15.2 INFLUENCE OF URBAN MORPHOLOGY ON STREET LEVEL CONCENTRATIONS: WATER CHANNEL AND FIELD STUDY IN THREE SOUTHERN CALIFORNIAN CITIES

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1. INTRODUCTION

Particulate matter emissions from transportation have a significant contribution on ambient air pollution in urban area. In 2002, $PM_{2.5}$ emissions by on-road vehicles contribute 11% to the total $PM_{2.5}$ emissions in Los Angeles County (EPA, 2002). In metropolitan cities, vehicular emission sources are in close proximity to pedestrian and residences. Hence, the arising traffic related concentration hotspots are of high concern for air quality study and health impact assessment.

Previous research has pointed out that the characteristics of dispersion are highly dependent on the urban morphology. Field experiments of dispersion through groups of regular arrays revealed that non-Gaussian distributions of plume in the first two rows were observed (Macdonald, 1998). This is specifically expressed through enhanced vertical mixing produced by the deflection of mean streamlines over the arrays (Macdonald, 1997) and the plume width could be increased by a factor of 2-4 with increasing obstacle width by a factor of 1 (Macdonald, 1998).

Lots of efforts were put on understanding air exchange mechanism, ventilation characteristics between above and within canyon in recent years. Baik (2002) ran a simple 2-D CFD, k-ε based, model and showed that the turbulent fluxes and advective fluxes have opposite contribution on net fluxes in an idealized street canyon. Turbulent fluxes contribute to the removal of pollutants while advective fluxes result in re-entrainment of pollutants. Large Eddy Simulation found that the time scales for pollutants escaping leeward side of canyon is about 30-60 s (Walton, 2002). Ventilation transfer velocity, w_T, relevant to momentum transfer into and out of the canopy was introduced to quantitatively analyze canopy ventilation (Barlow, 2002). A linear relationship exists between transfer velocity w_T and wind speed U_{ref} or U_H under certain wind speed conditions (U_{ref}>1 m/s or U_H >2 m/s) (Barlow, 2002; Pascheke, 2008). A first order eddy viscosity turbulence closure CFD model was used to investigate ultrafine particle fluxes in 2-D street canyons with varying aspect ratio (Tay, 2009). It was found that when dispersion is driven by forced convection, the turbulent fluxes dominate the ventilation process in the canyon. Meanwhile, a linear relationship was found between turbulent fluxes and wind speed. Exponential relationship exists between turbulent fluxes and turbulent intensity.

The limitation of present studies is such that most of them considered regular street canyon or urban arrays with specific aspect ratio. The argument or explanation of pollution dilution within street canyon using field data is seldom reported. The objective of this study was to investigate the influence of a wide range of meteorological and traffic-related variables on roadside $PM_{2.5}$ concentrations in mutative built environments and accordingly explore the impact of urban morphology on street level $PM_{2.5}$ concentration. This study was a part of the project *Near Source Modeling of Transportation Emissions in Built Environments Surrounding Major Arterials*, sponsored by UC Transportation Center (UCTC). The first part of this project has been presented in Pan et al. (2009). In present study, three specific built environments were involved, including high-rise settlement in Los Angeles, mid-rise settlement in Long Beach and low-rise settlement in Huntington Beach. Roadside $PM_{2.5}$ measurements were compared with ambient $PM_{2.5}$ concentrations observed by nearby monitoring stations. Localized variables, such as traffic counts, wind speed, wind direction, air temperature, vertical momentum flux,

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sensible heat flux and turbulent intensity, were considered for their contribution to surface level $PM_{2.5}$ concentrations. Laboratory simulations were conducted on scaled built environments (Los Angeles and Long Beach) in a water channel facility. Simultaneous PIV/PLIF technique was applied to acquire the flow velocity and plume concentration data in selected vertical planes.

2. FIELD DATA

Downtown Los Angeles represents high-rise settlement in this study. The heights of buildings in area of interest vary from 5 to 187 m. The average height is about 43 m. The arterial 6th Street is a three-lane, one-way roadway. There are two parking lanes on both sides. The street width is about 13 m. The average daily traffic (ADT) is 20,932 vehicles/day on 6th Street crossing with Grand Avenue, and 21,127 vehicles/day on 6th Street crossing with Olive Ave. The arterial Grand Ave. is also a three-lane, one-way roadway that is 13 m wide. The ADT on Grand Ave. is 15,748 vehicles/day on crossing with 7th Street, and 16,399 vehicles/day on crossing with 5th Street. Five sites were located near arterials measuring $PM_{2.5}$ concentration and recording traffic flow. Three sites (LA1, LA4 and LA5) were on 6th Street and the other two (LA2 and LA3) were on Grand Ave. Site LA6 equipped with one DustTrak and one sonic anemometer were on Pershing square which is an open area in downtown. Data were collected in June 19, 23 and 30, 2008.

In mid-rise settlement of Long Beach, the arterial Ocean Blvd. is a six-lane, two-way roadway that is about 22 m wide. Broadway is a three-lane, one-way roadway which is about 10 m wide. Traffic counts on Ocean Blvd. and Broadway are 37,800 and 14,200 vehicles/day. The buildings vary significantly in height from 5 to 104 m. The average height of buildings is about 22 m. There were two sites (LB1 and LB2) on Ocean Blvd. and two sites (LB3 and LB5) on Broadway measuring $PM_{2.5}$ concentration and recording traffic volume, one site on the roof of a 6-story parking garage measuring upper level $PM_{2.5}$ concentration and meteorological data. Measurement periods were on July 2, 7 and 9, 2008.

In Huntington Beach, the arterial Beach Blvd. is a six-lane, two-way roadway in the middle of which is plantings separating two ways. The street width is about 25 m. The ADT on Beach Blvd. is about 42,000-51,000 vehicles/day. Garfield is a four-lane, two-way roadway which is 15 m in width and averages around 12,000-16,000 vehicles/day in traffic volume. The average height of buildings is about 11 m. There were two sites on each arterial measuring $PM_{2.5}$ concentration and traffic flow, one site in a parking lot that separates arterials and buildings, measuring $PM_{2.5}$ concentration and meteorological data. Measurement periods were on July 16, 18 and 21, 2008.

3. GENERALIZED ADDITIVE MODEL

A generalized additive model (GAM) is a generalization of the usual linear regression model, which replaces the linear form of regression model with a sum of smooth functions of covariates (Hastie and Tibshirani, 1990). It can be described as:

$$Y = \sum_{j=1}^{p} s_j\left(X_j\right) + \varepsilon \tag{1}$$

Where Y is an independent variable, $s_j\left(X_j\right)$ is a smooth function of covariate, p is the total number of covariates, and ε is the error.

The application of GAM in analyzing air quality data has been in development for several years. Hourly pollution data such as PM_{10}, $PM_{2.5}$, NO_2 and NOx concentration, with corresponding traffic volume and meteorological conditions were collected in 2001-2003 and used to develop separate models (Aldrin, 2005). The relative contribution in percent of each predictor variable to pollution was estimated in each model. Traffic volumes and winds were the most important variables for all pollutants. Relative humidity has impact on the PM concentration. The effects of other predictor variables such as temperature, snow cover on the ground are less important. GAM was also used to model daily NOx, NO_2, CO concentration at a busy street canyon during the period 1998-2005 (Carslaw, 2007). Their model also showed that the reduction of overall traffic and meteorological factors appeared to account for the declined NOx concentration. In the most recent study, vehicle type (diesel or gasoline), driving style (passing or idling) and background pollution were also considered as predictor variables (Richmond-Bryant, 2009).

In our study, before GAM regression models were created, interdependency between roadside $PM_{2.5}$ concentration measurement and background $PM_{2.5}$ concentration were tested. Background $PM_{2.5}$ concentration data were obtained from nearby monitoring stations managed by South Coast Air Quality Management

District. The student t-test was applied to 1-hour average $PM_{2.5}$ concentrations data from 7 sites (six roadside sites and one nearby monitoring station) for each city. Null hypothesis was employed to each two sites in order to test the association between roadside and background concentrations. It was found that all roadside concentrations but one in Los Angeles (LA6) were significantly different from background concentrations.

Therefore, only variables expressing local meteorological and traffic conditions were considered in our models. The models of the log-transform of one-minute averaged $PM_{2.5}$ concentration were developed on a wide range of variables, including mean wind speed (*U*, *V* and *W*), wind direction (*WD*), air temperature (*Temp*), momentum flux (F_t), sensible heat flux (F_s), turbulent intensity (σ_w/u_*) and traffic count (*TC*) as the following:

$$\begin{aligned}\log\left(PM_{2.5}\right) = {} & s_1(U) + s_2(V) + s_3(W) \\ & + s_4(WD) + s_5(Temp) \\ & + s_6\left(F_t\right) + s_7\left(F_s\right) \\ & + s_8\left(\sigma_w/u_*\right) + s_9(TC) + \varepsilon\end{aligned} \tag{2}$$

Three separated models for three different cities were built using R programming language (R Development Core Team, 2006) with package ‘mgcv’ version 1.6-1 (Wood, 2006). mgcv use a penalized regression spline approach with automatic smoothness selection to fit the models. Standard errors on predictions and credible intervals were derived by a Bayesian approach. More details about mgcv could be found in Wood (2002 and 2006).

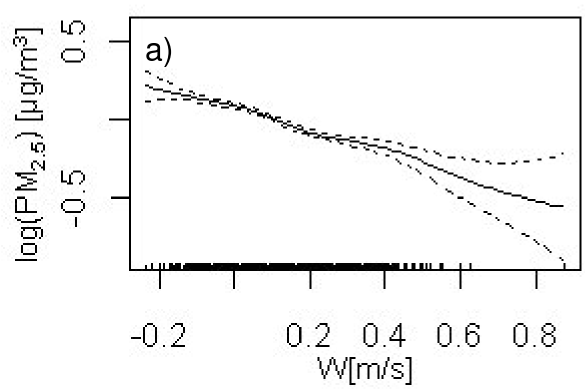
4. GAM RESULTS

For Los Angeles model and Huntington Beach model, $PM_{2.5}$ concentration and traffic variables were site-averaged over five sites (LA1, LA2, LA3, LA4 and LA5 for Los Angeles and HB1, HB2, HB3, HB4 and HB5 for Huntington Beach). Meteorological variables were taken from site 6 (LA6 and HB4). For Long Beach model, $PM_{2.5}$ concentration and traffic variables were site-averaged over four sites (LB1, LB2, LB3 and LB5). Meteorological variables were from site 6 (LB6) at the roof level.

Fig.1 shows two individual smooth functions for Los Angeles model. Smooth functions of vertical mean velocity (W) and turbulent intensity (σ_w/u_*) were presented here since there is a clear downward trend in concentration for both of them. p-values for *W*, and σ_w/u_* are <2e-16, and 3.12e-14, respectively. *W* indicates advection in vertical direction and σ_w/u_* indicates turbulent transport in vertical direction. As *W* varies from negative to positive, pollution was diluted at the surface. Turbulent transport, σ_w/u_*, has the same effect on pollution dilution when σ_w/u_* was in the range from 1 to 2. As expected due to the presence of high-rise buildings in Los Angeles, which increases vertical motions significantly, vertical dispersion had significant impact on surface $PM_{2.5}$ concentration.

Fig.2 shows two smooth functions for Huntington Beach model. The variables which had the most significant impact on $PM_{2.5}$ concentrations were horizontal mean wind component *U* and sensible heat flux. The increasing *U* from 0 to 2 m/s decreased $PM_{2.5}$ concentration. There is clear evidence that surface $PM_{2.5}$ concentration dropped when sensible heat flux increased from 100 to 300 W/m^2. It is expected since thermal turbulence increased as sensible heat flux increased, resulting in pollution dilution. Compared with Los Angeles model, vertical motion is less important, whilst horizontal motion and thermal turbulence are prime factors dominating pollution removal in Huntington Beach model.

Fig.3 shows smooth function of *U* for Long Beach model. The increasing horizontal mean wind component *U* at roof level caused the declining $PM_{2.5}$ concentrations. Although the magnitudes of turbulent intensity observed at roof level in Long Beach were higher than that at street level in Los Angeles (the average values were 1.6 for former and 1.4 for latter), no evidence shows decreasing turbulent intensity could decrease $PM_{2.5}$ concentration in Long Beach model.



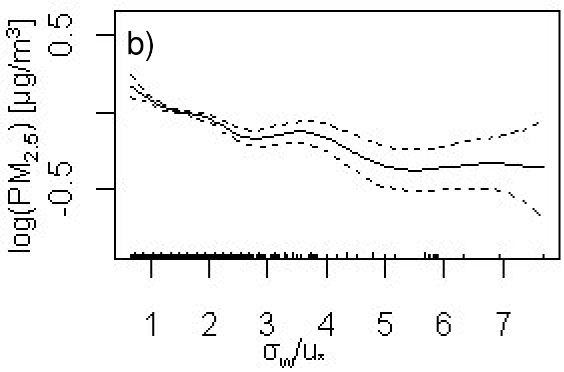


Fig.1. Fitted components of Los Angeles model: (a) smooth function of vertical mean velocity, s(W), (b) smooth function of turbulent intensity, s(σ_w/u_*). The dashed lines are the estimated 95% confidence intervals.

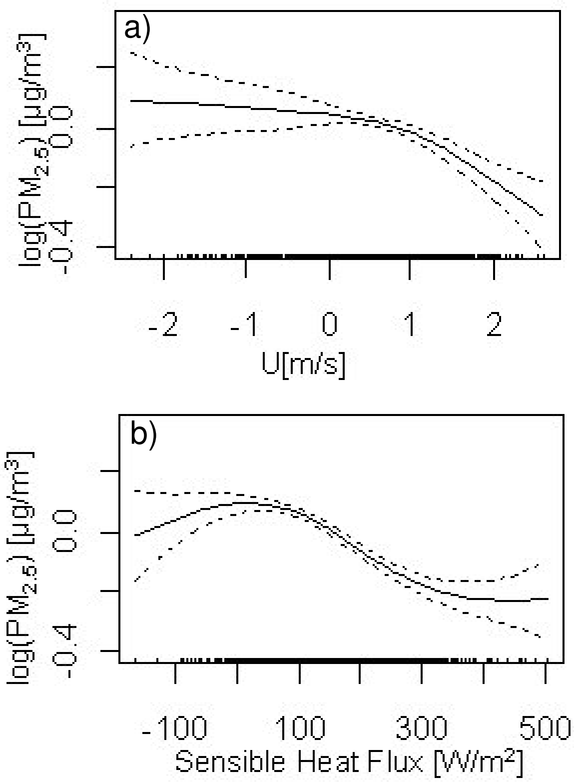


Fig.2. Fitted components of Huntington Beach model: (a) smooth function of horizontal mean velocity, s(U), (b) smooth function of sensible heat flux, s(F_s). The dashed lines are the estimated 95% confidence intervals.

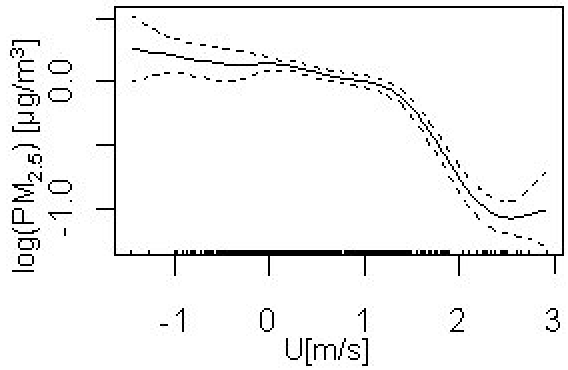


Fig.3. Smooth function of horizontal mean velocity, s(U), in Long Beach model. The dashed lines are the estimated 95% confidence intervals.

5. WATER CHANNEL SIMULATION

The highly polished acrylic models of Los Angeles and Long Beach were created in a water channel facility. Particle Image Velocimetry (PIV) was used to measure 2D velocity fields and Planar Laser Induced Fluorescence (PLIF) was applied to measure concentration distributions. Detailed description of model and experimental setup can be found in a previous study (Pan et al., 2009). In this study, we are focusing on investigating the influence of a specific target building (the translucent building in Fig.4) on concentration measurements and plume dispersion when a line source was continuously releasing at the ground level within a street canyon in Los Angeles case. Vertical profiles of concentration at leeward side and windward side were measured and compared to the case when the target building is absent.

Fig.5 shows dimensionless concentration profiles for case1 (with target building) and case2 (without target building). For case1, concentrations at leeward side were higher than windward side below Z/H*=0.4. Above the critical height, there was no concentration difference between two sides. The well-mixed plume was associated with the strong recirculating flow within the street canyon. The recirculation produced a downdraft flow at windward side which efficiently remove plume from very close to the surface, causing the concentration difference between two sides below Z/H*=0.4. The recirculation also resulted in dilution plume below Z/H*=1. Hence, the magnitude of concentrations below Z/H*=1 was relatively lower compared to case2. In case2, the typical street canyon recirculation vanished because of the absence of tall building. The concentrations in the wake of leeward side building were higher than windward side from surface to roof level.

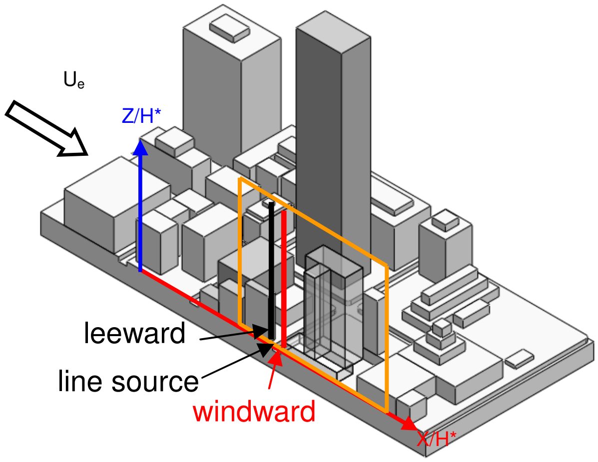


Fig.4. A schematic diagram of the measured plane (a golden rectangular) on the cross section view of building cluster. The target building is shown as a translucent block. H*=58 mm, the same as the height of the leeward building.

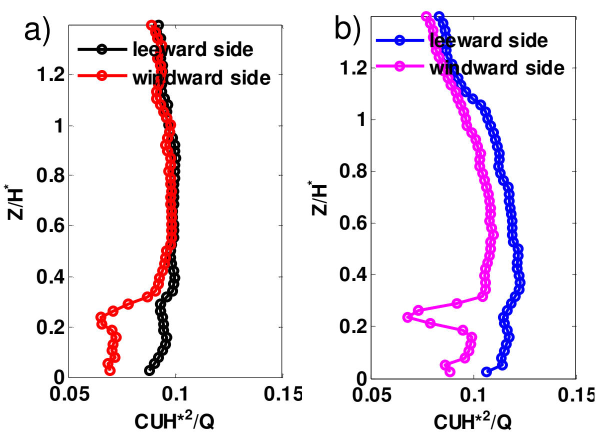


Fig.5. Comparison of vertical profiles of mean concentration between a) case1 (with target building) and b) case2 (without target building).

To study the influence of the target building on plume dispersion, the integral time scale of concentration fluctuations T_c were calculated. The definition of T_c was determined by the following equations introduced by Yee (2006):

$$T_c = \int_0^{\tau_*} R(\tau) d\tau \qquad (3)$$

Where $R(\tau) = \dfrac{\overline{c'(t)c'(t+\tau)}}{\overline{c'^2(t)}}$, c' is concentration fluctuation and τ_* is the lag time when $R(\tau_*) = 0.1$.

Fig.6 shows vertical profiles of dimensionless T_c for case1 and case2. As discussed by Yee (2006), because of the presence of buildings, the plume was less fragmented close to the surface, therefore longer T_c was observed below Z/H*=1 than above. The longer T_c observed in case1 compared to case2 means the turbulence-driven plume diffusion was less efficient when the target building was present. In our study, as Z/H* changing from 1 to 0, T_c was relatively uniform in both cases instead of continuously increasing as reported by Yee (2006).

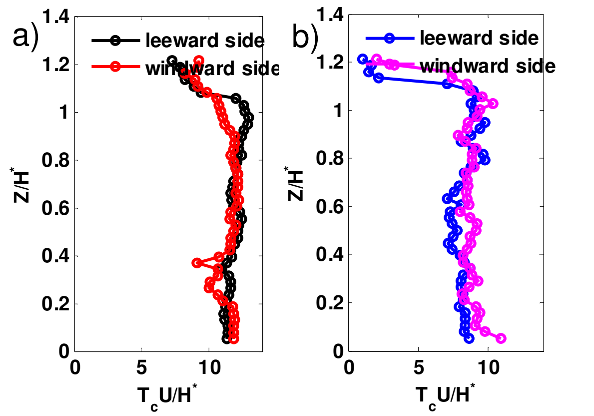


Fig.6. Comparison of vertical profiles of the integral time scale of concentration fluctuations between a) case1 (with target building) and b) case2 (without target building).

6. SUMMARY

- A generalized additive model regression model was built to study the influence of meteorological and traffic variables on roadside PM2.5 concentration. For high-rise settlement in Los Angeles model, increasing turbulent intensity (σ_w/u_*) and vertical mean velocity (W) had negative contributions on street level concentrations. Hence, vertical dispersion played an important role on pollution dispersion.
- For low-rise settlement in Huntington Beach model, the increasing horizontal mean velocity component (*U*) and sensible heat flux could reduce street level concentrations.
- For mid-rise settlement, the roof level mean velocity (*U*) could reduce street level concentrations.

- The influence of one-minute average traffic counts on street level concentration of $PM_{2.5}$ was not significant in this study. This is probably because the particles at the exhaust port of vehicles are mostly smaller than 1 µm. The direct relation between traffic counts with ambient PM2.5 measurement is not obvious.
- The results of laboratory concentration measurements show that the strong recirculation flow diluted plume within street canyon because of the present of target building.
- The integral time scale of concentration fluctuation within street canyon in case1 was longer than case2. It indicated turbulence-driven plume diffusion was less efficient when the target building was present.

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