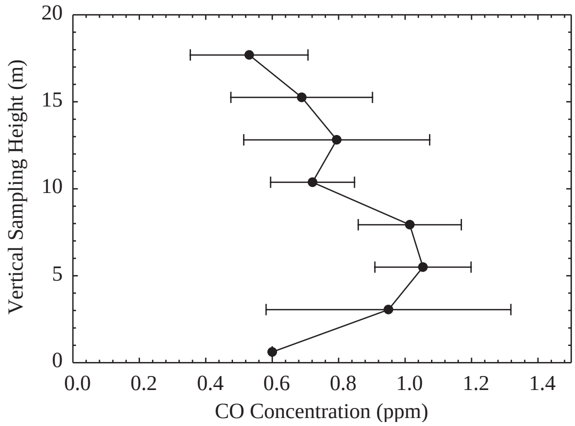

Fig. 1. CO concentration vertical profile 50 m downwind from the 405 Freeway. Error bars indicate one standard deviation.

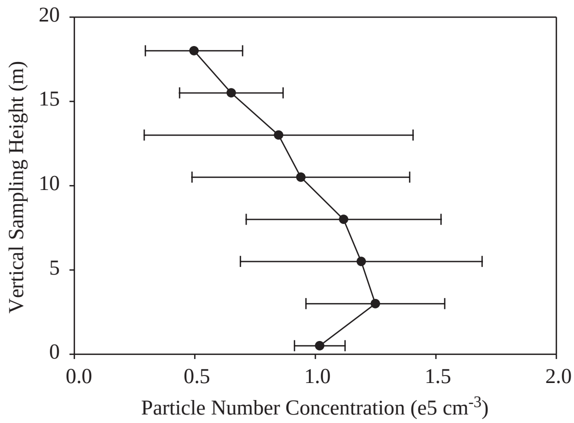

Fig. 2. Total particle number concentration (measured by a CPC) vertical profile 50 m downwind from the 405 Freeway. Error bars indicate one standard deviation.

Vertical concentration profile of total particle number concentration measured by CPC is shown in Fig. 2. Similar to the CO profile, the highest total particle number concentration occurred around 3 to 7 m above the ground. The dimple effect at 10 m was much weaker for total particle number concentrations. Comparing Figs. 1 and 2, it is seen that both of these two pollutants decayed at a similar rate from their centerline concentrations with respect to vertical height. Error bars in both Figs. 1 and 2 were considerably larger than those in previously reported horizontal profiles (Zhu et al., 2002b). In horizontal profiles, dispersion was the dominant process in determining pollutants' concentrations at a given downwind location from the source and is governed mainly by wind velocity. Due to a reliable sea breeze in the sampling area, relatively stable wind direction and speed were achieved during the sampling time. For vertical profiles the diffusion process is more important and is controlled by turbulence, which is much less predictable. These may partially explain the observed large error bars in Figs. 1 and 2. Nevertheless, the general shape of the vertical concentration profiles for both CO and total particle number concentrations were similar. The general shape seems to suggest that we have captured most of the plume.

4.2. Source strength and emission factor

In order to use the model developed in the previous section to predict particle number concentration at given downwind distance from the freeway, the line source strength for particle number concentration; q_l (particle $m^{-1}s^{-1}$) has to be determined. This can be done by integrating both sides of Eq. (8) from 0 to ∞ with respect to vertical height.

$$\int_0^\infty C(x,z)\,dz = \int_0^\infty \left(\frac{q_l}{Ux\sqrt{2\gamma\pi}}\left\{\exp\left(-\frac{(z-h)^2}{2\gamma x^2}\right) + \exp\left(-\frac{(z+h)^2}{2\gamma x^2}\right)\right\}\right) dz. \tag{11}$$

Comparing the right-hand side of Eq. (11) to an error function defined as

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-u^2}\,du. \tag{12}$$

Eq. (11) can be rewritten as

$$\int_0^\infty C(x,z)U(x,z)\,dz = \frac{q_l}{2}\left(\mathrm{erf}\left(\frac{z-h}{x\sqrt{2\gamma}}\right) + \mathrm{erf}\left(\frac{z+h}{x\sqrt{2\gamma}}\right)\right), \tag{13}$$

where z goes to infinity.

Since $\mathrm{erf}(\infty) = 1$, Eq. (13) is reduced to

$$q_l = \int_0^\infty C(x,z)U(x,z)\,dz, \tag{14}$$

where $C(x,z)$ is the concentration of particles as a function of sampling height z and $U(x,z)$ is the average wind speed at the sampling height z. q_l can also be viewed as the unit length flux F through the plane on the downwind side of the freeway (Gramotnev et al., 2003) which could be obtained by integrating the product of wind speed and particle number concentration with respect to increment of vertical height as was done in Eq. (14).

During the measurement period, more than 85% of the time, wind was blowing perpendicular from the freeway to the sampling site. Average wind speed and particle number concentration measured by the CPC at each sampling height as well as particle number concentration measured upwind of the freeway are summarized in Table 1. As shown in Table 1, average wind speeds were approximately constant with sampling height and had relatively small and similar standard deviations. This result is consistent with previous studies (Benson, 1989; Gramotnev et al., 2003).

Previously Gramotnev et al., have shown that at the height of ~15 m, the vertical concentration decreases to the background level by means of CALINE4 model. As shown in Table 1, in the current study vertical concentration at 17.7 m was still higher than the background concentration, which was usually about 3.5×10^4 particle cm^{-3} as reported in Zhu et al. (2002a). After subtracting the background concentration of 3.5×10^4 particle cm^{-3}, Eq. (14) was rewritten in terms of discrete sampling heights within our sampling range to get a measured source strength, q_l^*.

$$q_l^* \approx \sum_{0.6}^{17.7}(C(x,z) - C_{\mathrm{upwind}})U(x,z)\Delta z. \tag{15}$$

Based on data summarized in Table 1, q_l^* was calculated to be 1.44×10^{12} (particle $m^{-1}s^{-1}$). It should

Table 1
Average wind speed and particle number concentration as a function of sampling height

Sampling height, h (m)	Average wind speed, $U(h)$ (m s^{-1})	Average particle number concentration, $C(h)$ (particle cm^{-3})
0.6	1.3±0.5	1.0×10^5
3.0	1.3±0.4	1.2×10^5
5.5	1.3±0.4	1.2×10^5
8.0	1.3±0.5	1.0×10^5
10.4	1.4±0.5	0.9×10^5
12.8	1.5±0.5	0.8×10^5
15.3	1.3±0.4	0.7×10^5
17.7	1.4±0.4	0.5×10^5
Upwind	N/A	3.5×10^4

be noted q_l^* is not the real source strength. It is just a measured value based on data within our sampling height. Since our sampling height has only captured most of the plume, not the complete one, a scale factor must be introduced to achieve the real line source strength.

The scale factor, q_l/q_l^* could be determined by dividing the integrals of Eq. (8) with respect to our sampling height to that of infinity.

$$\frac{q_l^*}{q_l} = \frac{\mathrm{erf}\left(z - h/x\sqrt{2\gamma}\right) + \mathrm{erf}\left(z + h/x\sqrt{2\gamma}\right)}{\mathrm{erf}(\infty) + \mathrm{erf}(\infty)}. \quad (16)$$

The highest sampling height in the current study was 17.7 m ($z = 17.7$ m). The emission source was at 4.5 m above the ground ($h = 4.5$ m). Vertical sampling was conducted at a horizontal distance of 35 m from the edge of the freeway ($x = 35$ m). The turbulence parameter γ, was not directly measured in the current study. It was determined by using Eq. (12) in which the mean value of convective velocity scale found in the literature, 1.5 m s^{-1}, was used with average wind speed measured during vertical study, 1.3 m s^{-1}. The turbulence parameter γ was determined to be 0.21. For the highest sampling height, $z = 17.7$ m, $(z - h)/x\sqrt{2\gamma} = 0.58$ and $(z + h)/x\sqrt{2\gamma} = 0.97$. From error function table a value of 0.588 and 0.830 was obtained for these two terms, respectively. Since $q_l^*/q_l = (0.588 + 0.830)/(1 + 1) = 0.71$, the real line source strength was estimated to be $1.44 \times 10^{12}/0.71 = 2.0 \times 10^{12}$ (particle m^{-1} s^{-1}).

Source strength q_l was related to emission factors through traffic density by

$$q_l = E \times V, \quad (17)$$

where E is the average particle number emission factor from vehicles (particle vehicle^{-1} mile^{-1}) on the freeway; V is average traffic volume (vehicle s^{-1}). Average traffic was determined to be 3.9 vehicles s^{-1} based on traffic data recorded on the videotapes. Thus, the average particle number emission factor was calculated to be 8.3×10^{14} (particle vehicle^{-1} mile^{-1}) or 5.2×10^{11} (particle vehicle^{-1} m^{-1}).

This emission factor was within the range (1.8×10^{10}–2.0×10^{12} particle vehicle^{-1} m^{-1}) but at the higher end of what has been published in the literature (Abu-Allaban et al., 2002; Gramotnev et al., 2003; Hall and Dickens, 1999; Jamriska and Morawska, 2001; Johnson and Ferreira, 2001; Kittelson, 1998; Kittelson et al., 2001; Morawska et al., 1998; Wahlin et al., 2001; Weingartner et al., 1997). Published particle number concentration emission factor data cover a wide range mainly due to two factors. The first one is different driving pattern that includes different driving speeds, fuel usage, traffic compositions, etc. Among these factors the vehicle speed seems to be most important. Much higher particle number concentrations have been reported from fast driving vehicles. The current study was done near an Interstate highway where traffic speed was normally at 60 mile h^{-1} considerably higher than what has been reported in other studies done near major roads (Gramotnev et al., 2003). The second one is the use of different particle detecting instruments that measure particles in different size ranges by different research groups. Since a considerable fraction of freshly emitted particles are in the smallest ultrafine size range (<10 nm), an instrument that has a larger lower-cutoff size will report a smaller number concentration. The instrument we used in the current study detected particles down to 6 nm and would return a higher value compare to other instruments that normally cut off above 10 nm. These factors may explain the relatively high emission factor that we observed in the current study. It should also be noted that the emission factor obtained in this study should only be viewed as the overall average emission factor of the vehicle fleet on the freeway. Detailed analysis on traffic speed and composition would provide more information on emission factors for different vehicle category, for example: diesel vs. gasoline, as well as for different driving speed.

4.3. *Compare model prediction to previous experimental results*

The emission factor 8.3e14 (particle vehicle^{-1} mile^{-1}), was then plugged into Eq. (8) to predict horizontal particle number concentration profiles under conditions in which previous horizontal measurements were conducted (Zhu et al., 2002b). The emission height was set to the height of the freeway, 4.5 m; sampling height was 1.6 m. Wind speed was the average wind speed during horizontal sampling, 1.5 m s^{-1}, perpendicular to the freeway. Background particle number concentration was 3.5e4 particle cm^{-3}. Average traffic density was 3.8 vehicle s^{-1}, a little lower than during vertical sampling. Since no direct measurement was available for turbulence parameter data, γ was determined by using Eq. (12). Three γ values were used representing the low, medium and high convective velocity scale in the literature, namely, 1.0, 1.5 and 2.0 m s^{-1}. These three conditions result in values of 0.07, 0.16 and 0.28 for turbulence parameter.

Model prediction was then compared to previous measurement and presented in Fig. 3. Horizontal axis is the distance from the edge of the freeway in this figure whereas experimental data was previously reported as from the center of the freeway (Zhu et al., 2002b). Half width of the freeway, ~15 m, was subtracted from previously published results. The model with all three γ values predict a sharp increase close to the source due to the difference between the source and receptor height and an exponential decay with increasing downwind distance. In generally, the model developed in this study fits very well to the experimental data. It is noted that the model is moderately sensitive to γ values. All three curves give reasonable prediction to experimental data although the mean value of convective velocity scale seems to yield a better fit to experimental data. These results imply that atmospheric dispersion is by far the most important mechanisms in determining particle number concentration near freeways. Other aerosol or chemical processes may have an effect on the particle size distribution but not much on total particle number concentrations. Thus, the model developed in this study provides epidemiologists and toxicologists a simple tool to estimate ultrafine particle number concentrations near freeways for health-related studies.

4.4. Sensitivity analysis and model limitations

The model uses traffic information, which includes traffic volume and average particle number emission factors, and meteorological data, such as wind direction and speed, turbulence parameter, γ, as model input and predicts particle number concentrations at certain downwind distance from the freeway. The influence of turbulence parameter, γ, on model performance has been discussed above.

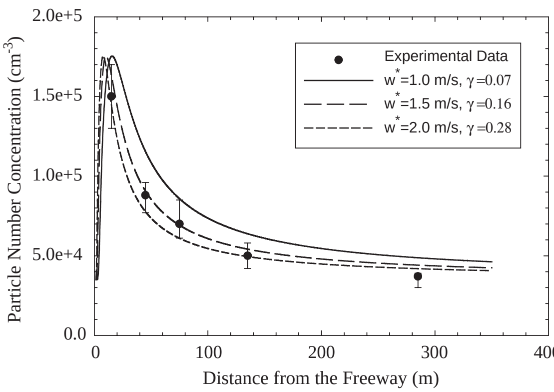

Fig. 3. Comparison of model predicted total particle number concentrations with experimental data near the 405 Freeway.

Another influencing factor in Eq. (8) is the emission factor. To test how sensitive the model is to different emission factors, Table 2 was prepared to compare model predicted particle number concentrations, based on different emission factors, to experimental data. The ratios of predicted to measured particle number concentration at different locations near the 405 Freeway were used in Table 2. Average emission factor achieved from vertical profile in the current study, 8.3×10^{14} (particle vehicle^{-1} mile^{-1}), was doubled and halved, respectively, to be used as test emission factors in Table 2. Mean convective velocity scale was used to calculate turbulent parameter. All other influencing factors remain the same.

There was about 10–30% underestimate and 40–100% overestimate in model performance when the emission factor was halved and doubled, respectively. With the estimated emission factors, the predicted particle number concentration is very close to what was previously observed. This good agreement is due to the fact that the emission factor used in the model was obtained near the same freeway under similar ambient conditions. Traffic composition and driving patterns were also very similar during vertical sampling and horizontal sampling periods. Care must be taken when determining the emission factor near busy roads or other freeways.

The average emission factor used in the model was obtained from vertical profile data we collected near the 405 Freeway in summer 2001. During our measurement, 93% of vehicles on the 405 Freeway were gasoline-powered cars or light trucks. It has been shown that diesel trucks emit much more particles than gasoline-powered vehicles (Abu-Allaban et al., 2004; Graskow et al., 1999; Jamriska and Morawska, 2001; Morawska et al., 1998). For freeways with a greater percentage of diesel trucks, higher emission factors would be expected. The average ambient temperature during our experiment is about 30 °C (Zhu et al., 2004). Particle emission factors are highly dependent on ambient temperature (Kittelson, 1998). Zhu et al. (2004) reported dramatically different ultrafine particle size distributions in winter season. Thus, to apply the current model to other ambient temperature conditions, proper emission

Table 2
Ratios of predicted to measured particle number concentration at different locations near the 405 Freeway

Emission factor (particle vehicle^{-1} mile^{-1})	Particle number concentration ratio (predicted/measured)				
	X^{a}= 15 m	X = 45 m	X = 75 m	X = 135 m	X = 285 m
4.2×10^{14}	0.71	0.79	0.80	0.89	1.07
8.3×10^{14}	1.17	1.13	1.06	1.08	1.19
1.7×10^{15}	2.09	1.83	1.59	1.47	1.44

[a] X is the downwind distance from the edge of the 405 Freeway.

factors should be selected from the literature (Abu-Allaban et al., 2002; Hall and Dickens, 1999; Jamriska and Morawska, 2001; Johnson and Ferreira, 2001; Kittelson, 1998; Kittelson et al., 2001; Morawska et al., 1998; Wahlin et al., 2001; Weingartner et al., 1997). It should be also noted that particle emission factors are also highly dependent on traffic speed (Hall and Dickens, 1999). The emission factor used in the current model is based on highway-speed data. To apply the model to busy streets, lower emission factors have to be assumed.

Other influencing factors are the finite width of the road. The current approach assumes that all the traffic volume lies on the edge of the freeway, the origin of the x-axis in Fig. 3. Examining Eq. (8), it is found that the position of the concentration maximum depends only on γ and h. Given the fact that the width of the road (~30 m) is much larger than the elevation of the source (~4.5 m), the position of the maximum occurred actually closer than 15 m from the curb of the freeway. To address the applicability of the model at distances comparable with the width of the freeway, Fig. 4 was prepared in which a nine-lane approach was used to compare results with the current single lane approach as well as experimental data. Each lane of the freeway (nine lanes in total) was treated as a single line source. The total traffic volume was assumed to be evenly distributed among all nine lanes. The contribution from each lane to the receptor was then added and compared to the experimental results. A γ value of 0.16 was used in this comparison. It is seen in Fig. 4 that this approach predicts a lower maximum particle concentration at a closer distance from the freeway compared to the single lane approach. However, at distances greater than 15 m downwind from the edge of the freeway, the two approaches give similar predictions.

The current study determined average emission factor for total particle number concentrations based on measured vertical profile and an atmospheric dispersion model. More data and detailed analyses of traffic and particle size distributions are needed, in the future, to determine particle emission factors for different vehicle category, for example, diesel vs. gasoline, as well as for different driving speeds.

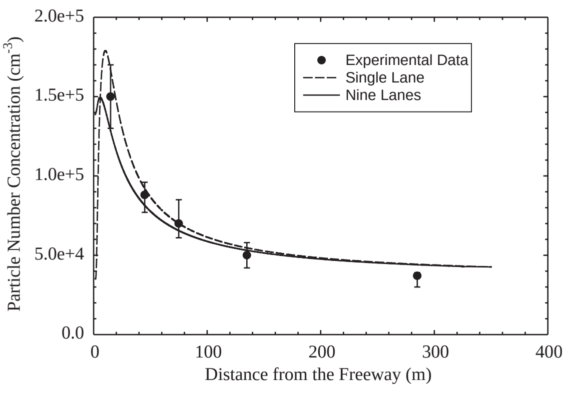

Fig. 4. Comparison of single-lane and nine-lane approach with experimental data near the 405 Freeway ($\gamma = 0.16$).

5. Conclusion

A simple analytical solution has been presented in this study to estimate particle number concentration near freeways based on measured vertical concentration profile. The model predicts particle number concentration near freeways very well. Atmospheric dispersion was found to be the dominant mechanisms in determining the particle number concentration near freeways. The analytical solution provides a reasonable estimation of the dispersion process in near field situations. Average particle number emission factor, 8.3×10^{14} particle vehicle^{-1} mile^{-1}, was determined based on vertical concentration profile and a scale factor obtained from the dispersion model. With proper particle number emission factors, traffic compositions, and meteorological data, particle number concentrations downwind of freeways can be quantitatively determined by the atmospheric dispersion model developed in this study.

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