



## Measurement of Diurnal Variations of PM<sub>2.5</sub> Mass Concentrations and Factors Affecting Pollutant Dispersion in Urban Street Canyons under Weak-Wind Conditions in Xi'an

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### ABSTRACT

Daytime variations of PM<sub>2.5</sub> concentration in three street canyons in Xi'an were measured during June 11–15, 2010. Weather conditions, including the ambient wind condition and the street canyon air temperature, were also recorded. These measurements were conducted on weak-wind summer days, when the mean ambient wind velocity was 1.26 m/s. The results show that, under weak-wind conditions, there were no good correlation between PM<sub>2.5</sub> concentrations and vehicle flux inside the street canyons. The vehicle related PM<sub>2.5</sub> concentrations accumulated in the daytime inside the street canyons. The PM<sub>2.5</sub> concentrations at the pedestrian level were of near uniform horizontal distribution. These results indicate the absence of the typical primary air flow re-circulation inside the street canyons under weak-wind conditions, and that the dispersion and transportation of vehicle exhausts inside and/or outside the street canyons are influenced by vehicle induced air flow and thermal induced buoyancy.

**Keywords:** PM<sub>2.5</sub> concentration; Weak-Wind condition; Street canyon; Xi'an.

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### INTRODUCTION

The links between certain respiratory health issues, such as the increase in asthma cases and mortality, and suspended particulate matter (Ali-Toudert and Mayer, 2006) in the atmosphere, especially in urban environments have been established by epidemiological and toxicological studies (Nag *et al.*, 2005; Cooke *et al.*, 2007). The dominant sources of PM<sub>2.5</sub> are from the traffic emissions in urban street canyons (Charron and Harrison, 2005).

High pollutants concentrations inside street canyons could also have an impact on indoor air quality (Chan *et al.*, 2001; Vardoulakis *et al.*, 2003; Ahmad *et al.*, 2005). It is therefore important to understand the dispersion and diurnal variation characteristics of pollutants in the street canyons under various urban meteorological conditions, to formulate effective strategies such as positioning of ventilation air intake, for emission control; and for urban planning. Several methods, such as laboratory-scale experiments (Pavageau and Schatzmann, 1999; Ahmad *et al.*, 2005), in-situ

measurements (Li *et al.*, 2007; Murena *et al.*, 2009; Shen *et al.*, 2010; Zhang *et al.*, 2011), computation fluid dynamics (CFD) simulations (Walton and Cheng, 2002; Xie *et al.*, 2009; Gu *et al.*, 2011; Zhang *et al.*, 2011), have been used to investigate the airflow and pollutant dispersion in urban street canyons.

However, in-situ measurements are still lack and can not fit the requirements for model validation (Kumar *et al.*, 2008). Especially measurements and simulations of the air flow and pollutant distributions and dispersions under weak-wind conditions are relatively rare.

When the mean ambient wind velocity lower than 1.5 m/s, the ambient wind induces too weak air flows in the urban canopy layer, thus there is no primary air flow vortex inside street canyons (Vardoulakis *et al.*, 2003). Moving vehicles and the thermal instability of the atmosphere induced air flows and turbulences are evident and they are main factors affecting on pollutant distribution and dispersions in urban street canyons under weak-wind conditions (Coppalle, 2001; Okamoto *et al.*, 2001), especially in the lower area of the street canyons. Xie *et al.* (2006) numerical simulation exhibited the strong effects of thermal condition of solid wall in street canyon on the air flow. Solazzo *et al.* (2007) introduced a vehicle induced turbulence model to the WinOSPM and achieved well simulations of the CO

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concentrations in urban street canyons under weak-wind conditions.

Tree plantings in street canyons can decrease the dispersion of pollutant from canyons to the air aloft (Ries and Eichhorn, 2001; Gu *et al.*, 2010). However, tree plantings would also change the thermal conditions inside the street canyons (Gu *et al.*, 2010). Thus, the difference of pollutant distributions and dispersion in street canyons with/without tree plantings under weak-wind conditions is interesting, which has not been well clarified.

In this work, day time variation  $PM_{2.5}$  concentrations and temperature were measured in urban street canyons with/without tree plantings in hot summer days in Xi'an, China. Traffic flux and ambient wind velocity were recorded as well. Main factors affecting on  $PM_{2.5}$  concentration variation and dispersion will be analyzed in the following.

## METHODOLOGY

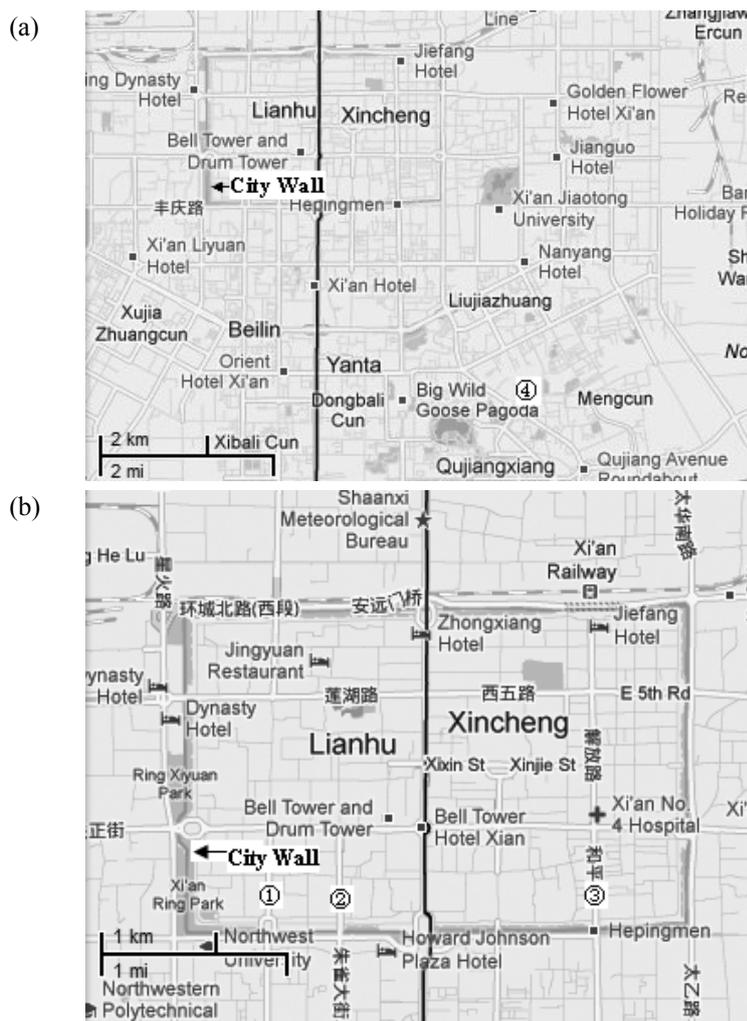
### Measurement Sites

The measurement sites were selected in three South-North street canyons within the City-Wall of Xi'an, which

are Tian Shui Jing Road (TSJR), Zhu Que Road (ZQR) and He Ping Road (HPR), respectively. The TSJR and ZQR with little tree plantings on both sides of the road can be described as the exposed street canyons. The HPR is well covered by tree planting canopy. The experiment sites are about 150 m from the City-Wall, as illustrated in Fig. 1. The three urban sites are located in three street canyons with similar geometry. The roads are about 40 m wide and the average building heights are about 25 m. Buildings heights along the HPR site are undulate, with an average altitude of 22 m. The TSJR and ZQR are nearly uniform street canyons. The streetscapes of the measurement sites are shown in Fig. 2. The background site is on a rooftop of a building in the suburban area, which is about 5 km from the city centre. Besides, household cooking activity in nearby villages, industrial emission and traffic emission are not found in the vicinity.

### Equipments and Measurements

In the present study, the diurnal variations of fine particle ( $PM_{2.5}$ ) mass concentrations were measured on the road side sites. The air temperature and wall temperature were



**Fig. 1.** The measurement sites. ①, ②, ③ and ④ are the measurement points of TSJR, ZQR, HPR and background site, respectively.



**Fig. 2.** The streetscapes of the measurement sites.

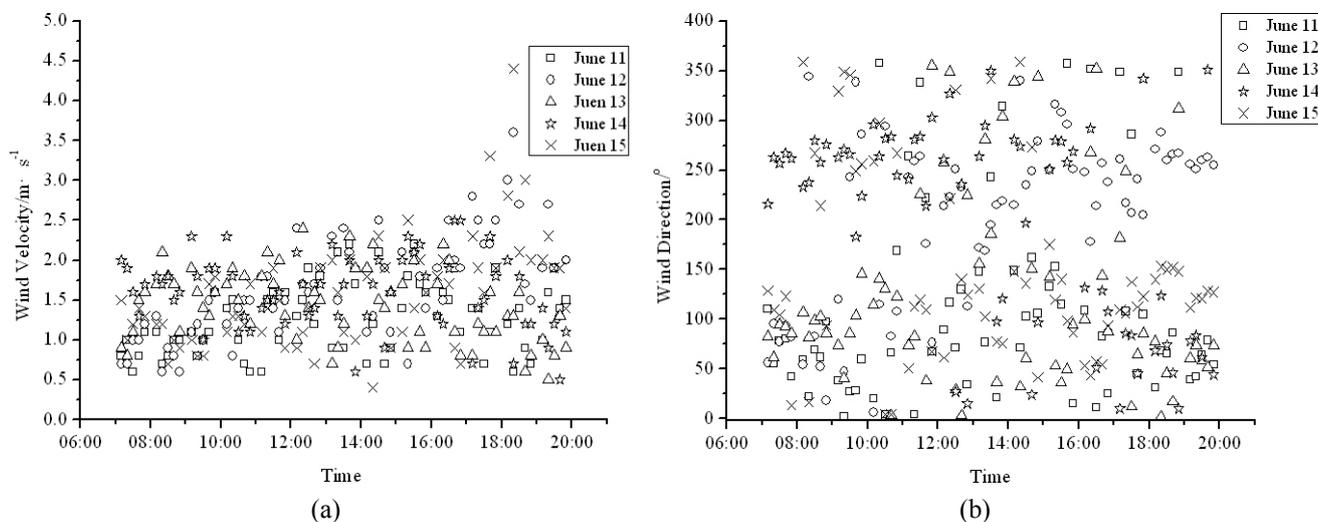
measured simultaneously. Fine particle mass concentrations were measured using a Dust Trak (Model 8520, TSI Inc., US), which measure the particle mass concentrations on principles of optics (Cheng, 2008). The solid wall temperatures (road surface and building surfaces) were measured using an Infrared Thermometer (ST380, Nicety) and the air temperatures were measured using an Air Thermometer (HTC-1, Apuhua). The traffic fluxes were recorded manually at 15min intervals during the sampling periods. The measurements were carried out from June 11, 2010 to June 15, 2010 for 5 days. As limited equipments were used, measurements were carried out site by site, *i.e.*, on June 11, measurements were done on site ② (ZQR); on June 12 and 14, measurements were done on site ③ (HPR); on June 13, measurements were done on site ① (TSJR); and the background fine particle mass concentration was monitored on day June 15 on site ④. All measurements started at 7:00 and ended at 19:00, except the one on June 11, which ended at 14:00 as the equipments were power off. The weather during the sampling periods was fine, with the sunshine and week-winds.

## RESULTS

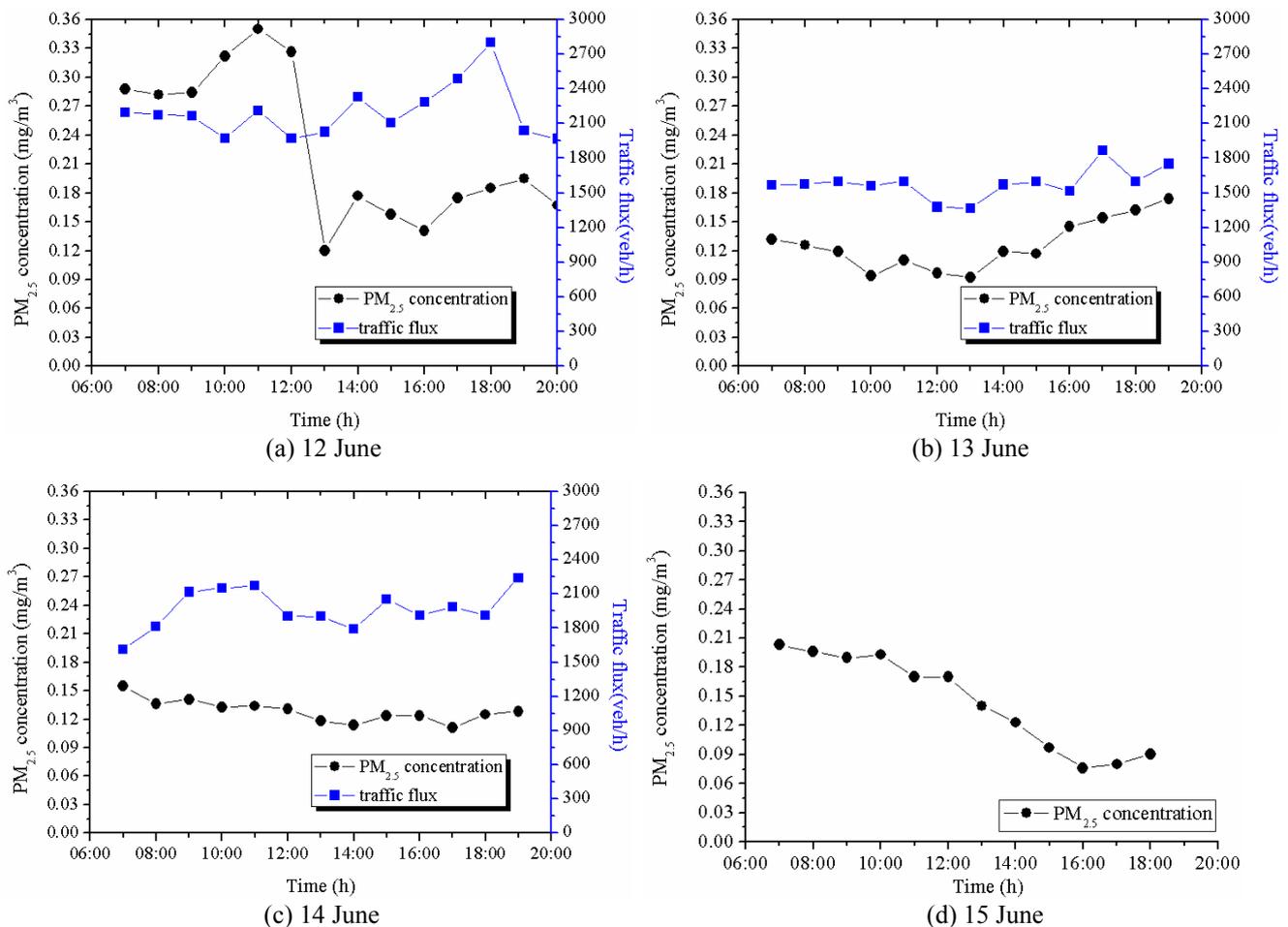
The wind speeds and wind directions recorded by a meteorological station of the Meteorological Agency of

Shaanxi Province during the sampling periods are shown in Fig. 3. The meteorological station locates in the suburbs 10 m above the ground. The average wind velocity was 1.26 m/s, belonging to weak-wind conditions according to a previous study by Coppalle *et al.* (2001). The wind direction changed frequently without obvious prevailing wind direction. Fig. 4 shows the temporal variation of fine particle mass concentrations and vehicle fluxes. Variations of pollutant concentrations at urban sites (Figs. 4(a–c)) have no relationship with the traffic fluxes as reported by Longley *et al.* (2004). As the three urban sites are located inside the City Wall, the heavy duty vehicles are less, which possess a low ratio between 3%–7% of the total traffic fluxes. The variation of fine particle mass concentration also shows no correlation with the wind velocities, as shown in Fig. 3. The ambient wind velocities of larger values in the evening time around 18:00, but the pollutant concentrations are higher in urban street canyons, as shown in Fig. 4(b) and (c).

The fine particle mass concentrations in the morning time for the three urban sites and the background site are high, which would result from the contraction of the atmospheric boundary layer at night. As the sun rising, the air temperature increases and the atmospheric boundary layer expands, which results in the fine particle mass concentrations decaying both in the urban and background



**Fig. 3.** Wind conditions in the five experiment days. (a) wind velocities; (b) wind directions.



**Fig. 4.** Measured day time variation of the fine particle mass concentrations and traffic fluxes.

sites. After 16:00, the solar radiations becomes weak, the atmospheric boundary layer starts contracting, result in the increase of the fine particle mass concentrations both in the urban sites or the background site. So, the fine particle mass concentrations in the urban site are higher in the morning and evening times and lower in the afternoon times between 14:00 to 16:00. It follows that the pollutant concentration variations in urban street canyons in these hot summer days are significantly impacted by the background concentrations.

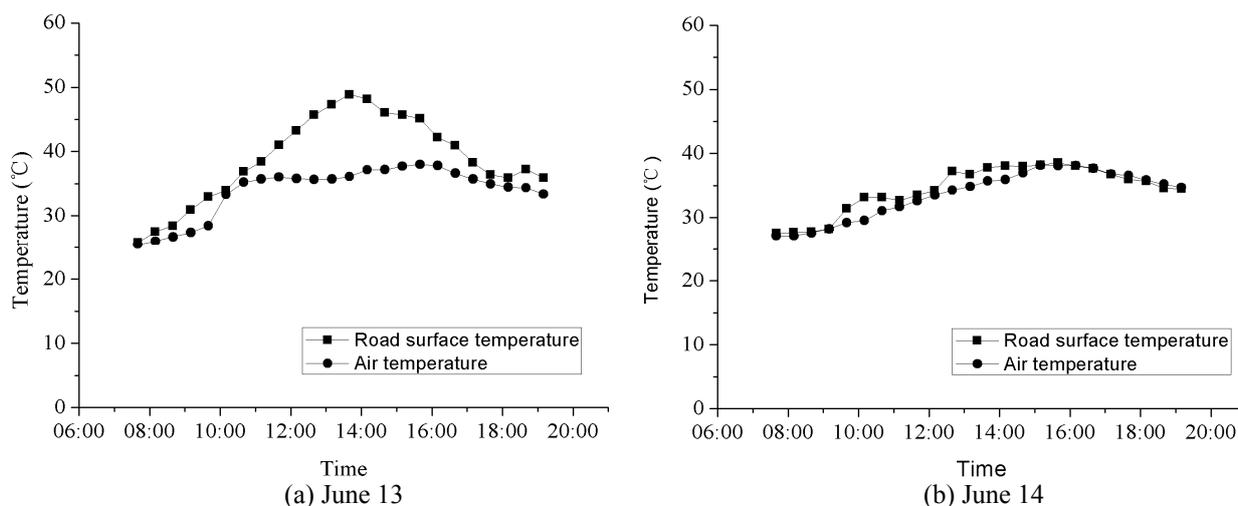
The variation of the fine particle mass concentrations in urban street canyon under weak-wind conditions show correlations with the air temperature as well. In urban street canyons with tree planting, the fine particle mass concentrations are decreasing slightly from the morning to about 17:00, while the air temperatures are keeping slight increasing (Fig. 5(b)). When the air temperatures are decreasing after 17:00, the fine particle mass concentrations are increasing. In urban street canyons without tree planting, the fine particle mass concentrations decays before 11:00, while the air temperatures inside the street canyon are increasing. When the air temperatures are decreasing after 16:00, the fine particle mass concentrations are increasing. The increasing of the air temperature indicates the instability of the atmosphere inside the urban street canyons. In hours from 11:00 to 16:00, while the air temperature keeps in a

near constant value around 36°C, the fine particle mass concentrations are fluctuating between 0.09 to 0.12 mg/m<sup>3</sup>, as shown in Fig. 4(b). Even though the road surface temperatures are much higher than the air temperatures, as shown in Fig. 5(a). It follows that the air temperature increasing is the main reason inducing the atmosphere instability inside urban street canyons, while the temperature difference of road surface and air has little effect on it. Generally, the instability of air dominates the variation of pollutants in these hot weak-wind summer days.

The fine particle mass concentration variation on day June 11 is different from the other days, as it was raining in Xi'an before June 10. The weather in the morning of June 12 was cloudy, with the sun shined on 10:00. It results in the fine particle mass concentration increase before 10:00 and a sharp decrease after 11:00 on June 12.

## DISCUSSIONS

The dispersion of pollutant from urban street canyons to the upper air is usually related to wind conditions, especially the wind velocity aloft (Depaul *et al.*, 1983). However, in such weak-wind hot summer days, the main factors affecting the pollutant dispersion in urban street canyons have not been well discussed. On the other hand, it is



**Fig. 5.** Measured day time variations of the air and road surface temperatures.

commonly known that the weak-wind condition would cause poor air quality in urban street canyons. Do the pollutants accumulate in these measurement days? These will be discussed in the following.

#### **Pollutant Accumulations**

Poor air qualities in urban street canyons have been frequently observed under weak-wind condition (Kukkonen *et al.*, 2001). The dominant sources of  $PM_{2.5}$  are from the traffic emissions in urban street canyons (Charron and Harrison, 2005). Under weak-wind conditions, variations of the fine particle mass concentrations in the urban street canyons are similar to that of the background fine particle mass concentrations (measured on the background site), as shown in Fig. 4. It suggests that the pollutant concentrations in urban street canyons in these hot summer days are significantly impacted by the regional pollution. Thus the pollutant concentrations inside urban street canyons are influenced by both the vehicle emissions and the regional pollution. The directly measured pollutant concentrations can not reflect the accumulations of vehicle emissions. The background concentrations are usually taken away from the total concentrations in order to show the contributions of vehicle emissions (Zhang *et al.*, 2011). However, in the current work, background concentrations are not measured simultaneously with the street canyon measurements. Thus we proposed the relative variations of concentrations (RVC), which is calculated by

$$RVC = (C_{i+1} - C_i) / C_i \quad (1)$$

where  $C_i$  is the measured average pollutant concentration in hour  $i$ .

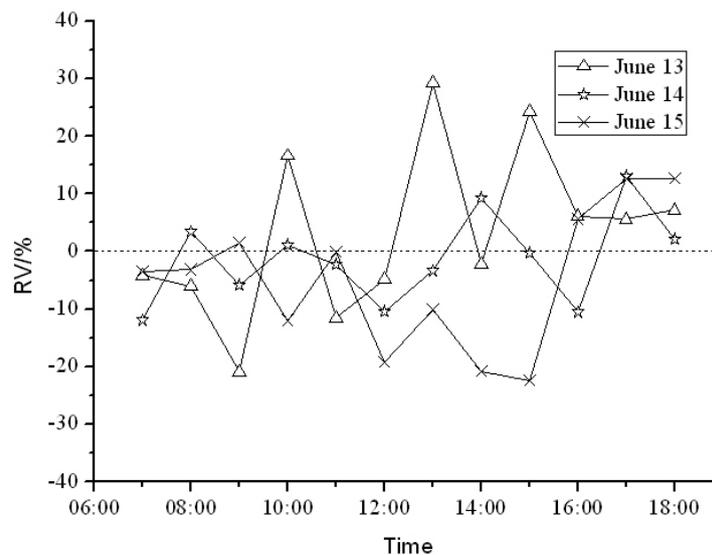
The variations of pollutant concentration at TSJR, HPR and the background sites are shown in Fig. 6. The negative value is indicative of decreased concentrations in the current hour, and the positive value is indicative of increased concentrations in the current hour. As seen from Fig. 6, the values of RVC inside the street canyons are much higher than that of the background during 12:00–16:00, showing

the accumulations of vehicle emissions inside the urban street canyons. Low RVC values were observed in the morning. The RVC values of the background concentrations are positive after 16:00, indicating the atmosphere boundary layer starts contracting.

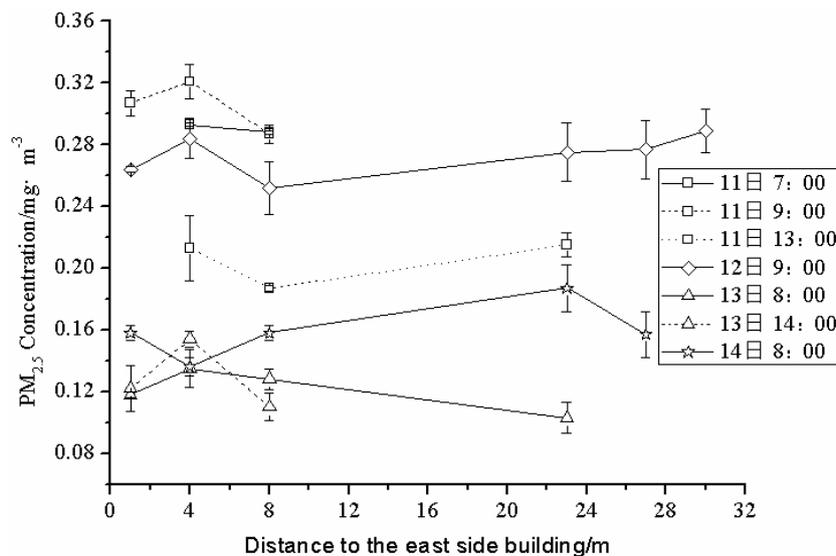
#### **Main Affecting Factors**

It has been proved that the temperature and/or the instability of street canyon air are main factors affecting on the pollution dispersion inside urban street canyons. If the ambient wind is strong enough to drive the air circulation inside urban street canyon, the pollutants arising from vehicles will transport to the leeward wall, and then transport to the upper layer with the air circulations (Hoydysh and Dabberdt, 1988; Walton and Cheng, 2002; Chan *et al.*, 2003; Li *et al.*, 2009), which results in the higher pollutant concentration near the leeward side than the windward side (Walton and Cheng, 2002; Li *et al.*, 2009). Traffic-induced turbulence also has significant effect on the pollutant distributions in urban street canyons (Depaul and Sheih, 1986; Qin and Kot, 1993). Fig. 7 shows the measured horizontal variations of the fine particle mass concentrations about 1 m above street level. It seems that no obvious variations were found from Fig. 7. It is concluded that under such weak-wind conditions, the ambient wind can not drive the air circulations inside street canyons, and the vehicle movements have mainly effects on the pollutant distributions in the urban street canyons.

When the ambient wind becomes strong enough and the air circulation is driven inside the urban street canyons, tree planting on road sides is a major contributor to enhance the pollutant accumulation inside the street canyons, as the tree planting makes the air recirculation strength weaken (Ries and Eichhorn, 2001; Gu *et al.*, 2010). In the present study, for the weak ambient wind, the particulate concentrations were comparable between the TSJR (no tree planting) and HPR (with tree planting) sites (Fig. 4(b) and (c)). However, the variations of the pollutant concentrations in the TSJR are different from those in the HPR in the afternoon times. The pollutant concentrations are increasing in the TSJR,



**Fig. 6.** Variations of the relative variations of concentrations (RVC). June 13 and 14 show results measured in urban street canyons; June 15 shows results measured on background site.



**Fig. 7.** Measured horizontal variations of fine particle mass concentrations.

but the pollutant concentrations maintain changeless or even decreasing in the HPR street canyon. It should be attributed to the tree plantings, which can also change the instability of air inside street canyons, as studied by Gu *et al.* (2010).

## CONCLUSIONS

The measurements show that, under weak-wind hot summer conditions, the  $PM_{2.5}$  concentrations inside urban street canyons have unsatisfactory correlation with the vehicle fluxes and the ambient wind velocities. The  $PM_{2.5}$  concentrations are significantly impacted by the background concentrations. The measured  $PM_{2.5}$  concentrations in urban street canyons become decaying from 12:00 to 16:00, while the  $PM_{2.5}$  from the vehicle exhausts accumulate

inside the street canyons in these hours. In order to get the clean air through traffic control, the current work suggests restricting the traffic flow in hours from 12:00 to 16:00 in weak-wind hot summer days.

The weak-wind velocities can not drive the primary air circulation inside street canyons. The main factors influencing the pollutant dispersion inside street canyons are the air temperature and/or the atmosphere instability.

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## DISCLAIMER

Reference to any companies or specific commercial products does not constitute.

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