Aerosol and Air Quality Research, 13: 1693–1701, 2013

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2013.04.0110

Particle Concentration on Freeways: Affecting Factors and a Simple Model Development

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ABSTRACT

A few field studies have reported high levels of in-cabin ultrafine particles and discussed certain contributing factors such as vehicle operations and atmospheric meteorological conditions. However, to generalize limited field study results to a wide range of conditions, a deeper understanding of affecting factors and a simple model that can predict on-road particle concentrations are essential. This paper has two objectives, first, to analyze the effects of surrounding vehicle density, relative freeway lane position, and vehicle speed on measured particle concentrations on two California freeways, I-405 (5% diesel) and I-710 (25% diesel). The second objective is to test the use of Emission Factor (EMFAC) 2007 and Caline4 (CL4) models in predicting on-road particle concentrations. Particle number and mass concentrations were collected using a mobile laboratory driving on the I-710 and I-405 freeways. Particle number concentration was found to be affected by the density of surrounding heavy duty diesel trucks which is consistent with previous studies. The highest particle number concentrations were measured in the outer lanes on the freeway and the lowest was in the inner lanes. The highest levels of particles were measured at vehicle speeds of 40–50 mph. Analysis of CL4 model was conducted using factor-of-two test. For the I-710, 85% of values were within the factor-of-two envelope, and for the I-405, 77% were within the envelope. Regression analysis showed that the model is able to account for 43% of the variability on the I-710 and 26% of the variability on the I-405. The use of CL4 in conjunction with EMFAC shows promise as a simple tool to estimate on-road $PM_{2.5}$ concentration.

Keywords: Ultrafine particles; $PM_{2.5}$; Vehicle emissions; On-road; Caline4; EMFAC.

INTRODUCTION

Exposure to particulate matter (PM) and in particular, ultrafine particles (UFPs, diameter < 100 nm), have been associated with increasing mortality and morbidity rates by many epidemiological studies (Johnston *et al.*, 2000; Donaldson *et al.*, 2002; MacNee and Donaldson, 2003; Gilmour *et al.*, 2004; Kleinman *et al.*, 2008; Nemmar and Inuwa, 2008; Zuurbier *et al.*, 2011). In an urban area, traffic emissions are the dominant source of UFPs and other air pollutants (Cyrys *et al.*, 2008). On-road studies found that 17–50% of total daily UFP exposure was from on-road vehicle emissions during commutes (Zhu *et al.*, 2007; Fruin *et al.*, 2008; Wallace and Ott, 2011).

Differences in on-road concentrations of PM are results of several factors, such as vehicle types, traffic intensity, and meteorology. Many studies have attempted to identify the factors associated with high pollutant concentrations and their relative contributions. Olivares *et al.* (2007) found a distinctive dependence of particle number concentration, normalized by NO_x, on ambient temperature and relative humidity in a street canyon. Weijers *et al.* (2004) explained the large spatial differences in UFP concentrations with traffic density and driving patterns. A study in Denmark also found that traffic density, especially of diesel vehicles, was an important explanatory variable for particle number concentration along roads (Palmgren *et al.*, 2003). Fruin *et al.* (2008) showed 60–70% of the variability in their measurement of UFP, black carbon (BC), NO_x and particle-bound polycyclic aromatic hydrocarbons (PM-PAHs) could be attributed to diesel truck density and hour of day (as an indicator of wind speed).The cited studies have analyzed and identified important factors affecting on-road levels of PM. However, there still remain knowledge gaps on factors affecting on-road PM levels.

From the perspective of commuter exposure, it is important to consider the in-cabin to on-road (I/O) ratio for pollutant concentrations. Several studies have found that the I/O ratio for UFP is approximately 50% and can be as high as 90% and are affected by ventilation settings, vehicle speed,

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vehicle age, and filter efficiency (Xu and Zhu, 2009; Hudda *et al.*, 2011; Xu *et al.*, 2011; Bigazzi and Figliozzi, 2012). Furthermore, in-cabin PM concentrations depend directly on ambient and on-road levels (Geiss *et al.*, 2010). While models estimating in-cabin exposures are being developed (Liu and Frey, 2011; Hudda *et al.*, 2012), there are no established models that predict on-road PM concentrations. Having a model for on-road PM levels can be a cost effective method to provide the critical link to assess in-cabin exposures. Emission Factor (EMFAC) 2007 is a modeling program developed by the California Air Resources Board (ARB) to estimate emission rates of various pollutants from motor vehicles traveling on California roadways. Estimates of emission inventories can be generated by the model on state-wide and regional scales. The EMFAC model accounts for large scale seasonal effects and also vehicle effects (i.e., driving speed) in its emission factor predictions. When combined with the Caline4 (CL4) dispersion model, exposures to vehicle emitted pollutants can be predicted. The application of these models have shown good results for modeling near-roadway and urban concentrations of PM (Benson, 1984; Yura *et al.*, 2007b; Chen *et al.*, 2008). However, it has not been tested for use in prediction of on-road PM concentration. This paper will use the measured PM data from Zhu *et al.* (2008) to achieve two objectives. First, examine the impacts of freeway lane, traffic speed, and traffic makeup, on PM levels on the I-710 and I-405. Second, evaluate to what extent the EMFAC and CL4 models can predict on-road PM levels.

METHODS

Measurement and Data Set

A full description of the on-road data collection was presented by Zhu *et al.* (2008). Briefly, a mobile laboratory was used to collect air pollutant concentrations on two Los Angeles freeways, I-405 and I-710. I-405 is one of the busiest freeways in the US, with nine to ten lanes and approximately 5% diesel traffic, while I-710 is a truck-shipping route with nine to ten lanes and about 25% of heavy duty diesel trucks (HDDT) (Zhu *et al.*, 2002a, b). Experiments were conducted for each freeway (I-710 and I-405) once each month in the period from June 2006 to May 2007. One supplemental experiment was conducted in May 2008 totaling 13 experiments for each freeway. Each experiment was approximately two hours from 10 am to 12 pm, during which the van made continuous loops on the designated routes as labeled in Fig. 1. Instruments used during the experiments and their resolution as listed in Table 1. Pollutant concentration measurements were organized into one minute averages and UFP size distribution measurements were kept at two minute resolution. The meteorological data, including wind speed, wind direction, temperature, and relative humidity were obtained from weather monitoring

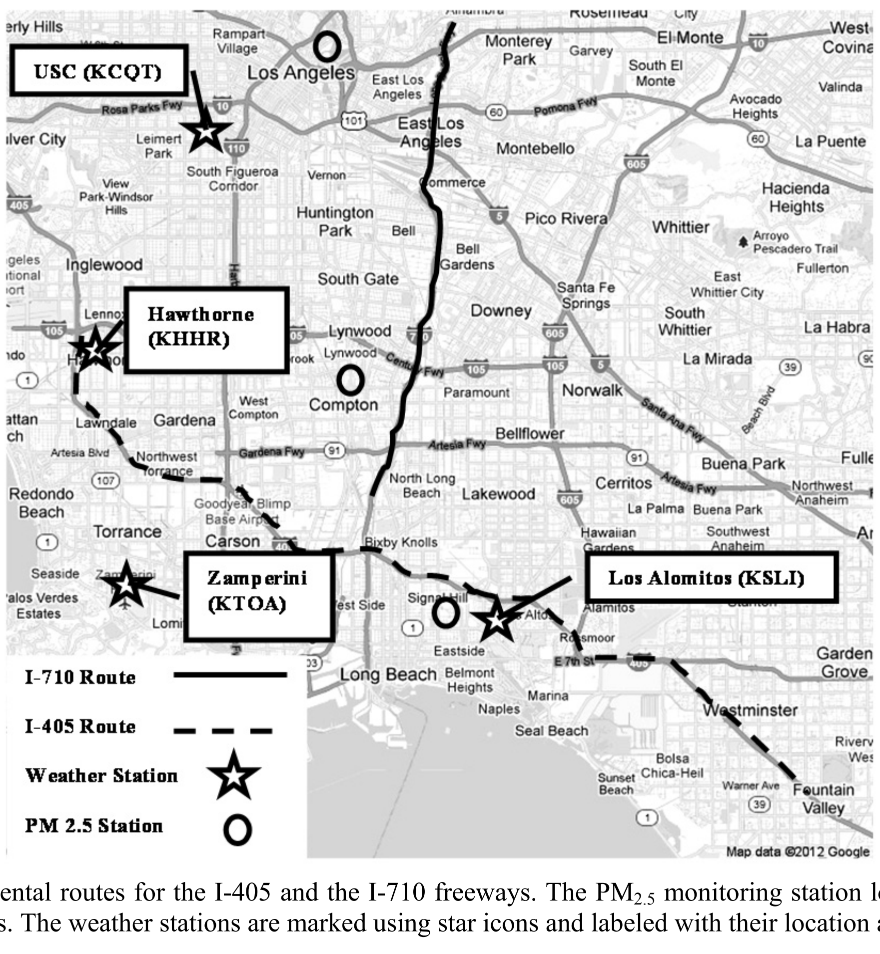

Fig. 1. The experimental routes for the I-405 and the I-710 freeways. The $PM_{2.5}$ monitoring station locations are marked using the circle icons. The weather stations are marked using star icons and labeled with their location and (station) names.

Table 1. Measured environmental parameters and instrument response times.

Species/Parameter	Instrument	Response time (sec.)
UFP size distribution	TSI, SMPS 3936 with DMA 3081	100 up, 20 down scan
Particle number concentration	TSI, CPC 3785	1
$PM_{2.5}$ (Real-time)	TSI, DustTrak 8520	60
$PM_{2.5}$ (Integrated)	SKC, PEM Sampler	N/A
BC	Magee Scientific, AE-42	60
CO, CO_2, RH, Temp.	TSI, Q-Trak Plus	60
PM-PAH	EcoChem, PAS 2000	30
NO, NO_2, NO_x	API, 200AU	1

stations near the I-710 and I-405 freeways (Fig. 1). In general, the prevailing wind directions were coming from west to east and were approximately perpendicular to the freeway experimental routes.

The mobile laboratory was a modified 2002 Chevrolet Express 9-passenger van used for vanpools. Details of the mobile laboratory are described in Zhu *et al.* (2008). The ratio of PM number concentration inside the van to on-road levels, measured using two condensation particle counters, is approximately 85 ± 5% (Zhu *et al.*, 2008). The measured in-cabin $PM_{2.5}$ concentration was divided by this factor (0.85) to obtain the on-road concentration. The high I/O ratio measured in the mobile laboratory could be attributed to the lack of an air filter in the ventilation system of the van. Factors affecting the in-cabin concentration considered in this paper include freeways, freeway lanes, surrounding traffic make-up, and traffic speeds.

Model Estimation of $PM_{2.5}$

There are currently no established models that can predict on-road air pollutant concentrations. The CL4 program is a dispersion modeling software to estimate exposures to CO from mobile sources (Benson, 1992) and has been adapted to estimate urban and near roadway concentrations of PM (Gramotnev *et al.*, 2003; Batterman *et al.*, 2010). The CL4 model has not been validated for dispersion of UFP and EMFAC is only equipped to generate emission factors for $PM_{2.5}$. Therefore, in this paper the two model programs were used only to estimate on-road $PM_{2.5}$ levels. Required inputs include meteorological conditions, roadway geometry, emission factors, and traffic volumes. In addition the software allows for the input of background $PM_{2.5}$ concentrations, which were obtained from ARB monitoring stations. The station locations are marked in Fig. 1, daily average $PM_{2.5}$ levels were used because hourly data were not available. The length of experimental route is approximately 27,000 m for the I-710 and 46,000 m for the I-405. CL4 requires the modeled line source to be divided into "links" less than 10,000 m. The I-710 was divided into four equal links (6,750 m) and the I-405 into five links (9,200 m). The average width for one direction (four lanes) of the I-710 and the I-405 is 20 m and 23 m respectively. A roadside receptor of 6.4 m away from each link was used. This was the closest distance that can be used while maintaining the validity of model results (Chen *et al.*, 2008; Liu and Frey, 2011). Meteorological data obtained from the weather stations for each corresponding freeway (Fig. 1) and the experimental dates were used for the program inputs. Traffic volume data were obtained for the two hour period of each experiment date from monitoring stations managed by Caltrans Performance Measurement System (PeMS) located along the experiment routes (23 stations for I-710 and 57 stations for I-405).

The EMFAC2007 model is used to generate average emission factors for a whole vehicle fleet or certain vehicle classes (i.e., light duty automobile, light duty trucks, etc.) in a specified geographical region (i.e., South Coast Air Basin). In general, it provides good estimates of PM_{10} and $PM_{2.5}$ emission factors relative to other modeling programs (Smit *et al.*, 2010; Park *et al.*, 2011). Emission factors were generated for the experimental runs on the I-710 and I-405 freeways using the corresponding temperature, humidity, and vehicle speed data. Because the vehicle composition on the freeways may not be representative of the regional vehicle composition, the emission factors needed to be weighted accordingly. In general, the I-710 freeway is approximately 25% HDDT while the I-405 is approximately 5% HDDT (Zhu *et al.*, 2002a, b). Therefore, EMFAC generated emission factors for light duty automobile (LDA) and HDDT were weighted accordingly.

RESULTS AND DISCUSSION

Traffic Make-up Effects

Fig. 2 presents total particle number concentrations as a function of number of vehicles surrounding the testing van based on collected video images (Zhu *et al.*, 2008). Four types of vehicles were considered: passenger cars, pick-up trucks, light-duty diesel vehicles, and HDDT. For each type, the number of surrounding vehicles and frequencies of that vehicle type are shown by the gray bars.

The van was generally surrounded by more non-diesel than diesel vehicles. A clear increase of total particle number concentrations with increasing number of surrounding HDDT was observed in Fig. 2(d). No strong relationship was observed between total particle number concentrations and the other three types of vehicles, as shown in Figs. 2(a), (b), and (c). When there was no surrounding HDDT, the average particle number concentration was about 7.5×10^4 cm^{-3}. It increased by 33% when two HDDT were present. When there were more than three surrounding HDDT, the average particle number concentration inside the van was more than 1.2×10^5 cm^{-3}. Such increases of UFPs with surrounding diesel truck traffic have also been reported by Westerdahl *et al.* (2005) and Fruin *et al.* (2008).

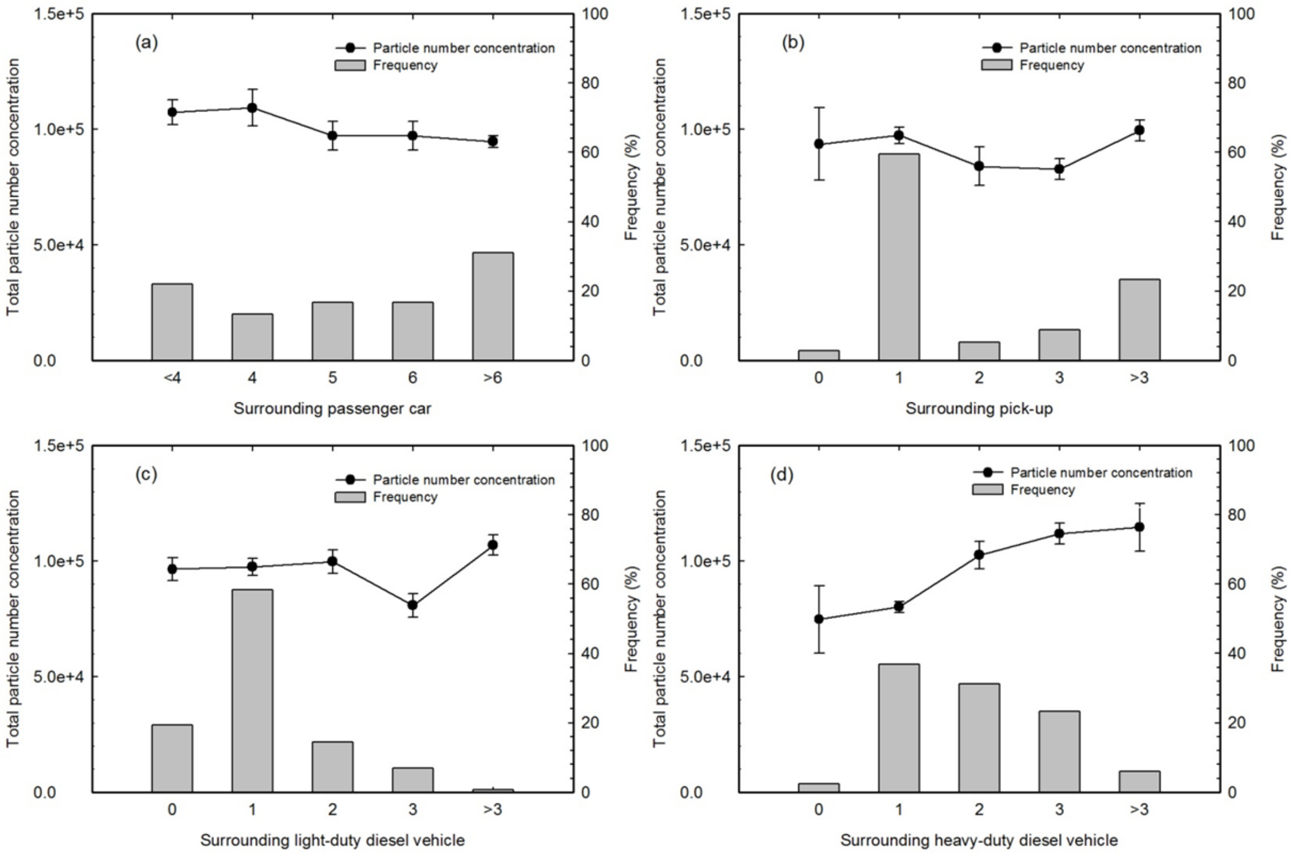

Fig. 2. Total particle number concentration versus number of surrounding vehicles of four different types, (a) passenger car, (b) pick-up truck, (c) light-duty diesel, and (d) heavy-duty diesel. Data from both freeways were averaged. Error bars indicate standard error. Gray bars present the frequency that a certain number of vehicles were surrounding the test van.

Freeway Lane Effects

Fig. 3 shows the difference of measured particle concentrations while traveling on different lanes on both freeways. Each point represents an average of approximately 60 and 150 one-minute measurements on the I-710 and I-405, respectively. Fig. 3(a) shows the average concentrations for I-405 and Fig. 3(b) shows the average concentrations for I-710. The closed symbols represent the particle number concentration and the open symbols represent the $PM_{2.5}$ mass concentration. In general, measured particle number and mass concentrations were higher on the I-710 than I-405. There are some inter-lane variations in the particle number concentrations measured on the I-405, but the range is relatively small from 7.0×10^4 to 8.0×10^4 cm^{-3}. The variation by lane was much greater on the I-710. The average particle number concentration across the lanes ranged from 8.0×10^4 to 1.2×10^5 cm^{-3}. Average $PM_{2.5}$ mass concentrations across the lanes ranged from 38.0 to 54.0 $\mu g/m^3$ on the I-405 and from 46.0 to 59.0 $\mu g/m^3$ on the I-710.

The profile of particle number concentration across the lanes on the I-405 does not present any patterns and does not track with the concentration profile of $PM_{2.5}$. On the I-710, the particle number concentrations in the middle lanes were lower than those on the outside lanes. The lowest was observed on lane 6, while the highest was on lane 1 and 8. The $PM_{2.5}$ profile is similar to the particle number profile in that the lowest concentrations were measured in lane 6. The understanding of the vehicle lane effect on particle concentration is complex because there are several contributing factors. One factor is the restriction of HDDT, which are the strongest source of PM on the I-710 (Fruin *et al.*, 2008), to the right two lanes for multilane highways with four or more lanes one way (California Vehicle Code 21655). Another factor is the interaction between cross-winds and vehicle induced turbulence (VIT). In general, the cross-winds serve to disperse emitted pollutants and VIT can contribute to their vertical diffusion, which ultimately affects downwind particle concentrations (Gordon *et al.*, 2012). However, the presence of road barriers (e.g., sound walls, center dividers, and vehicles) can increase on-road particle concentrations by creating stagnant zones downwind of a barrier (Hagler *et al.*, 2011). Furthermore, wakes left by moving vehicles create eddies that entrain emitted pollutants (Baker, 2001) and affect particle formation dynamics (Carpentieri and Kumar, 2011). These factors contribute to the variability in the concentration of PM measured across the lanes of I-405 and I-710. Tests directed at measuring VIT effects are needed and will prove valuable in improving model predictions of particle concentration.

Vehicle Speed Effects

The influence of driving speed on the concentration

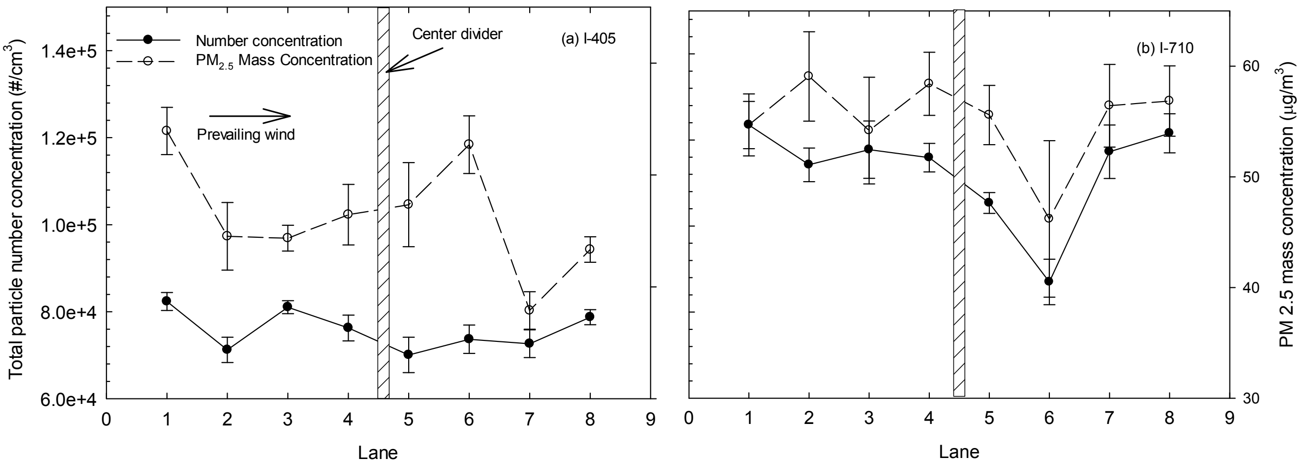

Fig. 3. Effects of relative lane positions on particle number concentrations and PM $_{2.5}$ mass concentrations for (a) all measurements on I-405, and (b) all measurements on I-710. The prevailing wind direction goes from lane 1 to lane 8. The freeway center divider is between lanes 4 and 5. Closed symbols represent particle number concentration and open symbols represent PM $_{2.5}$ mass concentration. Error bars display standard errors.

levels in the test van varied with different air pollutants (Fig. 4). A slight peak in particle number concentration of 1.25×10^5 cm^{-3} was associated with the speed around 40-50 mph. Competing processes are involved with respect to particle concentration and vehicle speed. Particle emissions, especially the nuclei mode particles, from tail pipes increased with vehicle speed (Giechaskiel *et al.*, 2005). Faster driving speeds also increases the I/O ratio for the particle concentration (Xu and Zhu, 2009; Hudda *et al.*, 2011). This results in the increase in UFP concentrations with faster van speeds. However, faster vehicle speed also increases the particle deposition rate of particles inside the cabin (Gong *et al.*, 2009). Faster vehicle speed also increases the distance between vehicles that may contribute to lower particle number concentration. A similar trend was observed for the NO_x and PM-PAHs concentration. Kean *et al.* (2003), found NO_x and CO emission factors increase with vehicle speed but plateau around 55 mph. Measured NO_x and CO concentrations increased with vehicle speeds up to 50 mph (Fig. 4). At higher speeds, concentrations decrease due to lower traffic density and increased air dilution (Vogt *et al.*, 2003; Ning and Sioutas, 2010). $PM_{2.5}$ and CO concentration inside the van didn't change much with driving speeds. But for BC, the trend was a little different. When the van speed was lower than 50 mph, the BC levels were constant. When the van speed was higher than 50 mph, BC concentrations decreased with the speed. BC is formed from the incomplete combustion of fuel. Lower driving speed increases the percentage of incomplete combustion and therefore resulted in higher BC (Owen, 2005).

Model Estimation of $PM_{2.5}$

The CL4 model used emission factors predicted by EMFAC to estimate in-cabin $PM_{2.5}$ concentrations. The model estimate was compared to gravimetric $PM_{2.5}$ measurements inside the van. The "factor-of-two" plot was used to assess model performance. If, 75% of the data points fall within the factor-of-two envelop, the model results are considered good in predicting true values (Benson, 1984; Yura *et al.*, 2007a; Chen *et al.*, 2008; Liu and Frey, 2011). Figs. 5(a) and 5(b) show that approximately 85% of the points for the I-710 and 77% of the points for the I-405 fall within the factor-of-two envelope. Therefore, the CL4 together with EMFAC gave good predictions of on-road $PM_{2.5}$ concentrations.

A linear regression analysis was performed for the I-710 and I-405 data sets (Figs. 5(c) and 5(d)). The calculated R^2 value for the I-710 was approximately 43%, implying that CL4 model together with EMFAC generated emission factors can capture about 40% of the data variability in predicting on-road $PM_{2.5}$ concentrations. The calculated R^2 value for the I-405 was not as high (26%). The data points for both freeways were all within the 95% prediction interval (PI) but only 61% of the points were within the 95% confidence interval (CI).

The regression analysis results suggest that the CL4 model can account for some of the parameters affecting the concentration of on-road $PM_{2.5}$, but a large percentage is unaccounted. The CL4 models particle dispersion from a line source and accounts for large meteorological conditions such as wind direction and speed. However, it does not account for smaller scale effects such as what lane the vehicle is traveling in. Variability in particle concentration is seen across lanes on both freeways. This effect is most strongly observed on the I-710 (Fig. 3(b)) where particle concentrations decreased dramatically in lane 6. An important factor is VIT on the formation and dispersion process for on-road particles. Studies have shown that VIT has a strong influence of dispersion model predictions (Rao *et al.*, 2002; Sahlodin *et al.*, 2007). However, more studies directed at understanding VIT effects for on-road particles are still needed. Furthermore, surrounding HDDT density clearly effected the measured number concentration, but such an effect is not reflected in the EMFAC estimated emission factor used in the CL4 model. Despite the shortcomings of CL4 in predicting on-road $PM_{2.5}$ concentrations, the

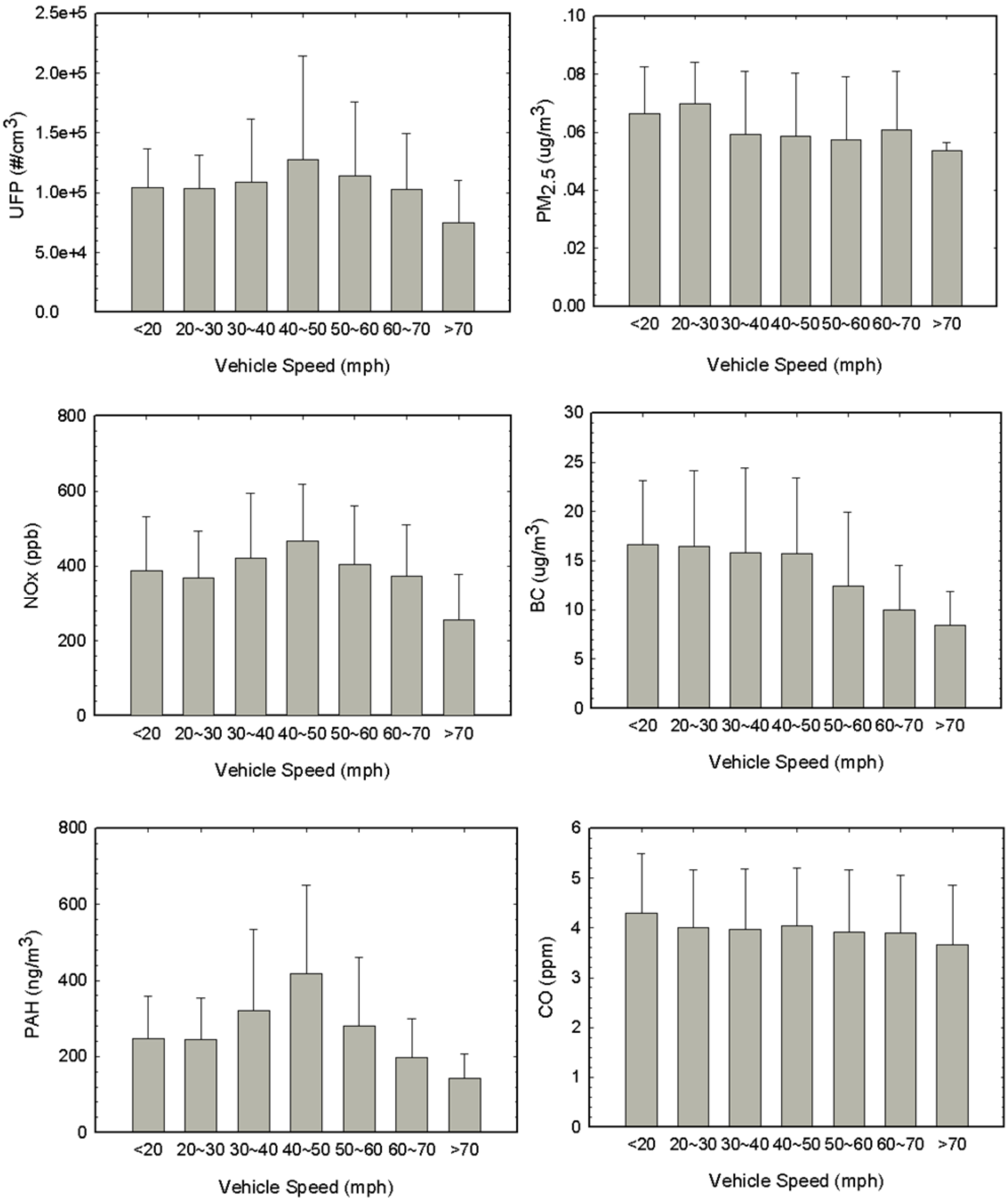

Fig. 4. Effects of driving speeds on air pollutant concentrations. Error bars display standard deviation.

results were still considered good based on the factor-of-two analysis. This suggests that there is some merit in using CL4 in conjunction with a weighted EMFAC emission factor to predict on-road PM concentrations and warrants more in-depth analysis to improve the model prediction.

CONCLUSIONS

Analysis of the effect of surrounding vehicle type on in-cabin PM concentration revealed that particle number concentration has a positive relationship with HDDT. On the I-710, lanes 1 and 8 had the highest average particle concentration while lane 6 had the lowest. This could be due to the restriction of HDDT to the right two lanes on California freeways, thus concentrating the strongest source of on-road PM. Inter-lane variability of particle concentration is observed on both freeways. Factors such as cross-winds, VIT, and the position of HDDT possibly account for the variability. When vehicle speeds were between 40 and 50 mph, the highest particle number concentration, NO_x concentration, and PM-PAH concentrations were observed. Concentrations of BC decreased as a function of vehicle speeds above 50 mph and are likely due to the efficiency of the fuel combustion process at higher speeds.

While there is currently a strong effort to develop in-cabin particle exposure models, there is a gap with on-road particle model. EMFAC emission model and CL4 dispersion model were tested to see if they can be used to estimate on-road levels $PM_{2.5}$. Results indicate that the models are acceptable (more than 75% within factor-of-two envelope)

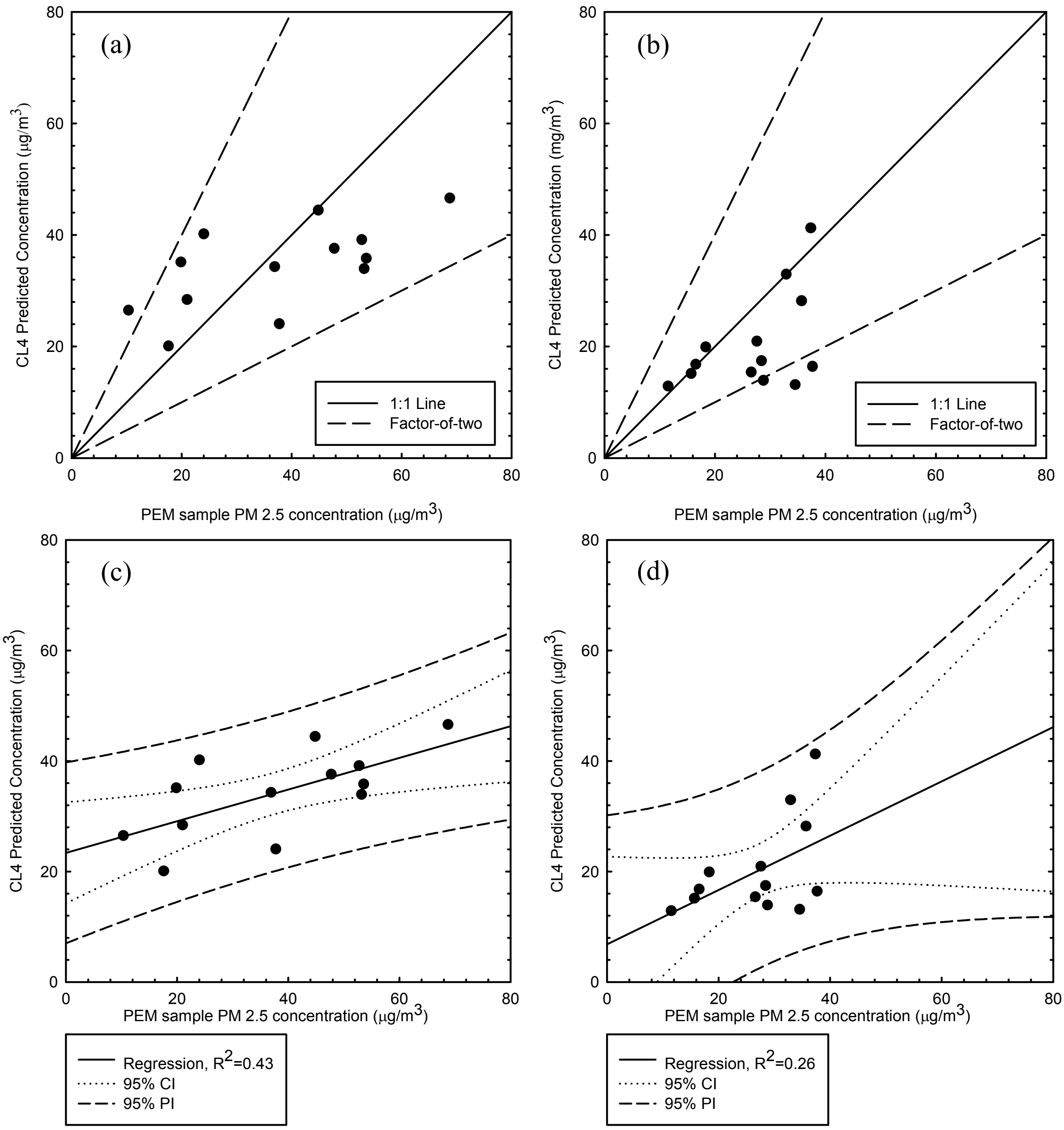

Fig. 5. Gravimetric $PM_{2.5}$ measurements versus Caline4 Model $PM_{2.5}$ predictions for (a) the I-710 freeway and (b) the I-405 freeway. Linear regression with the 95% confidence and prediction intervals are shown in (c) for I-710 and in (d) for I-405.

at estimating on-road $PM_{2.5}$ concentrations. However, the models only accounted for at most 43% of the variability. The factor analysis results suggests that the small scale factors (surrounding vehicle make-up and vehicle lane) may not be reflected in the models input parameters. Regardless, there is potential to effectively use these models and thus warrants more in-depth analysis.

ACKNOWLEDGEMENTS

This work was supported by the Southern California Particle Center and Supersite: U.S. Environmental Protection Agency grant number R82735201, California Air Resources Board contract number 04-324 and the Southern California Environmental Health Center, National Institute of Environmental Health Sciences (NIEHS) Grant # 5 P30 ES07048.

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Received for review, April 3, 2013
Accepted, June 5, 2013