Effect of short-term regional traffic restriction on urban submicron particulate pollution

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ABSTRACT

During the 2013 and 2015 Lanzhou International Marathon Events (LIME1 and LIME2), the local government made a significant effort to improve traffic conditions and air quality by implementing traffic restriction measures. To fill the gap in information on the effect of short-period (several hours) traffic control on urban air quality, submicron particle size distributions and meteorological data were measured simultaneously during June 2013 and June 2015 in urban Lanzhou. The number and surface area concentrations of particles in the 100–200 nm range declined by 67.2% and 65.0% for LIME1 due to traffic control, while they decreased by 39.2% and 37.1% for LIME2. The impact of traffic restriction on air pollution near the sampling site lagged behind the traffic control period for LIME2. In addition, the effect of traffic restriction on air pollution near the sampling site was dependent on the distance between the relative orientation of the sampling site and traffic-restricted zones, as well as meteorological conditions such as wind direction. The influence of traffic restrictions on the particle concentrations differed for different particle sizes. The size range most affected by traffic restriction was 60–200 and 60–300 nm for number and surface area concentrations in the urban environment, respectively, while for the particle volume concentration it was the 100–600 nm range. This study will provide a basis for implementation of future urban traffic-induced particulate pollution control measures.

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Introduction

Urban air quality is of increasing concern due to its significant climatic, environmental and health effects. In recent years, some short-term or long-term air pollution events have been reported frequently in many Chinese cities (Chai et al., 2014; Chan and Yao, 2008; Chen and Xie, 2014; Cheng et al., 2013; Li et al., 2014; Qu et al., 2010; Wang et al., 2008), especially the long-lasting haze-fog episodes in central and eastern China in January 2013 (Guo et al., 2014; Han et al., 2014; Huang et al., 2014; Wang et al., 2014; Zhang et al., 2014). Atmospheric particles, especially the fine fractions originating from direct emissions from motor vehicles and gas-to-particle conversion of vapor-phase precursors, are one of the most important pollutants affecting urban air quality. It has been estimated that 90% of urban air pollution in fast-growing cities in developing countries can be attributed to vehicle emissions (UNEP, 2010). Many studies have investigated the effect of traffic on ambient particulate matter pollutants near major roads or highways (Boogaard et al., 2010; Zhang et al., 2004, 2005) and near bus terminals (Cheng et al., 2011). The particle number concentration near busy freeways is three times higher than the background level 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). Emission controls by traffic management, as the primary measure to improve air quality and solve traffic congestion, have been adopted during several recent important events in China e.g. the 2008 Beijing Olympic Games, 2010 Shanghai World Exposition and Guangzhou Asian Games, and 2013 Nanjing Asian Youth Games, and have been shown to be an effective measure for emission reduction (Hao et al., 2011; Li et al., 2010; Schleicher et al., 2011, 2012; Wang and Xie, 2009; Wang et al., 2010; Worden et al., 2012; Zhou 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 has been largely unknown despite its potential to be a mitigation measure for air pollution, especially for alleviating air pollution under adverse meteorological conditions.

As a typical fast-growing city in northwestern China, the rapid urban expansion in Lanzhou has resulted in a sharp increase in vehicle ownership and traffic congestion. Like many cities in northern China, particulate matter is one of the most prevalent pollutants in Lanzhou. Although some actions have been taken over the years to reduce emissions of aerosol particles, the particulate pollution remains severe (Yu et al., 2010). In an attempt to improve air quality, large-scale road infrastructure projects and temporary traffic control measures are currently underway in Lanzhou. Presently, many studies on the impact of motor vehicle emissions on particle concentrations in China focus on economically developed areas such as Beijing, Shanghai and Guangzhou (Cheng et al., 2008; Hao et al., 2011; Schleicher et al., 2011, 2012; Shen et al., 2011; Wang et al., 2010; Witte et al., 2009; Zhang et al., 2011), with much less attention to northwestern cities (Zhao et al., 2014), regardless of their very different economic development level and energy structure. During the 2013 and 2015 Lanzhou International Marathon, strict traffic restriction measures were implemented by the local government on 15 June 2013 and 13 June 2015 for 7 hr. Fig. 1 shows the traffic-restricted zones and the routes of the two Lanzhou International Marathon Events, which provide a unique opportunity to study the effect of short-term traffic control on urban air quality in a heavily congested and densely populated valley city in northwest China.

The objective of this study is to investigate the impact of short-period traffic control on urban air quality, especially submicron particle number concentrations, using in situ observations, and quantify the contribution of on-road traffic to urban particle concentrations in different size ranges, as well as evaluate the difference in the reduction of particle concentrations between two Lanzhou International Marathon Events due to different traffic-restricted zones. The study will provide a basis for the formulation of future urban particulate pollution control measures.

1. Data and methods

1.1. Sampling site

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 (CAREERI), Chinese Academy of Sciences, located in the eastern part of the Lanzhou urban area. There are two major roads with traffic volume of 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. 1), and the other is about 300 m west of the building (Tianshui Road in Fig. 1). There are no large stationary pollution sources in its surroundings in summer, and the main activities are residential and commercial. The study of Imhof et al. (2005) found that the background concentration of urban particulate pollutants was attained at 30 m above ground. Our instrument did not 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

Fig. 1 – Routes of the 2013 and 2015 Lanzhou International Marathon Events (the white line represents part route of the 2015 Lanzhou International Marathon).
scope of our study. The particles directly emitted from motor vehicles gradually grew by aerosol dynamic processes, such as intra- or inter-modal coagulation and condensation, as the particles were transported to our sampling site. So, although there was only one observation site within or near the restricted zones (Fig. 1), the sampling site is representative for studying the effect of short-term traffic control on urban submicron particulate pollution.

1.2. Measurement

Continuous submicron particle size distributions (10–600 nm) were measured using a scanning mobility particle sizer (SMPS model 3936, TSI, USA) during June 2013 and June 2015, respectively. The SMPS measures particle size distribution using an electrical mobility detection technique, which uses a bipolar charger in the Electrostatic Classifier to charge the particles to a known charge distribution. The particles are then classified according to their traverse ability in an electrical field, and the number of particles in a specified size range is counted by a Condensation Particle Counter (CPC). The criteria for aerosol and sheath flows were set to 0.3 L/min and 3 L/min, and the saturator, condenser, optics and cabinet temperatures were 39°C, 14°C, 40°C and 25.7°C, respectively. The parameters were checked every two weeks. The diffusional and gravitational losses for the inlet lines of SMPS also were considered during the experiment. The SMPS impactor was cleaned every day. Meanwhile, the sample and sheath flow rates of the SMPS were examined periodically with a bubble flow meter to insure the good performance of the instrument. As part of the study, the SMPS was calibrated using monodisperse aerosols prior to their deployment in the field. In addition, ten-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 also was counted during June 2013 every hour. Hourly mean SO2, NO2 and CO concentrations at the Lanzhou Institute of Biological Products near our sampling site published online by China National Environmental Monitoring Center were also used in this study. Beijing Time (BT) (=UTC + 8) was used throughout this paper.

As mentioned above, temporary traffic control measures were taken on 15 June 2013 (weekend) and 13 June 2015 (weekend) for the 2013 and 2015 Lanzhou International Marathon events (referred as LIME1 and LIME2 respectively hereafter) were fitted using a multivariate logarithm normal distribution. The formula of the log-normal distribution is given as follows:

\[
\frac{dN}{d\log D_p} = \sum_{i=1}^{n_m} N_i \exp\left( -\frac{(\log D_p - \log D_{p,i})^2}{2\sigma_i^2} \right)
\]

where \(N_i\), \(D_{p,i}\), and \(\sigma_i\) are the total number concentration, the number mode diameter and the standard deviation of mode \(i\), respectively. \(n\) is the number of individual log-normal modes that characterize the particle size distribution. The fit criterion was chosen to satisfy a goodness of fit test at 5% significance level with minimum number of modes (Shrestha et al., 2010), and no modes are therefore allowed to have a spacing less than \(\log D_{p,i} < 0.15\), which roughly corresponds to a ratio of \(D_{p,i}\)'s > 1.4 (Tunved et al., 2003). In the study, \(n = 2\) for LIME1 and LIME2.

The study focused on the impact of local short-period (several hours) traffic restriction on urban submicron particulate pollution revealed by online particle size distribution measurements. To better assess the effect of traffic control on urban submicron particulate pollution, a regression model between particle number concentrations and meteorological variables was used. It is assumed that the measured particle number concentration \(N\) (cm\(^{-3}\)) in a certain size range can be mathematically expressed as a function of ambient temperature and local wind speed (Hussein et al., 2006; Mølgaard et al., 2012):

\[
\log(N) = N_0 + a_1 T + a_2 U^2 + b_1 U + b_2 U^2
\]

where log denotes the natural logarithm, \(N\) is the particle number concentration (cm\(^{-3}\)) of a certain size fraction, \(N_0\), \(a_1\), \(a_2\), \(b_1\) and \(b_2\) are constants, \(T\) and \(U\) are the temperature (K) and wind speed (m/sec), respectively. To minimize the effect of weather conditions and pollution sources, a regression model was established using the size-resolved particle number concentrations, wind speed and temperature observed during

1.3. Data analysis

The particle number, surface area and volume concentrations were exported using TSI software AIM (Aerosol Instrument Manager). The particle number concentration was measured directly by the scanning mobility particle sizer, while the surface area and the volume concentrations were calculated with the following formulas assuming spherical particles:

\[
\begin{align*}

p_1(D_p) &= \pi \frac{1}{6} D_p^3

p_2(D_p) &= \pi \frac{1}{4} \frac{1}{6} \frac{1}{6} D_p^3

p_3(D_p) &= \pi \frac{1}{4} \frac{1}{4} \frac{1}{6} \frac{1}{6} D_p^3

\end{align*}
\]

where \(p_1(D_p)\) (cm\(^{-3}\)), \(p_2(D_p)\) (μm\(^2\)/cm\(^3\)) and \(p_3(D_p)\) (μm\(^3\)/cm\(^3\)) are particle number, surface area and volume concentrations at particle size \(D_p\) (μm), respectively.

In order to determine the effect of traffic restriction on the modal structure of particle number size distributions (PNSDs), the hourly mean PNSDs during the 2013 and 2015 Lanzhou International Marathon Events (referred as LIME1 and LIME2 respectively hereafter) were fitted using a multivariate logarithm normal distribution. The formula of the log-normal distribution is given as follows:

\[
\frac{dN}{d\log D_p} = \sum_{i=1}^{n_m} N_i \exp\left( -\frac{(\log D_p - \log D_{p,i})^2}{2\sigma_i^2} \right)
\]

where \(N_i\), \(D_{p,i}\), and \(\sigma_i\) are the total number concentration, the number mode diameter and the standard deviation of mode \(i\), respectively. \(n\) is the number of individual log-normal modes that characterize the particle size distribution. The fit criterion was chosen to satisfy a goodness of fit test at 5% significance level with minimum number of modes (Shrestha et al., 2010), and no modes are therefore allowed to have a spacing less than \(\log D_{p,i} < 0.15\), which roughly corresponds to a ratio of \(D_{p,i}\)'s > 1.4 (Tunved et al., 2003). In the study, \(n = 2\) for LIME1 and LIME2.

The study focused on the impact of local short-period (several hours) traffic restriction on urban submicron particulate pollution revealed by online particle size distribution measurements. To better assess the effect of traffic control on urban submicron particulate pollution, a regression model between particle number concentrations and meteorological conditions and traffic volume differences between weekdays (from Monday to Friday) and weekends (Saturday and Sunday).
07:00–14:00 (traffic control period) from all days of June 2013 and 2015 except rainy and heavily polluted days. The effect of traffic control on submicron particulate pollution was assessed by comparing the model-predicted and measured size-resolved particle number concentrations during the traffic control period. The differences between the predicted and measured size-resolved particle number concentrations during the traffic control period can be considered to be the effect of traffic control.

2. Results and discussion

2.1. Overview

To better understand the impact of short-period traffic restriction (several hours) on urban particulate matter pollution, variations of daily mean ultrafine particle number concentrations (particles less than 100 nm) and meteorological conditions including wind speed, temperature and relative humidity during June 2013 and June 2015 are given first in Fig. 2. As can be seen from Fig. 2, the particle number concentrations in the 10–100 nm range in most days in June 2013 were significantly higher than those in June 2015, while the meteorological conditions in June 2013 and June 2015 were comparable. The above phenomenon was mainly related to the fact that air pollution sources in urban areas were reduced over this time and more clean energy such as CNG (Compressed Natural Gas) was used in urban Lanzhou. However, the number concentrations of ultrafine particles in the two traffic-restricted days (the 2013 and 2015 Lanzhou International marathon days are represented by arrows) were much lower than those before the 2013 and 2015 Lanzhou International Marathon Events, indicating that short-term traffic controls can effectively alleviate urban air pollution.

Schleicher et al. (2012) showed that application of aerosol source control measures, such as reducing traffic, had a huge impact on the aerosol pollution in Beijing by studying atmospheric particles before, during, and after the period of the Olympic Summer Games in Beijing, China, in August 2008.

Fig. 2 – Variations of daily mean ultrafine particle number concentrations (10–100 nm) and meteorological conditions during June 2013 and June 2015. The arrows represent Lanzhou International marathon days (traffic-restricted days) in 2013 and 2015.
Additionally, the study by Zhao et al. (2014) indicated that particle number, surface area and volume concentrations in the size range of 0.5–10 μm on the 2012 Lanzhou International Marathon day (Sunday) were 63.2%, 53.0% and 47.2% lower than those on a normal Sunday. Although the particles emitted from motor vehicles are mainly concentrated in the ultrafine fractions (Buonanno et al., 2009; Wehner et al., 2002), studies on the effect of short-period traffic restriction on urban air pollution and especially ultrafine particles have been scarce in northwestern China.

2.2. Meteorological conditions and precursor gases

Both meteorological conditions and emissions from motor vehicles have significant effects on submicron particle concentrations and their size distributions in urban areas (Hussein et al., 2004; Zhao et al., 2015). For example, Zhao et al. (2015) showed that number concentrations of particles in Aitken and accumulation modes mainly depended on wind speed in spring and winter, while they depended not only on wind speed but also on temperature in summer and fall in an

Fig. 3 – Diurnal variations of hourly mean temperature, relative humidity, wind speed, SO₂, NO₂ and CO concentrations for 15 (traffic-restricted day) and 22 June 2013 (normal weekend) (a–f) and 13 (traffic-restricted day) and 14 June 2015 (normal weekend). The thick black lines above x-axes represent the traffic control periods on 15 June 2013 and 13 June 2015.
urban area of complex terrain in Northwestern China. In order to minimize the effect of the weekly variation in traffic volumes, meteorological conditions for weekends in June 2013 and 2015 were analyzed, and 22 June 2013 and 14 June 2015 were selected as normal weekend days for comparison with 15 June 2013 and 13 June 2015 (traffic-restricted days) in the following analysis. Fig. 3 shows the diurnal variations of hourly mean temperature, relative humidity and wind speed for 15 (traffic-restricted day) and 22 June 2013 (normal weekend) and 13 (traffic-restricted day) and 14 June 2015 (normal weekend). The average meteorological conditions during 11:00–14:00 on 15 and 22 June 2013 (LIME1) and 14:00–18:00 on 13 and 14 June 2015 (LIME2) and the weather conditions for the four days at the sampling site also are summarized in Table 1. The period of 14:00–18:00 for LIME2 is selected in the following sections because the impact of traffic restriction on air pollution near the sampling site was found to lag behind the traffic control period (11:00–14:00), which will be presented in detail in Section 2.3. In addition, the diurnal variations of hourly mean SO₂, NO₂ and CO concentrations measured at Lanzhou Institute of Biological Products near our sampling site for the traffic-restricted days (15 June 2013 and 13 June 2015) and the normal weekend days (22 June 2013 and 14 June 2015) are also compared in Fig. 3, and the mean concentrations of the precursor gases during 11:00–14:00 (2013) and 14:00–18:00 (2015) on the two traffic-restricted days and the two normal weekend days are also given in Table 1.

It can be seen from Fig. 3 and Table 1 that the meteorological conditions were similar during 11:00–14:00 on 15 June (traffic-restricted day) and 22 June 2013, and were also similar during 14:00–18:00 on 13 June (traffic-restricted day) and 14 June 2015. Furthermore, the wind directions were almost identical between 11:00 and 14:00 on the two days for LIME1 and during 14:00–18:00 on the two days for LIME2 (data not shown). The gaseous pollutant concentrations during the traffic-affected period (11:00–14:00) of traffic-restricted days were significantly lower than those of normal weekend days, especially NO₂ concentrations for LIME1. The NO₂ mean concentration during 11:00–14:00 for the normal weekend day was 2.43 times higher than that for the traffic-restricted day. However, the SO₂ and NO₂ concentrations during the traffic-affected period (14:00–18:00) in the traffic-restricted day and normal weekend day for LIME2 were comparable, with only the CO mean concentration for the normal weekend day being 0.20 times higher than that for the traffic-restricted day. The above analyses indicate that the effect of traffic control on gaseous pollutants near the sampling site during LIME1 was more significant than that during LIME2. As other pollution sources, such as industry, were similar between traffic-restricted days and normal weekend days, the main difference was related to motor vehicle emissions. In the following, the effect of traffic control measures on urban air quality is also analyzed by comparing the particle concentrations and their size distributions on the two days for the period of 11:00–14:00 (LIME1) and 14:00–18:00 (LIME2) when meteorological conditions were comparable, while the influence of different traffic-restricted zones for LIME1 and LIME2 on air pollution near the sampling site is evaluated by comparing the decrease in particle concentrations in different size bins near the sampling site due to traffic restriction (see also Fig. 1).

2.3. Submicron particle concentrations and their size distributions

2.3.1. Particle concentrations

In order to better assess the effect of traffic control measures on urban particulate pollution in different size bins, particles in the size ranges 10–500 nm were divided into 5 size bins, i.e. 10–20 nm, 20–50 nm, 50–100 nm, 100–200 nm and 200–500 nm. Figs. 4 and 5 show the diurnal variations of hourly mean particle number concentrations in the 5 size bins for 15 June 2013 (traffic-restricted day) and 22 June 2013 (normal weekend) and 13 June 2015 (traffic-restricted day) and 14 June 2015 (normal weekend), respectively. The particle number concentrations in the 50–100 nm, 100–200 nm and 200–500 nm size bins on the normal weekend day were significantly higher than those on 15 June 2013 (traffic-restricted day) during the temporary traffic control period (07:00–14:00) for LIME1 (Fig. 4). However, the number concentrations of particles in the three size bins during the traffic control period on 13 June 2015 were much higher than those on the normal weekend day for LIME2 (Fig. 5). Thereafter, until 21:00 the size-resolved particle number concentrations and especially particles in the 100–200 nm range on the traffic-restricted day were lower than those on the normal weekend day, which may be related to the fact that more clean air was transported to the sampling site after controlling traffic emissions, due to the northwesterly prevailing winds within the city of Lanzhou (see also Fig. 1). In addition, the diurnal variations of particle number concentration in 10–20 nm and 20–50 nm ranges were inconsistent with those in other size bins, with the highest values around or after noon, when new particle formation events easily occurred due to stronger solar radiation at that time (Hamed et al., 2007; Zhao et al., 2015). The above analyses indicated that short-term traffic restriction can

<table>
<thead>
<tr>
<th>Date</th>
<th>Beijing time</th>
<th>WS (m/sec)</th>
<th>T (°C)</th>
<th>RH (%)</th>
<th>SO₂ (μg/m³)</th>
<th>NO₂ (μg/m³)</th>
<th>CO (mg/m³)</th>
<th>WC</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 June 2013</td>
<td>11:00–14:00</td>
<td>1.2 ± 0.3</td>
<td>24.0 ± 0.7</td>
<td>49.2 ± 2.8</td>
<td>15.5 ± 4.2</td>
<td>3.5 ± 0.6</td>
<td>0.3 ± 0.1</td>
<td>Cloudy</td>
</tr>
<tr>
<td>22 June 2013</td>
<td>14:00–18:00</td>
<td>1.1 ± 0.4</td>
<td>24.2 ± 1.6</td>
<td>42.1 ± 10.0</td>
<td>20.0 ± 6.5</td>
<td>15.5 ± 3.9</td>
<td>0.7 ± 0.3</td>
<td>Cloudy</td>
</tr>
<tr>
<td>13 June 2015</td>
<td>14:00–18:00</td>
<td>2.5 ± 0.2</td>
<td>26.0 ± 0.2</td>
<td>14.5 ± 0.8</td>
<td>9.8 ± 4.7</td>
<td>17.0 ± 4.2</td>
<td>0.9 ± 0.1</td>
<td>Cloudy</td>
</tr>
<tr>
<td>14 June 2015</td>
<td>11:00–14:00</td>
<td>3.1 ± 0.6</td>
<td>27.1 ± 0.2</td>
<td>20.4 ± 0.8</td>
<td>10.0 ± 3.2</td>
<td>16.8 ± 4.4</td>
<td>1.1 ± 0.2</td>
<td>Cloudy</td>
</tr>
</tbody>
</table>

WS: wind speed; T: temperature; RH: relative humidity; WC: weather conditions.
significantly improve urban air quality, and aerosol particles between 50 nm and 500 nm in the urban atmosphere markedly decreased due to traffic control. Furthermore, the air pollution near the sampling site greatly depended on the distance between the sampling site and traffic-restricted zones, and meteorological conditions such as wind directions.

The mean particle number and surface area concentrations in different size bins in the periods of 11:00–14:00 for LIME1 and 14:00–18:00 for LIME2 are shown in Table 2. The motor vehicle counts and meteorological conditions during the 14:00–18:00 period in the traffic-restricted day and normal weekend day for LIME2 were comparable (see Table 1 and Fig. 6). So, the impact of short-period traffic restriction during LIME2 on air pollution near the sampling site can be evaluated by comparing the particle concentrations during 14:00–18:00 on the two days. Traffic control measures can effectively reduce particles in the size ranges of 50–100 nm and 100–200 nm in the urban atmosphere (Table 2). The differences in particle number concentrations in the 50–100 nm range between normal weekend and traffic-restricted days for LIME1 and LIME2 were 3881.9 cm$^{-3}$ and 398.8 cm$^{-3}$, which were almost the highest among those in the five size bins, while the differences in particle surface area concentrations in the 100–200 nm range between the two days for LIME1 and

Fig. 4 – Diurnal variations of hourly mean particle number concentrations for different size bins (10–20 nm, 20–50 nm, 50–100 nm, 100–200 nm and 200–500 nm) for 15 June 2013 (traffic-restricted day) and 22 June 2013 (normal weekend). The thick black lines above x-axes represent the traffic control periods on 15 June 2013.
LIME2 were much higher than those in other size ranges. Additionally, for the period with similar meteorological conditions (11:00–14:00) for LIME1, the number and surface area concentrations of particles in the 100–200 nm range were (1567.8 ± 193.8) cm$^{-3}$ and (104.8 ± 11.8) μm$^2$/cm$^3$ on 15 June 2013 (traffic-restricted day), which were 67.2% and 65.0% lower than those on 22 June 2013 (normal weekend). However, for the period of 14:00–18:00 for LIME2, particle number and surface area concentrations in the 100–200 nm size range were (592.4 ± 134.9) cm$^{-3}$ and (35.0 ± 7.9) μm$^2$/cm$^3$ on 13 June 2015 (traffic-restricted day), which were 39.2% and 37.1% lower than those on 14 June 2015 (normal weekend). The air quality near the sampling site was more effectively improved during LIME1 than that during LIME2 due to traffic controls, indicating that the extent of the effect of traffic restriction on air pollution near the sampling site strongly depended on the distance between the relative orientation of the sampling site and traffic-restricted zones, as well as meteorological conditions such as wind direction.

Some meteorological variables, such as the ambient temperature and local wind conditions, have been found to be important factors controlling the number concentrations of submicron particles (Freutel et al., 2013; Hussein et al., 2006; Nicolás et al., 2009; Vakeva et al., 2000; Wehner and...
Wiedensohler, 2003; Zhao et al., 2015). In some European cities, size-fractionated particle number concentrations were evaluated on the basis of a regression model between particle number concentrations and meteorological variables (Hussein et al., 2006; Mølgaard et al., 2012, 2013). As seen from Fig. 7, the particle number concentrations (PNC) predicted by the regression model based on Eq. (3) were much higher than those measured in all size bins for LIME1 due to traffic restriction, while the predicted PNCs in 10–20 nm and 20–50 nm ranges were unexpectedly lower than those measured in the corresponding size ranges for LIME2, which may be related to the new particle formation events during LIME2 (see also Fig. 9).

Based on the regression model, the number concentrations of particles in the five size ranges were reduced by 8.8%–49.6% with the maximum reduction in the 50–100 nm range for LIME1, while they decreased by 14.3%–36.8% for LIME2, which were comparable to the results from the above analyses.

It is interesting to compare the above results for the Lanzhou International Marathon to the PM2.5 and PM10 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 PM2.5 and PM10 over Beijing, respectively. A 12% decrease in PM10 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, especially during LIME1, 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 compared to more developed regions in China. In addition, the topography of Lanzhou, which is 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 concentration in different size bins in the periods of 11:00–14:00 (2013) and 14:00–18:00 (2015) in traffic-restricted day and normal weekend.a

<table>
<thead>
<tr>
<th>Concentrations (nm)</th>
<th>Normal weekend (22 June 2013 14 June 2015)</th>
<th>Traffic-restricted day (15 June 2013 13 June 2015)</th>
<th>Reduction</th>
<th>Reduced percentages (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number (cm⁻³)</td>
<td></td>
<td></td>
<td>429.9</td>
<td>11.8</td>
</tr>
<tr>
<td>10–20</td>
<td>3640.9 ± 1079.6</td>
<td>3211.0 ± 2363.2</td>
<td>-58.2</td>
<td>-3.1</td>
</tr>
<tr>
<td>20–50</td>
<td>1903.2 ± 904.6</td>
<td>1961.4 ± 317.9</td>
<td>789.2</td>
<td>6.7</td>
</tr>
<tr>
<td>50–100</td>
<td>7850.1 ± 6493.3</td>
<td>5553.0 ± 696.7</td>
<td>2297.1</td>
<td>29.3</td>
</tr>
<tr>
<td>200–500</td>
<td>8449.4 ± 1330.0</td>
<td>2567.5 ± 807.4</td>
<td>3881.9</td>
<td>60.2</td>
</tr>
<tr>
<td>100–200</td>
<td>2025.4 ± 147.5</td>
<td>1626.6 ± 307.0</td>
<td>398.8</td>
<td>19.7</td>
</tr>
<tr>
<td>200–500</td>
<td>4780.9 ± 1801.4</td>
<td>1567.8 ± 193.8</td>
<td>3213.1</td>
<td>67.2</td>
</tr>
<tr>
<td>50–100</td>
<td>974.4 ± 51.3</td>
<td>592.4 ± 134.9</td>
<td>382.0</td>
<td>39.2</td>
</tr>
<tr>
<td>100–200</td>
<td>1090.3 ± 509.6</td>
<td>607.0 ± 95.2</td>
<td>483.3</td>
<td>44.3</td>
</tr>
<tr>
<td>200–500</td>
<td>1075 ± 9.6</td>
<td>92.1 ± 22.5</td>
<td>93.4</td>
<td>14.3</td>
</tr>
<tr>
<td>Surface area (μm²/cm³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10–20</td>
<td>3.7 ± 1.1</td>
<td>3.4 ± 2.4</td>
<td>0.3</td>
<td>8.1</td>
</tr>
<tr>
<td>20–50</td>
<td>61.2 ± 21.3</td>
<td>53.5 ± 25.4</td>
<td>7.7</td>
<td>12.6</td>
</tr>
<tr>
<td>50–100</td>
<td>24.4 ± 13.2</td>
<td>17.2 ± 2.6</td>
<td>7.2</td>
<td>29.5</td>
</tr>
<tr>
<td>200–500</td>
<td>1079 ± 28.1</td>
<td>39.4 ± 11.3</td>
<td>68.5</td>
<td>63.5</td>
</tr>
<tr>
<td>50–100</td>
<td>34.2 ± 1.8</td>
<td>25.7 ± 5.1</td>
<td>8.5</td>
<td>24.9</td>
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<tr>
<td>200–500</td>
<td>299.8 ± 116.3</td>
<td>104.8 ± 11.8</td>
<td>190.0</td>
<td>65.0</td>
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<tr>
<td>20–50</td>
<td>55.6 ± 2.8</td>
<td>35.0 ± 7.9</td>
<td>20.6</td>
<td>37.1</td>
</tr>
<tr>
<td>100–200</td>
<td>265.1 ± 125.6</td>
<td>148.3 ± 25.0</td>
<td>116.8</td>
<td>44.1</td>
</tr>
<tr>
<td>200–500</td>
<td>23.2 ± 2.2</td>
<td>21.2 ± 5.6</td>
<td>2.0</td>
<td>8.6</td>
</tr>
</tbody>
</table>

a The concentrations in the period of 14:00–18:00 (2015) for normal weekend and traffic-restricted day were showed with boldface; the values in the fifth column were difference of the concentrations between the third and fourth columns.

![Fig. 6 – Variations of motor vehicle counts in both travel directions at Donggang West Road in traffic-restricted day and normal weekend day. The thick black lines above x-axes represent the traffic control periods.](image)
In order to understand the impact of traffic control on size-resolved particle number concentrations in the urban atmosphere, Fig. 8 presents the average particle number, surface area and volume size distributions during 11:00–14:00 on the traffic-restricted day (15 June 2013) and the normal weekend day (22 June 2013) for LIME1 and 14:00–18:00 on the traffic-restricted day (13 June 2015) and the normal weekend day (14 June 2015) for LIME2. Particle concentrations in different size bins during LIME1 were much higher than those during LIME2 due to decreases in primary emissions from some industries and power plants during the period 2013–2015. Obvious discrepancies between these size distributions (15 vs. 22 June 2013; 13 vs. 14 June 2015) can be seen, indicating that the short-period traffic restriction greatly affected the particle size distributions at the sampling site. The differences in these size distributions between traffic-restricted days and normal weekend days for LIME1 were more significant than those between the two days for LIME2, which indicated that the effect of short-term traffic control on air quality around the sampling site depended more on the distance between the sampling site and traffic-restricted zones. The four PNSDs had a major peak in the 20–40 nm range due to the impact of new particle formation events that occurred mainly at or after noon. The PNSDs on the two normal weekend days (22 June 2013 and 14 June 2015) had weak peaks at ~100 nm, while the peak was missing on the two traffic-restricted days (15 June 2013 and 13 June 2015). The influence of traffic restrictions on the particle concentrations differed for different particle size ranges. The most affected size ranges for the number and surface area concentrations in the urban environment were in the 60–200 nm and 60–300 nm ranges, respectively. However, for the particle volume concentration, the most affected size range was 100–600 nm. The above results are in accordance with those found in another study. Generally, aerosol particles directly emitted from motor vehicles fall mainly in the ultrafine fraction ($D_p < 100$ nm) and especially the 40–60 nm range, while our study and the study by Cheng et al. (2008) found traffic restrictions also had a significant effect on accumulation mode particles, which was mainly because the sampling sites were located at 32 m and 20 m above the ground level for our study and the study by Cheng et al. (2008). So, the newly emitted Aitken mode particles from motor vehicles gradually grew to the accumulation mode through aerosol dynamic processes, such as intra- or inter-modal coagulation and condensation, as the particles were transported to the sampling site. Thus the size range most affected by traffic restriction for number concentration from our study was larger than that in other studies.

Additionally, the hourly mean PNSDs during the 2013 and 2015 Lanzhou International Marathon Events (LIME1 and LIME2) were fitted using a multivariate logarithm normal distribution to determine the effect of traffic restriction on the modal structure of PNSDs. As can be seen from Table 3, traffic control had the most significant effect on particle sizes ~ (107.0 ± 20.4) nm and ~ (72.4 ± 3.9) nm near the sampling site for LIME1 and LIME2, respectively. Furthermore, traffic restriction during LIME1 was more effective than that during LIME2 for improving the air quality near the sampling site, as the traffic-restricted zone for LIME1 was closer to the sampling site than that for LIME2.
In order to better evaluate the effect of traffic control measures on PNSDs in urban areas, diurnal variations of PNSDs on 22 June (normal weekend day) and 15 June 2013 (traffic-restricted day), and 14 June (normal weekend day) and 13 June 2015 (traffic-restricted day) are shown in Fig. 9. The number concentrations of nucleation mode particles abruptly increased around or after noon due to the occurrence of new particle formation events, and then the newly formed particles gradually grew to accumulation mode by some dynamic processes such as coagulation of particles. Additionally, the Aitken and accumulation mode particle number concentrations were high during nighttime to early morning on 22 June 2013 and 13 June 2015 due to the weak winds and poor diffusion conditions during nighttime, trapping the particles near the surface layer. Until noon, the severe particulate pollution was diluted with the development of the atmospheric boundary layer and increased wind speed near the ground surface.

3. Conclusions

Particle size distributions and meteorological data were measured simultaneously during June 2013 and June 2015 with the aim of investigating the effect of short-term traffic restriction on urban air quality, and especially submicron particle concentrations and their size distributions, taking advantage of the opportunity provided by implementation of strict traffic control measures during the 2013 and 2015 Lanzhou International Marathon Events (LIME1 and LIME2). To minimize the effect of weekly variation in traffic volume, meteorological conditions for weekends in June 2013 and 2015 were analyzed, and 22 June 2013 and 14 June 2015 were selected as normal weekend days for comparison with 15 June 2013 and 13 June 2015 (traffic-restricted days) in this study. In addition, the influence of the different traffic-restricted zones for LIME1 and LIME2 on air quality near the sampling site was evaluated by comparing the decreases in particle concentrations in different size bins near the sampling site due to traffic restriction. This study will provide a basis for implementation of future urban particulate pollution control measures. The main conclusions are given below.

The particles in the size ranges of 50–100 nm and 100–200 nm in the urban atmosphere can be considerably decreased by short-period traffic control measures. Such short-duration sectorial restriction measures implemented periodically have the potential to improve air quality in urban areas. The impact of traffic restriction on air pollution near the sampling site lagged behind the traffic control period for LIME2. For a period with similar meteorological conditions (11:00–14:00) for LIME1, the number and surface area concentrations of particles in the range 100–200 nm on 15 June 2013

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**Table 3** – The multivariate logarithm normal distribution fitting parameters of hourly averaged particle number size distributions in the period of 11:00–14:00 (2013) and 14:00–18:00 (2015) in traffic-restricted day and normal weekend.

<table>
<thead>
<tr>
<th>Date</th>
<th>Beijing time</th>
<th>Mode 1</th>
<th>Mode 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N/cm−3</td>
<td>GSD</td>
<td>CMD/nm</td>
</tr>
<tr>
<td>15 June 2013</td>
<td>11:00–14:00</td>
<td>19760.3 ± 7031.5</td>
<td>1.4 ± 0.0</td>
</tr>
<tr>
<td>22 June 2013</td>
<td>11:00–14:00</td>
<td>22428.8 ± 9300.0</td>
<td>1.5 ± 0.2</td>
</tr>
<tr>
<td>13 June 2015</td>
<td>14:00–18:00</td>
<td>4846.6 ± 747.8</td>
<td>1.3 ± 0.04</td>
</tr>
<tr>
<td>14 June 2015</td>
<td>11:00–14:00</td>
<td>9092.6 ± 5573.9</td>
<td>1.4 ± 0.04</td>
</tr>
</tbody>
</table>

GSD: geometric standard deviation; CMD: count median diameter.
traffic-restricted day) were 67.2% and 65.0% lower than those on 22 June 2013 (normal weekend day). However, for the period of 14:00–18:00 for LIME2, the particle number and surface area concentrations in the 100–200 nm range on 13 June 2015 (traffic-restricted day) were 39.2% and 37.1% lower than those on 14 June 2015 (normal weekend day). The effect of traffic restriction on air pollution near the sampling site depended on the distance between and relative orientation of the sampling site and traffic-restricted zones, and meteorological conditions such as wind direction.

The influence of traffic restrictions on the particle concentrations differed for different particle sizes. The size range most affected by traffic restriction was 60–200 nm and 60–300 nm for number and surface area concentrations in the urban environment, respectively, while for the particle volume concentration it was 100–600 nm. The results from multivariate logarithm normal distribution fitting indicated that traffic control had the most significant effect on particle sizes (~ (107.0 ± 20.4) nm and ~ (72.4 ± 3.9) nm near the sampling site for LIME1 and LIME2, respectively. Furthermore, traffic restriction during LIME1 was more effective than that during LIME2 for improving air quality near the sampling site, as the traffic-restricted zone for LIME2 was closer to the sampling site than that for LIME1. Therefore, future short-term control of traffic emission should be adopted during some important events in urban areas to solve traffic congestion and protect human health. Furthermore, the distance between the relative orientation of the areas of concern and the traffic-restricted roads and the predominant wind direction in a specific city should be taken into account in formulating future traffic control measures.

Acknowledgments

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REFERENCES


