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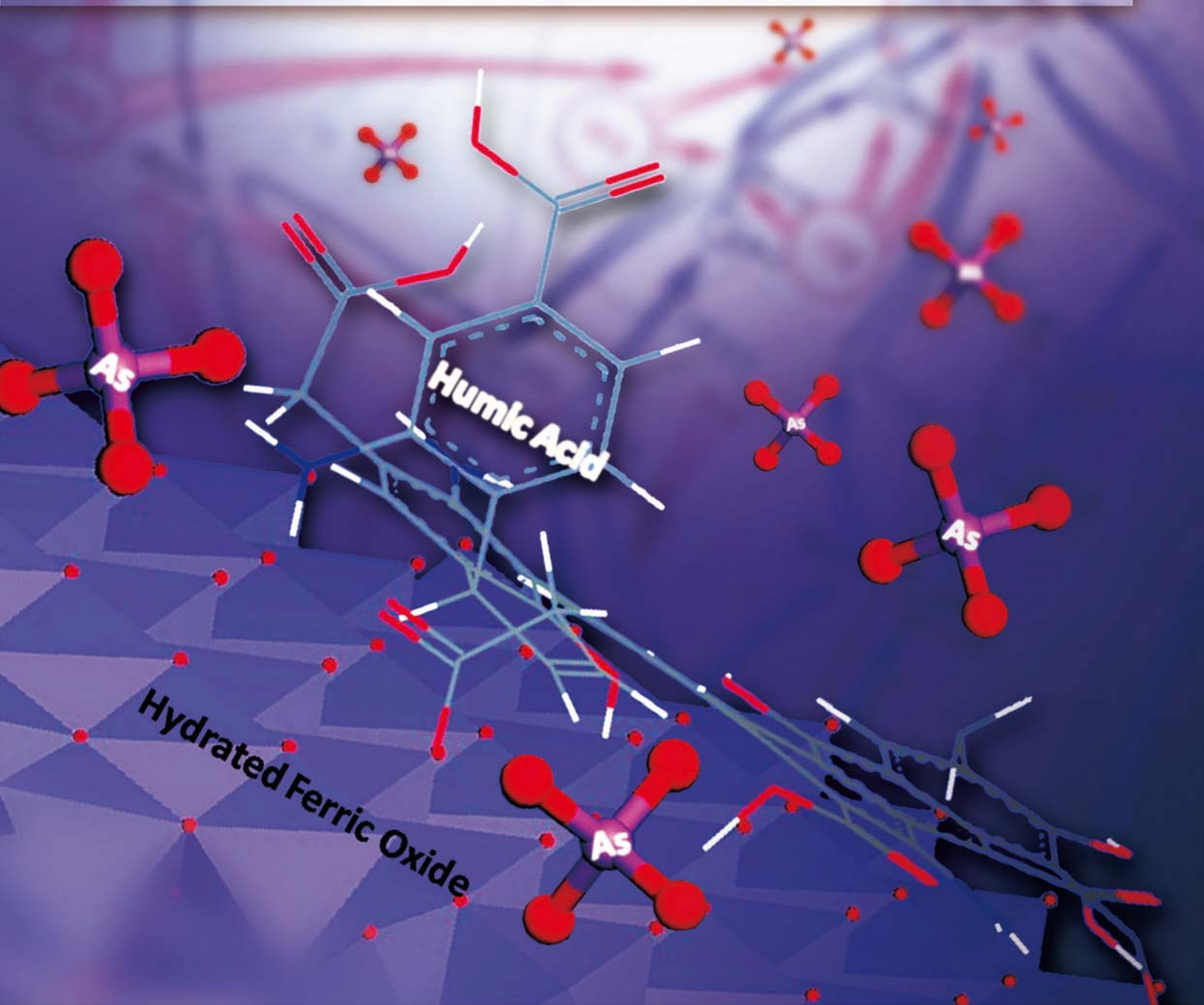

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Effect of traffic restriction on atmospheric particle concentrations and their size distributions in urban Lanzhou, Northwestern China

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ABSTRACT

During the 2012 Lanzhou International Marathon, the local government made a significant effort to improve traffic conditions and air quality by implementing traffic restriction measures. To evaluate the direct effect of these measures on urban air quality, especially particle concentrations and their size distributions, atmospheric particle size distributions (0.5–20 μm) obtained using an aerodynamic particle sizer (model 3321, TSI, USA) in June 2012 were analyzed. It was found that the particle number, surface area and volume concentrations for size range 0.5–10 μm were (15.0±2.1) cm^{-3}, (11.8±2.6) $\mu m^2/cm^3$ and (1.9±0.6) $\mu m^2/cm^3$, respectively, on the traffic-restricted day (Sunday), which is 63.2%, 53.0% and 47.2% lower than those on a normal Sunday. For number and surface area concentrations, the most affected size range was 0.5–0.7 and 0.5–0.8 μm, respectively, while for volume concentration, the most affected size ranges were 0.5–0.8, 1.7–2.0 and 5.0–5.4 μm. Number and volume concentrations of particles in size range 0.5–1.0 μm correlated well with the number of non-CNG (Compressed Natural Gas) powered vehicles, while their correlation with the number of CNG-powered vehicles was very low, suggesting that reasonable urban traffic controls along with vehicle technology improvements could play an important role in improving urban air quality.

Introduction

Atmospheric particles, originating from direct emissions or from gas-to-particle conversion of vapor precursors, are one of the most important pollutants affecting urban air quality. Particles emitted from motor vehicles are among the major particulate pollution sources, especially fine particles. It has been estimated that 90% of urban air pollution in fast-growing cities in developing countries is attributable to motor vehicle emissions (UNEP, 2010). In China, motor vehicles have been identified as the second major contributor of PM_{10} and $PM_{2.5}$ in the Pearl River Delta and the primary local source of $PM_{2.5}$ in Beijing (Liu and He, 2012). Many studies have investigated the impact of traffic on ambient particulate concentrations near major roads and highways (Zhang et al., 2004, 2005; Boogaard et al., 2010), near bus terminals (Cheng et al., 2011), and during traffic control periods (Wang et al., 2010; Hao et al., 2011). These studies show that the particle number concentration near busy freeways is three orders of magnitude higher than the number concentration in an urban environment (Boogaard et al., 2010), and it decreases rapidly with increasing distance from the roadside (Buonanno et al., 2009; Zhu et al., 2002). Furthermore, there is evidence that traffic density and meteorological conditions both have important effects on particle number concentrations (Hussein et al., 2004). Emission restrictions by traffic management have been adopted during several recent important events in China, e.g. the 2008 Beijing Olympic Games, 2010 Guangzhou Asian Games and 2010 Shanghai World Exposition, as the primary measure to

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improve air quality and to solve traffic congestion, and have been shown to be an effective measure of emission reduction (Hao et al., 2011; Wang et al., 2010). While the benefit of traffic management lasting for tens of days or several months is generally appreciated, until now the impact of local short-period (several hours) traffic restriction on urban air quality is largely unknown despite its potential to be a mitigation measure for air pollution, especially for alleviating air pollution under adverse meteorological conditions.

Lanzhou is a typical fast-growing city in Northwestern China. The rapid urban growth has resulted in rapid increase in vehicle ownership and traffic congestion. Like many cities in northern China, particulate matter is one of the most formidable air quality and public health issues in Lanzhou. Actions towards reducing emissions of aerosol particles have been put into effect for years, but the levels of particulate pollution remain high. Yu et al. (2010) showed that the annual mean mass concentration of PM_{10} in urban Lanzhou had decreased from 236 $\mu g/m^3$ in 2001 to 127 $\mu g/m^3$ in 2007, but this still exceeds the national Grade II standard for annual mean PM_{10} concentration (100 $\mu g/m^3$) by 27%. In an attempt to improve air quality, large-scale road infrastructure projects and temporary traffic control measures are currently underway in Lanzhou. From a policy perspective, it is very important and informative to evaluate the effectiveness of these measures. Presently, many studies about traffic impact on particle concentrations in China focus on economically developed areas such as Beijing, Shanghai and Guangzhou (Wang et al., 2010; Witte et al., 2009; Shen et al., 2011; Hao et al., 2011), with much less attention to cities in northwestern China, regardless of their very different economic development level and energy structure. During the 2012 Lanzhou International Marathon, strict traffic restriction measures were implemented by the local government on 10 June 2012 for seven hours. **Figure 1** shows the traffic-restricted zone and the route of the 2012 Lanzhou International Marathon. The 2012 Lanzhou International Marathon event provided a unique opportunity to study the impact of short-period traffic control on urban particulate matter pollution in a heavily congested and densely populated valley city in Northwestern China.

Fig. 1 Route of the 2012 Lanzhou International Marathon.

The objective of this study is to investigate the effect of short-period traffic restriction on urban air quality, especially the particle concentrations and their size distributions, using *in situ* observations, and quantify the contribution of on-road traffic to urban particle concentrations in different size ranges, as well as provide a basis for the formulation of future urban particulate pollution control measures.

1 Methods

1.1 Sampling site

Figure 2 shows the location of Lanzhou and the sampling site. There are two major roads with traffic volume more than 2000 cars per hour near the sampling site, one of which is 20 m from the research building (Donggang West Road in **Fig. 2**), and the other is about 300 m west of the building (Tianshui Road in **Fig. 2**). The sampling site was on the roof of a 32 m high research building of the Cold and Arid Regions Environmental and Engineering Research Institute (CAREEI), Chinese Academy of Sciences, located in the eastern part of the Lanzhou urban area. There are no large stationary pollution sources in its surroundings in summer, and the main activities are residential and commercial. A study by Imhof et al. (2005) indicated that at 30 m above ground, the background concentration was attained. So, our instrument did not directly measure the direct exhaust emissions from vehicles, but captured the particle concentrations and size distributions representing the Lanzhou urban environment. Thus particles directly emitted from combustion and their effect on the near-road environment are not within the scope of our study.

2 Measurement

Continuous particle size distributions (0.5–20 μm) were measured using an aerodynamic particle sizer (model

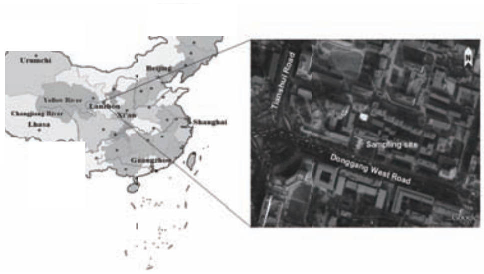

Fig. 2 A map of China and sketch map of sampling site.

3321, TSI, USA) during June 2012. The APS 3321 is a time-of-flight spectrometer that measures the velocity of particles in an accelerating airflow through a nozzle. Aerosol is drawn into the inlet and is immediately split into a sample flow (1 L/min) through the inner nozzle, and a sheath flow (4 L/min) through the outer nozzle. Particle sizes were binned into 52 channels with a time resolution of 5 min per scan. During the experiment, the inner and outer nozzle of the APS was cleaned every two weeks. Meanwhile, the sample flow through the inner nozzle, and the sheath flow through the outer nozzle were examined periodically with a bubble flow meter to insure the good performance of the APS. As part of the study, the aerodynamic particle sizer's (model 3321, TSI, USA) time-of-flight response was calibrated using monodisperse aerosols prior to deployment in the field. In addition, invalid data were eliminated based on the percentage of events 1–4 and data were removed from further analysis when event 2 accounted for less than 75% of the total data samples.

One-min meteorological data, including air temperature, relative humidity and wind speed and direction, were obtained with an automatic meteorological station co-located with the sampling site. The number of motor vehicles passing the sampling site (in both directions) through the Donggang West Road was counted during the experiment every hour.

As mentioned above, temporary traffic control measures were implemented on 10 June 2012 (Sunday) for the 2012 Lanzhou International Marathon event during 7:00–14:30 (Beijing time, same thereafter), when all motor vehicles (including public transport) were prohibited from the Marathon route (**Fig. 1**). For a more accurate assessment of traffic restriction effects on atmospheric particle concentrations and their size distributions, two days (both are Sundays), i.e. 10 June 2012 (traffic-restricted day) and 17 June 2012 (normal Sunday), with similar meteorological conditions, were selected for detailed analysis in the following sections to eliminate the effects of meteorological conditions and traffic volume differences between weekdays (from Monday to Friday) and weekends (Saturday and Sunday).

3 Results and discussion

3.1 Meteorological conditions

Both meteorological conditions and traffic volume have significant effects on particle concentrations and their size distributions. In order to minimize the effect of weekly variation in traffic volumes, meteorological conditions for Sundays in June 2012 were analyzed, and 17 June 2012 (Sunday) was selected as a normal Sunday for comparison with 10 June 2012 (traffic-restricted day) in the following analysis. **Figure 3** shows the 10 min-averaged wind speed, temperature and relative humidity between 00:00 and 18:00 on 10 June (traffic-restricted day) and 17 June (normal Sunday), 2012. The average meteorological conditions and the traffic volume during 08:00–11:00 and 11:00–14:00 on the two days and the weather conditions for the preceding two days at the sampling site are summarized in **Table 1**. It can be seen from **Fig. 3** that the meteorological conditions were similar during 11:00–14:00 on 10 June (traffic-restricted day) and 17 June, 2012. Moreover, the wind direction was almost identical between 11:00 and 14:00 on the two days (**Fig. 4**). In the following, the effect of traffic control on urban air quality is analyzed by comparing the particle concentrations and size distributions on the two days for the period of 11:00–14:00 when meteorological conditions were comparable, while the influence of meteorological conditions is evaluated by comparing the particle concentrations for the period of 08:00–11:00, when differences in meteorological conditions were significant (**Table 1**).

Table 1 Meteorological conditions and traffic volume through the Donggang West Road during 10 June, 2012 (traffic-restricted day) and 17 June, 2012 (normal Sunday)

Study period		Wind speed (m/sec)	Temperature (°C)	Relative humidity (%)	Traffic counts[a] (veh/hr)	Weather conditions
10 June, 2012	08:00–11:00	2.0±0.9	21.9±0.3	29.0±1.2	0 **0**	No precipitation for June 8–10, 2012
	11:00–14:00	1.4±0.4	24.5±0.9	25.3±1.8	0 **0**	
17 June, 2012	08:00–11:00	1.6±0.5	20.7±1.2	45.6±4.6	1788 (876) [b] **1356 (744)** [b]	No precipitation for June 15–17, 2012
	11:00–14:00	1.8±0.4	25.4±1.6	29.8±5.3	1680 (1020) [b] **1440 (840)** [b]	

[a] Traffic count from west to east is in plain font and that from east to west is in bold;
[b] The number of all types of vehicles (the number of non-CNG powered vehicles).

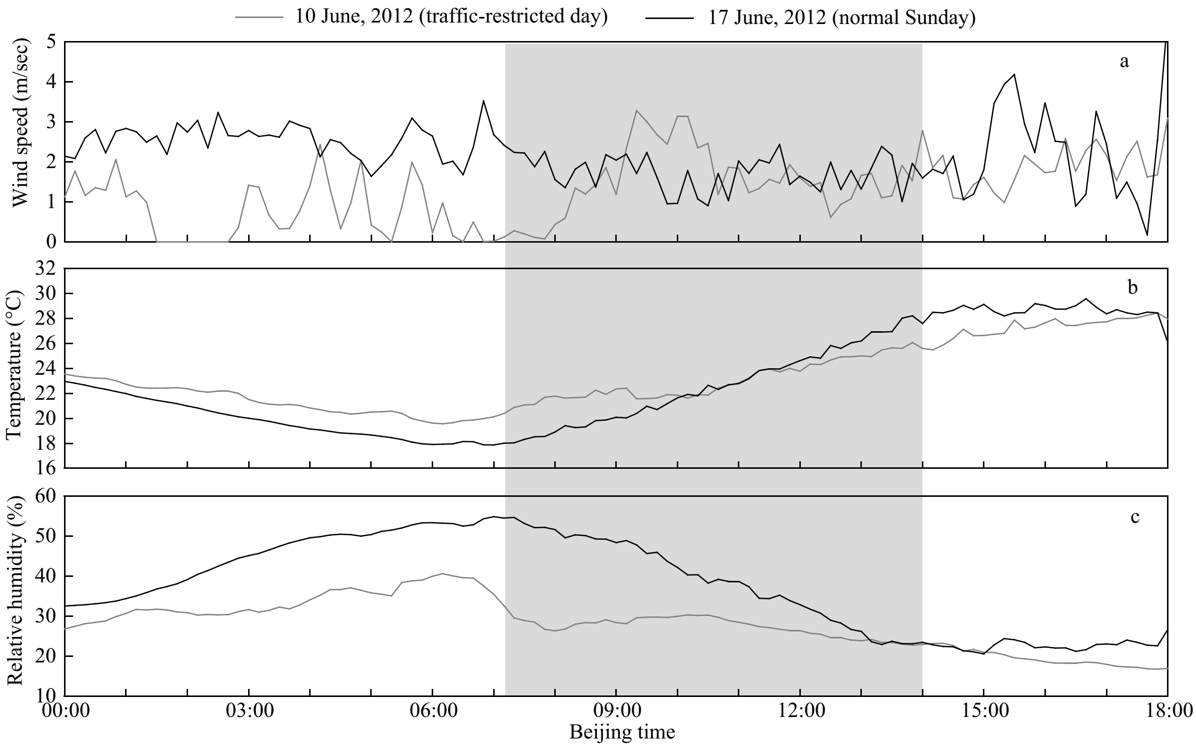

Fig. 3 10 min-averaged wind speed (a), temperature (b) and relative humidity (c) between 00:00 and 18:00 for 10 June, 2012 (traffic-restricted day) and 17 June, 2012 (normal Sunday) (gray shaded period represents the traffic control period on 10 June, 2012).

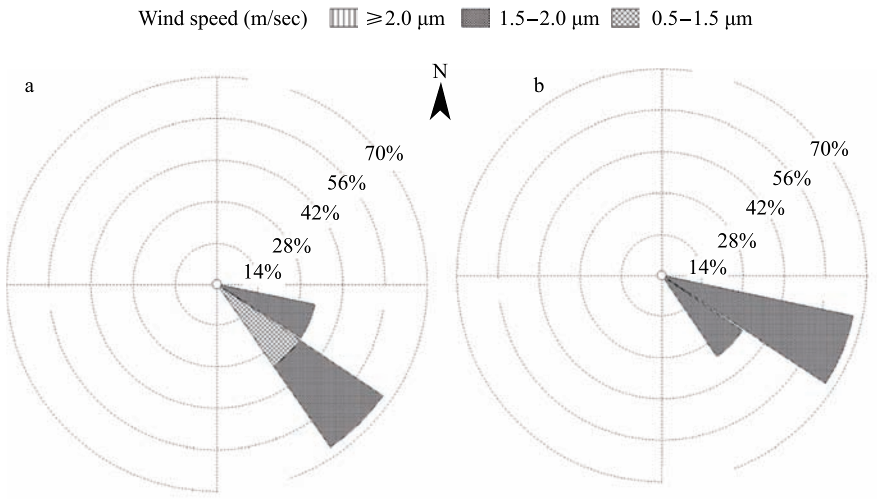

Fig. 4 Wind rose during 11:00–14:00 for (a) 10 June, 2012 (traffic-restricted day) and (b) 17 June, 2012 (normal Sunday).

3.2 Particle concentrations and their size distributions

3.2.1 Particle concentrations

In order to better understand the effect of traffic control on urban particulate pollution in different size ranges, particles in the size range 0.5–20 μm were divided into 4 size bins, i.e. 0.5–1.0, 1.0–2.5, 2.5–10 and 10–20 μm. **Figure 5** shows the time variation of particle number, surface area and volume concentrations in different size ranges between 00:00 and 18:00 on 10 June (traffic-restricted day) and 17 June (normal Sunday), 2012. The particle number, surface area and volume concentrations in the size range 0.5–1.0 μm on the normal Sunday were significantly higher than those on 10 June (traffic-restricted day) during the temporary traffic control period (08:00–14:00), while there was no significant difference in particle concentrations in size ranges 1.0–2.5 and 2.5–10 μm on the two days during the same period (**Fig. 5**), indicating the primary effect of motor vehicle emissions on particles smaller than 1 μm.

For the period with similar meteorological conditions (11:00–14:00), the particle number, surface area and volume concentrations in size range 0.5–10 μm were (15.0±2.1) cm^{-3}, (11.8±2.6) $\mu m^2/cm^3$ and (1.9±0.6) $\mu m^3/cm^3$, respectively, on 10 June (traffic-restricted day), which is 63.2%, 53.0% and 47.2% lower than those on 17 June (normal Sunday) (**Table 2**). The particle number, surface area and volume concentrations in size range 0.5–1.0 μm averaged over 11:00–14:00 decreased by 25.5 cm^{-3}, 11.1 $\mu m^2/cm^3$ and 0.8 $\mu m^3/cm^3$, respectively, on 10 June as compared to 17 June, 2012, which accounted for 98.8%, 83.5% and 47.1% of the total decrease in the size range 0.5–10 μm, indicating the significant effect of motor vehicle emissions on fine particles.

If the decrease in particle concentrations during the period of 11:00–14:00 on 10 June (traffic-restricted day) was assumed to be due to traffic control alone, it can be inferred from **Table 2** that the higher wind speed and drier air during 08:00 to 11:00 on the traffic restricted day as compared to the normal Sunday led to a decrease of 16.5 cm^{-3}, 5.0 $\mu m^2/cm^3$ and 0.3 $\mu m^3/cm^3$ in particle number, surface area and volume concentrations in 0.5–1.0 μm, respectively, which accounted for 97.5%, 60.2% and 21.4% of the total decrease in 0.5–10 μm. It is interesting to compare the above results for the Lanzhou International Marathon to the $PM_{2.5}$ and PM_{10} reductions during the Beijing Olympic Games. Liu and He (2012), and Schleicher et al. (2011) concluded that during the 2008 Olympic Games the aggressive emission reduction measures resulted in a decrease of 27%–33% and 34.7%–44.0% in $PM_{2.5}$ and PM_{10} over Beijing, respectively. A 12% decrease in PM_{10} over Shanghai urban areas was reported by a Mid-Expo Air Quality Report (CAI-Asia 2010). For the Lanzhou International Marathon, we found a slightly higher decrease in particulate matter concentrations, although traffic control was implemented only in a limited area for several hours in contrast to the much larger control area for a longer period in the Beijing and Shanghai cases, which is possibly related to the different industrial and energy structure and the low emissions standards for motor vehicles in Lanzhou as compared to more developed regions in China. Moreover, the topography of Lanzhou, trough-shaped, makes the air pollutant concentration in the urban area depend more on the amount of local emissions (Zhang and Chen, 1994).

Table 2 Statistics of particle concentrations in different size bins for the periods of 11:00–14:00 and 08:00–11:00 for 10 June, 2012 (traffic-restricted day) and 17 June, 2012 (normal Sunday) [a]

Concentration	Size range (μm)	Normal Sunday (17 June, 2012)	Traffic-restricted day (10 June, 2012)	Decrease of concentration [b]	Decrease in percentage
Number (cm^{-3})	0.5–1.0 μm	40.0±9.2	14.5±1.9	25.5	63.8%
		64.5±8.2	**22.5±5.6**	**42.0**	**65.1%**
	1.0–2.5 μm	0.7±0.1	0.5±0.2	0.2	28.6%
		0.8±0.1	**1.0±0.4**	**−0.2**	**−25.0%**
	2.5–10 μm	0.03±0.01	0.01±0.01	0.02	66.7%
		0.03±0.02	**0.04±0.02**	**−0.01**	**−33.3%**
	0.5–10 μm	40.8±9.2	15.0±2.1	25.8	63.2%
		65.4±8.2	**23.5±5.9**	**41.9**	**64.1%**
Surface area ($\mu m^2/cm^3$)	0.5–1.0 μm	19.3±3.9	8.2±1.3	11.1	57.5%
		30.5±3.7	**14.4±4.1**	**16.1**	**52.8%**
	1.0–2.5 μm	4.6±0.5	3.1±1.1	1.5	32.6%
		5.5±0.9	**6.6±2.5**	**−1.1**	**−20.0%**
	2.5–10 μm	1.1±0.5	0.5±0.5	0.6	54.5%
		1.2±0.8	**1.3±0.9**	**−0.1**	**−8.3%**
	0.5–10 μm	25.1±4.0	11.8±2.6	13.3	53.0%
		37.2±4.3	**22.2±6.9**	**15.0**	**40.3%**
Volume ($\mu m^3/cm^3$)	0.5–1.0 μm	1.6±0.3	0.8±0.1	0.8	50.0%
		2.6±0.3	**1.5±0.4**	**1.1**	**42.3%**
	1.0–2.5 μm	1.2±0.1	0.8±0.3	0.4	33.3%
		1.4±0.2	**1.7±0.7**	**−0.3**	**−21.4%**
	2.5–10 μm	0.7±0.4	0.3±0.3	0.4	57.1%
		0.8±0.6	**0.8±0.6**	**0.0**	**0.0%**
	0.5–10 μm	3.6±0.6	1.9±0.6	1.7	47.2%
		4.7±0.8	**4.0±1.6**	**0.7**	**14.9%**

[a] Particle concentrations averaged over 11:00–14:00 and 08:00–11:00 are shown in plain and bold font, respectively;
[b] Particle concentrations on normal Sunday subtracted by that on traffic-restricted day.

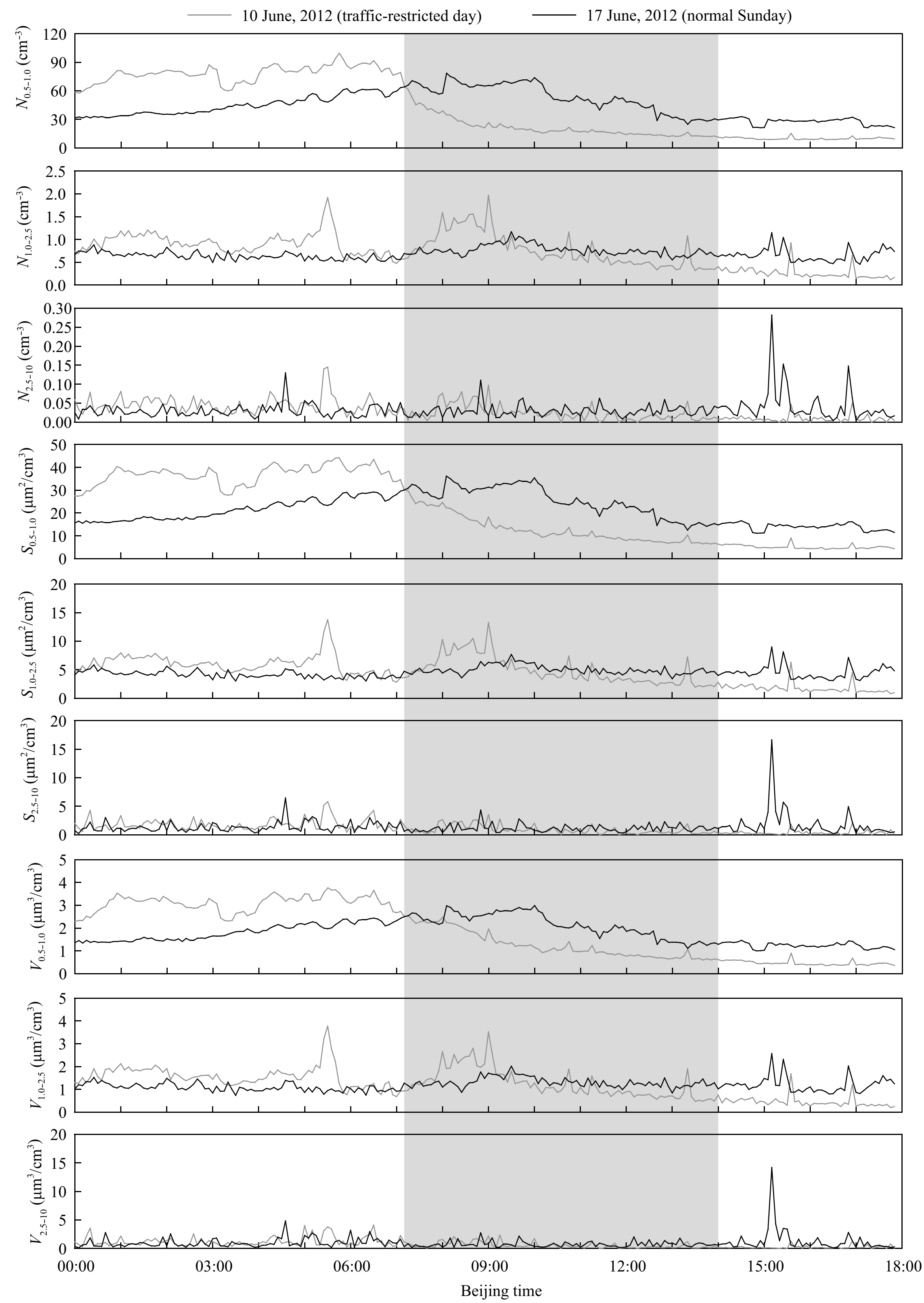

Fig. 5 Time series of atmospheric particle concentrations for different size bins (0.5–1.0, 1.0–2.5, 2.5–10) for 10 June, 2012 (traffic-restricted day) and 17 June, 2012 (normal Sunday). The gray shaded region represents the traffic control period. *N*: particle number, *S*: surface area, *V*: volume.

3.2.2 Particle size distributions

Figure 6 presents the average particle number, surface area and volume size distributions during 11:00–14:00 on the traffic-restricted day (10 June, 2012) and the normal Sunday (17 June, 2012). Obvious discrepancies between these size distributions (10 vs. 17 June 2012) can be seen. The mean particle number concentration decreases with increasing particle size on both days. The mean particle surface area concentration has a weak peak in 1.037–1.114 μm on normal Sunday, while it decreases slowly with increasing particle size on the traffic-restricted day. The average particle volume size distribution is bimodal with peaks at 0.542–0.58 and 1.382–1.486 μm, respectively, on the normal Sunday, while it is unimodal with a peak at 1.197–1.286 μm on the traffic-restricted day. The most affected size ranges for number and surface area concentrations were in 0.5–0.7 μm and 0.5–0.8 μm ranges, respectively, which is in accordance with those found in another study (Cheng et al., 2008). For the particle volume concentration, the most affected size ranges were 0.5–0.8, 1.7–2.0 and 5.0–5.4 μm.

Gao et al. (2007) studied the size distribution of exhausted particles from a gasoline passenger car and showed that most exhausted particles are less than 1 μm. Ondráček et al. (2011), based on results from spectrometers and a BLPI (Berner Low Pressure Impactor), showed that the particle mass size distribution near a busy freeway and suburban crossroad had a peak around 5 μm. Wang et al. (2001) studied the particle size distributions in the Tanyugou highway tunnel and demonstrated that the particle number size distribution had a peak around 0.7 μm, and the mass size distribution had peaks in the size range 4–7 μm, which is consistent with the size distribution properties from our study.

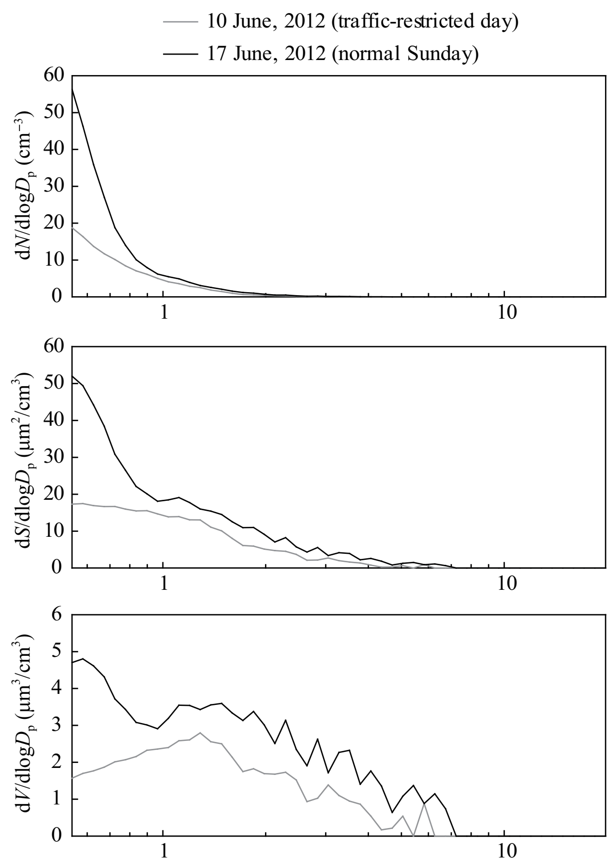

Fig. 6 Mean particle number, surface area and volume size distributions during 11:00–14:00 for 10 June, 2012 (traffic-restricted day) and 17 June, 2012 (normal Sunday).

3.3 Diurnal variation of particle concentrations

To further illustrate the effect of short-period traffic restriction on urban air quality, the diurnal evolution of particle number concentrations in size range 0.5–1.0 μm on 10 June 2012 (traffic-restricted day) and the averages over weekends and weekdays in June 2012 that had similar meteorological conditions as 10 June 2012 are provided in **Fig. 7**. It is seen that the diurnal variations are significantly different between 10 June and the two averages, in particular, the morning peak is missing on 10 June. As expected, the daytime (07:00–17:00) particle number concentrations were lower on weekends than on weekdays, but the morning peak was still there, although shifted one hour later on weekends. The above results indicate the possible benefit of short-period traffic restriction (several hours) in improving urban air quality as compared to long-term restrictions, such as those implemented during the 2008 Beijing Olympic Games, the 2010 Shanghai World Expo and the 2010 Guangzhou Asian Games, which may affect normal human activities and industry to some extent. More data are needed to obtain consolidated results, but as shown above the effect is obvious and the result is also of benefit to other cities.

The correlation coefficients between atmospheric particle number and volume concentrations in different size bins and motor vehicle counts in both travel directions at Donggang West Road are provided in **Table 3**. The correlation of particle concentrations in 0.5–1.0 μm with that in 1.0–2.5 μm is higher than that with other size ranges, indicating that particles in the two size bins have

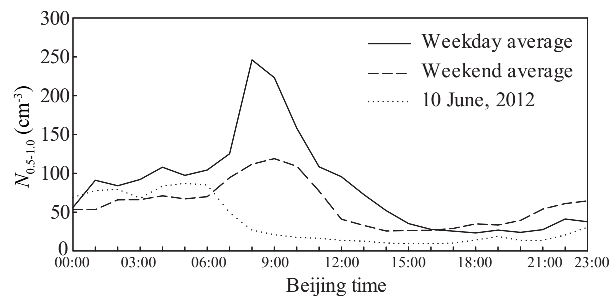

Fig. 7 Diurnal evolution of particle number concentration in the size range 0.5–1.0 μm on 10 June (traffic-restricted day), and the averages for weekends and weekdays in June 2012.

Table 3 Correlation between atmospheric particle number and volume concentrations in different size ranges and motor vehicle counts on 17th June, 2012 (normal Sunday) [a]

Item	$N_{0.5-1.0}$	$N_{1.0-2.5}$	$N_{2.5-10}$	West→East vehicle counts		East→ West vehicle counts	
	$V_{0.5-1.0}$	$V_{1.0-2.5}$	$V_{2.5-10}$	non-CNG powered	CNG-powered	non-CNG powered	CNG-powered
$N_{0.5-1.0}$	**1**	**0.82**	0.23	**0.75**	−0.08	**0.57**	0.33
$V_{0.5-1.0}$	**1**	**0.65**	0.16	**0.81**	−0.18	**0.72**	0.28
$N_{1.0-2.5}$		**1**	0.33	0.34	−0.17	0.23	0.16
$V_{1.0-2.5}$		**1**	0.30	0.24	−0.21	0.14	0.07
$N_{2.5-10}$			**1**	0.14	−0.43	0.22	−0.20
$V_{2.5-10}$			**1**	0.11	<u>−0.48</u>	0.23	−0.25

[a] Numbers in bold (underlined) are significant at 0.01 (0.05) level.

similar sources at the site (**Table 3**). The correlation between particle volume (number) concentrations in 0.5–1.0 μm and the non-CNG powered vehicle counts in both travel directions (west to east and east to west) are 0.81 and 0.72 (0.75 and 0.57), respectively, which is significant at level 0.01, while the correlation with the number of CNG-powered vehicles is very low and insignificant, indicating that urban air quality was mainly affected by non-CNG powered vehicles and the main particle range affected was 0.5–1.0 μm. Some researchers have studied the particle and gaseous pollutant emissions from CNG-powered and non-CNG powered vehicles and investigated their impacts on urban air quality (Ristovski et al., 2000, 2004; Suthawaree et al., 2012; Wang et al., 2009). These studies indicated that converting a petrol-operating vehicle to CNG-powered has the potential to reduce particle emissions and improve in air quality.

4 Conclusions

Our results indicated that the short-period traffic restriction indeed alleviated urban particle pollution in Lanzhou in some extent, although it is not as obvious as in other studies due to the short control period. A considerable decrease in particle concentrations during the traffic control period was observed. Such short-duration sectoral restriction measures implemented periodically have the potential to improve air quality in Lanzhou. The size range most affected by traffic restriction was 0.5–0.7 and 0.5–0.8 μm for number and surface area concentrations, respectively, while for volume concentration it was 0.5–0.8, 1.7–2.0 and 5.0–5.4 μm. A close correlation with the number of non-CNG powered vehicles is found for particles in size range 0.5–1.0 μm, which is missing in the relation to the number of CNG-powered vehicles.

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