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The impact of transportation control measures on emission reductions during the 2008 Olympic Games in Beijing, China

Yu Zhou [a], Ye Wu [a], Liu Yang [a], Lixin Fu [a], Kebin He [a], Shuxiao Wang [a], Jiming Hao [a,*], Jinchuan Chen [b], Chunyan Li [b]

[a] *Department of Environmental Science and Engineering, and State Key Joint Laboratory of Environment Simulation and Pollution Control, Tsinghua University, Beijing 100084, PR China*

[b] *Beijing Transportation Research Center, Beijing 100055, PR China*

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ABSTRACT

Traffic congestion and air pollution were two major challenges for the planners of the 2008 Olympic Games in Beijing. The Beijing municipal government implemented a package of temporary transportation control measures during the event. In this paper, we report the results of a recent research project that investigated the effects of these measures on urban motor vehicle emissions in Beijing. Bottom–up methodology has been used to develop grid-based emission inventories with micro-scale vehicle activities and speed-dependent emission factors. The urban traffic emissions of volatile organic compounds (VOC), carbon monoxide (CO), nitrogen oxides (NO_x) and particulate matter with an aerodynamic diameter of 10 μm or less (PM_{10}) during the 2008 Olympics were reduced by 55.5%, 56.8%, 45.7% and 51.6%, respectively, as compared to the grid-based emission inventory before the Olympics. Emission intensity was derived from curbside air quality monitoring at the North 4th Ring Road site, located about 7 km from the National Stadium. Comparison between the emission intensity before and during the 2008 Olympics shows a reduction of 44.5% and 49.0% in daily CO and NO_x emission from motor vehicles. The results suggest that reasonable traffic system improvement strategies along with vehicle technology improvements can contribute to controlling total motor vehicle emissions in Beijing after the Olympic Games.

1. Introduction

Urban traffic emissions are a major source of air pollution in many cities in China (Fu et al., 2001). The rapid private motorization trend has aggravated the challenge to urban air quality improvement in some large cites (He et al., 2002; Walsh, 2007). Researchers have identified mobile sources as one of the most important contributors to air pollution in Beijing (Hao et al., 2001; Hao and Wang, 2005). On-road measurements have also found road traffic to be a major cause of ultra-fine particles in Beijing (Westerdahl et al., 2009). The total vehicle population in Beijing has almost tripled to more than 3 million during the last 10 years (BSB, 2008) and the increasing trend toward private vehicle ownership is expected to continue (Huo et al., 2007).

In order to reduce the impact of vehicles on urban air quality, the municipal government of Beijing has adopted many vehicle emission control strategies since 1999 (Hao et al., 2006). A summary of motor vehicle emission standards recently adopted in Beijing is shown in Table 1. Euro IV was adopted for all new light-duty vehicles (LDV) and some new heavy-duty diesel engines (HDDE) before the opening of the Olympic event. Beijing upgraded its annual Inspection and Maintenance (I/M) program from a two-speed idle test to an Acceleration Simulation Mode (ASM) test in 2003. The sulfur content of vehicle fuel has been reduced below 50 ppm since the beginning of 2008. Other control programs include an in-use vehicle emission labeling system along with downtown travel restrictions, a compressed natural gas (CNG) bus program, extensive retrofitting, and more.

Since 2001, when Beijing won the bid to host the 2008 Olympics, air quality for the competition was a major concern as particulate matter and ozone were expected to be the most important air quality problems (Streets et al., 2007). Cities holding mega-events such as the Olympic Games usually try to achieve good air quality and traffic conditions by means of a variety of strategies including temporary vehicle use controls. The experience gained during the 2004 Athens Olympic Games (Frantzeskakis and Frantzeskakis, 2006), the 2002 Busan Asian Games (Lee et al., 2005) and the 1996 Atlanta Olympic Games (Friedman et al., 2001) have demonstrated

* Corresponding author. Tel.: +86 10 62782195; fax: +86 10 62773650.
E-mail address: hjm-den@tsinghua.edu.cn (J. Hao).

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Table 1
Summary of vehicle emission standards adopted in Beijing.

	Euro I	Euro II	Euro III	Euro IV
LDV[a]	1999-1-1	2003-1-1	2005-12-30	2008-3-1
HDDE[b]	2000-1-1	2003-1-1	2005-12-30	2008-7-1[c]

[a] Light-duty vehicles.
[b] Heavy-duty diesel engines.
[c] Only for public fleets including buses, postal and sanitation vehicles.

Table 2
Influence of transportation control measures on the main factors of traffic emissions.

Strategies	Factors influencing traffic emissions		
	Fleet composition	Speed	Total activity
Travel restriction by odd–even license		√	√
Truck operational restrictions	√		√
Removal of yellow labeled vehicles	√		√

that temporary traffic management strategies can be successful not only to improve urban traffic conditions but also to improve air quality. The hospital visitation rate investigated in Busan before and after the Summer Asian Games showed that the fourteen consecutive days of traffic volume control were related to a significant decrease in hospitalization for childhood asthma (Lee et al., 2007).

Beijing held the 2008 Olympic Games from August 8 to August 24, 2008. As a densely populated city with more than 16 million residents and 3 million motor vehicles, urban traffic and ambient air quality improvement were the two important challenges. In June 2008, the local government of Beijing promulgated temporary transportation control measures to be implemented during the event. Private vehicles could only operate on odd or even days depending on the last digit of their license plates. Seventy percent of government vehicles were ordered off the road during the event. Trucks could only operate inside the 6th Ring Road from midnight to 6 am unless they were issued special passes. Most vehicles with yellow environmental labels (usually referred as “high emitting vehicles”) were banned from the roads throughout Beijing.

This research classified the study periods as “before” and “during” the Beijing Olympic Games to evaluate the effect of temporary transportation control measures adopted throughout the event. Field traffic flow monitoring and a calibrated transportation simulation platform based on geographic information system (GIS) have been applied in this study to achieve road network activity and operational speed in urban Beijing with a 1 km × 1 km resolution. A bottom–up methodology was applied to develop motor vehicle emission inventories before and during the Games. The effectiveness of transportation control measures has been evaluated by comparing these grid-based emission inventories. The emission reduction benefit has also been evaluated by the emission intensity derived from reverse modeling of curbside air quality monitoring results.

2. Methodology

2.1. Traffic modeling

The urban area of Beijing is divided into 2055 grid cells, each of which is 1 km × 1 km. An urban transportation simulation platform (Li et al., 2008) based on TransCAD has been applied in this study to estimate the vehicle kilometers traveled (VKT) and the average speed in these cells. Annual traffic flow monitoring, travel demand management policies (Wang et al., 2008b) as well as personal trip mode investigation has been applied as basic inputs to the simulation platform. Simulated road link activities are further transformed into grid-based activities. Motor vehicles identified in traffic volume monitoring and modeling have been classified into six categories including LDV, taxis, light-duty trucks (LDT), heavy-duty trucks (HDT), buses and heavy-duty vehicles (HDV). Daily and peak hour VKT for each vehicle category and average speed have been estimated by the system. Information provided in each grid cell includes geographic coordinates, road length, average speed and daily VKT for each vehicle category.

The Beijing Transportation Research Center conducted a special investigation on continuous traffic monitoring on 132 road links in urban Beijing before and during the Olympic Games to estimate the variation in transportation activity on a geographic scale. The results of this investigation, as well as routine spatial and temporal origin–destination flow investigations for residents in Beijing, were used to calibrate the transportation control scenarios in the simulation platform.

2.2. Emission factor development

MOBILE5B-China, a localized model based on US Environmental Protection Agency (US EPA) MOBILE5b and PART5 was applied in this study to estimate speed-dependent vehicle emission factors. MOBILE5B-China was first developed in 1994 (Fu et al., 1997). Fleet configuration, operational characteristics and internal basic emission factors have been modified based on local research findings (Fu et al., 1999, 2000; Hao et al., 2000, 2001; Hu et al., 2006; Tang et al., 2000; Wu et al., 2002). In the most recent update to adapt this model to be used in Beijing, a portable emission measurement system (PEMS) was used to develop speed-dependent emission correction factors (Hu et al., 2004; Wang et al., 2008a; Yao et al., 2007), and crossroad remote sensing was applied to monitor the fleet emission status (Zhou et al., 2007). The application of these real-world emission measurement technologies helped to improve the reliability of MOBILE5B-China in Beijing. The model has already been used in several studies to derive emission factors for developing motor vehicle emission inventories for Beijing (Hao et al., 2000, 2001; Hao and Wang, 2005).

In this study, a special module has been developed for estimating the effect of transportation control measures on the average vehicle emission factor. The emission factor was mainly influenced by the control measures adopted during the Games in two ways.

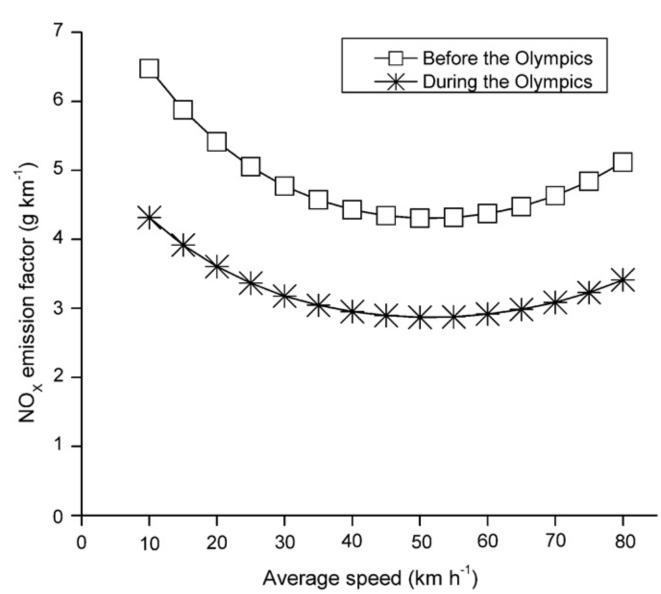

Fig. 1. Speed-dependent average NO_x emission factors for HDT before and during the Olympics.

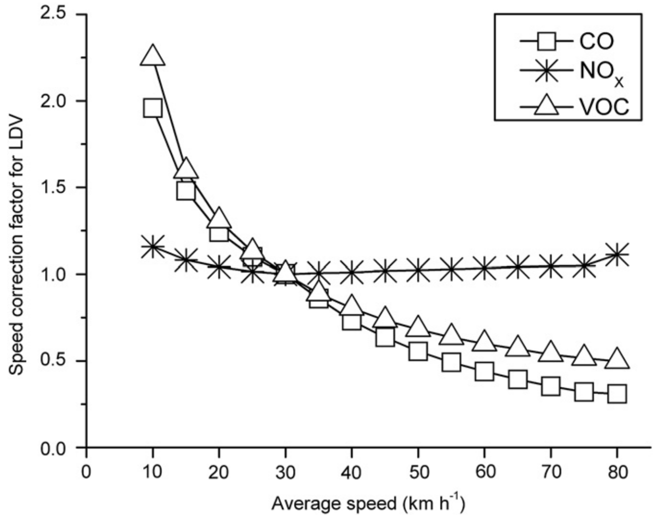

Fig. 2. Speed correction factor for emission factors for LDV.

First, vehicle operation parameters such as speed have been affected by traffic flow control, which is one of the most important factors affecting emissions. Second, fleet technology configurations have also been changed as yellow labeled vehicles were banned throughout Beijing and strict operational restrictions were also placed on trucks. Table 2 lists the influence of the detailed transportation control measures on the major factors related to traffic emissions. The special module has been setup to consider the co-effects of vehicle operational parameters and fleet configurations on average emission factors.

The overall vehicle fleet change has been taken into consideration to evaluate its effect on the average emission factor. The registration distribution of yellow labeled vehicles in Beijing has been investigated within the local I/M database. Green environmental labels have been issued in Beijing to gasoline vehicles meeting at least Euro I and diesel vehicles meeting at least Euro III requirements. Other vehicles were issued yellow environmental labels. The average age of the light-duty fleet and heavy-duty fleet operating in urban area of Beijing during the Olympics was reduced by 0.48 and 3.55 years, respectively, as yellow labeled vehicles were mostly banned while the Olympic Games were underway.

By the end of 2007, about 347 000 yellow labeled vehicles were still in use in Beijing, which was 11% of the total fleet. The fleet composition of HDT has been changed the most because diesel

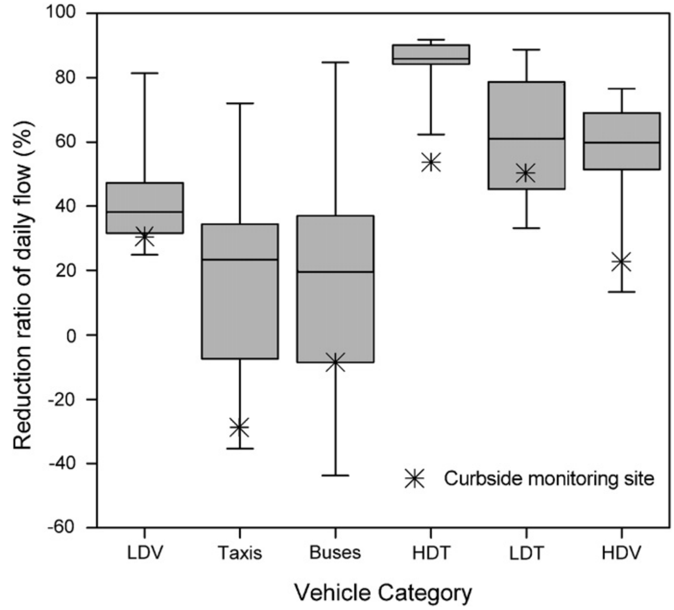

Fig. 4. Daily traffic flow reduction ratio monitored during the Olympics. Line within box: Median value; Top line of box: third quartile; Bottom line of box: first quartile; Top outlier: maximum; Bottom outlier: minimum.

trucks can only get a green label if they can meet at least Euro III emission standards in Beijing, which has been enforced since the end of 2005. Fig. 1 shows the change of speed-dependent average NO_x emission factors for HDT (up to 80 km h^{-1}) before and during the Beijing Olympics. The average emission factor of HDT has been reduced by 33% during the Games. It should be noted that not all the trucks with yellow environmental labels were banned. The municipal government has issued special passes to some yellow labeled trucks to guarantee the progress of important projects.

The speed-dependent emission factors for VOC, CO and NO_x for each vehicle class are calculated within MOBILE5B-China. Fig. 2 shows the relationship between the emission correction factor and the average speed for LDV relative to the baseline speed of 30 km h^{-1}. It shows that the VOC and CO emission factors have a significant relationship with speed, and generally decrease with increasing speeds. The NO_x emission factors, which are less sensitive to speed changes, follow a parabolic path and tend to decrease to 35 km h^{-1} and then increase.

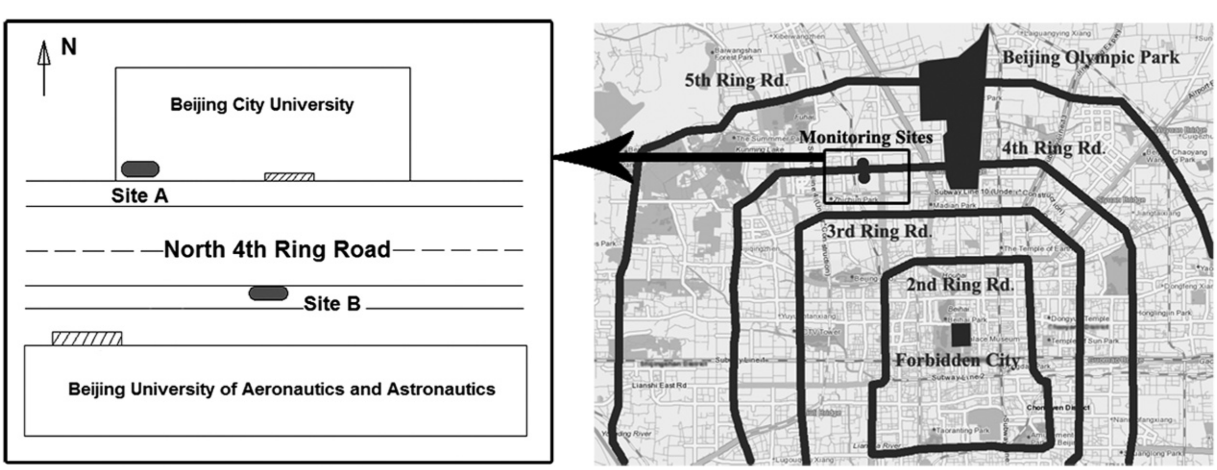

Fig. 3. Location of curbside monitoring sites.

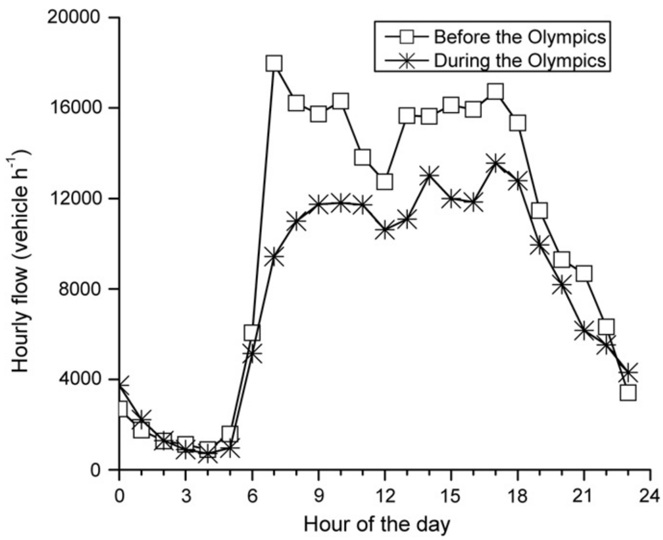

Fig. 5. Variation of weekday traffic flow at the North 4th Ring road before and during the Olympics.

Real-world vehicle emission measurements on a fixed route have been carried out with PEMS in Beijing before and during the Games. The details of the measurements can be found in a report (Tsinghua University, 2008). PEMS measurements on 5 light-duty gasoline vehicles show that the average reduction of their CO, HC and NO_x emission factors were 26.8%, 28.7% and 0.8%, respectively, during the Games as the trip average speed increased from 26.8 km h^{-1} to 34.6 km h^{-1}. This agrees with the modeling output in this study. As shown in Fig. 2, the modeled CO, VOC and NO_x emission factor reductions for LDV for the same speed increment are 21.8%, 21.1% and 1.1%, respectively. The real-world measurements again show CO and VOC are sensitive to the change of vehicle speed, but not NO_x. Also, the similarity in the decreased level of the three air pollutants from both measurements and modeling work confirms the good performance of our MOBILE5B-China emission factor model.

2.3. Emission reduction benefit evaluation

2.3.1. Grid-based emission inventory development

Traditional top–down inventory methodology applied uniform emission factors for the same vehicle category, or emissions were allocated using the spatial surrogates from a larger geographic scale. This methodology may not reflect the real vehicle emission conditions on a local scale. A more accurate vehicle emission inventory can be developed using a bottom–up approach that relies on more detailed emission factors and vehicle activity data from a travel demand model (TDM). TDM used for transportation planning can provide more thorough information on the spatial distribution of roadway types, vehicle activity, and speed along those roads.

In order to quantify the emission reduction benefit of the transportation control measures adopted, a bottom–up methodology has been applied in this study to build emission inventories for the urban areas before and during the Games. Grid-based vehicular speeds from traffic modeling are used to obtain emission factors for each vehicle type in each grid cell. This approach is physically representative of realistic traffic conditions in each grid cell of the urban area. Emissions in each grid cell were calculated by multiplying the VKT and speed-dependent emission factors for the six vehicle categories:

$$Q_c^P = \sum_{i=1}^{6} EF_{i,c}^P \times VKT_{i,c} \tag{1}$$

where, Q_c^P is the emissions of pollutant P in cell c, g; $EF_{i,c}^P$ is the speed-dependent emission factor of pollutant P for vehicle category i in cell c, g km^{-1}; $VKT_{i,c}$ is the total vehicle kilometers traveled of vehicle category i in cell c, km. The emissions were summed over all grid cells to obtain total urban emissions. The details of this bottom–up methodology for developing motor vehicle emission inventory please refer to our another paper (Wang et al., 2009).

2.3.2. Emission reduction benefit derived from curbside monitoring

Two sampling sites were set up on the sidewalks of the North 4th Ring Road, about 26 m from the road centerline. Measurements were taken at 2 m above the ground. The detailed location of the sites is shown in Fig. 3, which is approximately 7 km from the Olympic Park. The monitoring was performed before the Olympics (June 22–July 5, 2008) and during the Olympics (July 28–August 22, 2008). Hourly traffic volume was counted throughout the monitoring periods

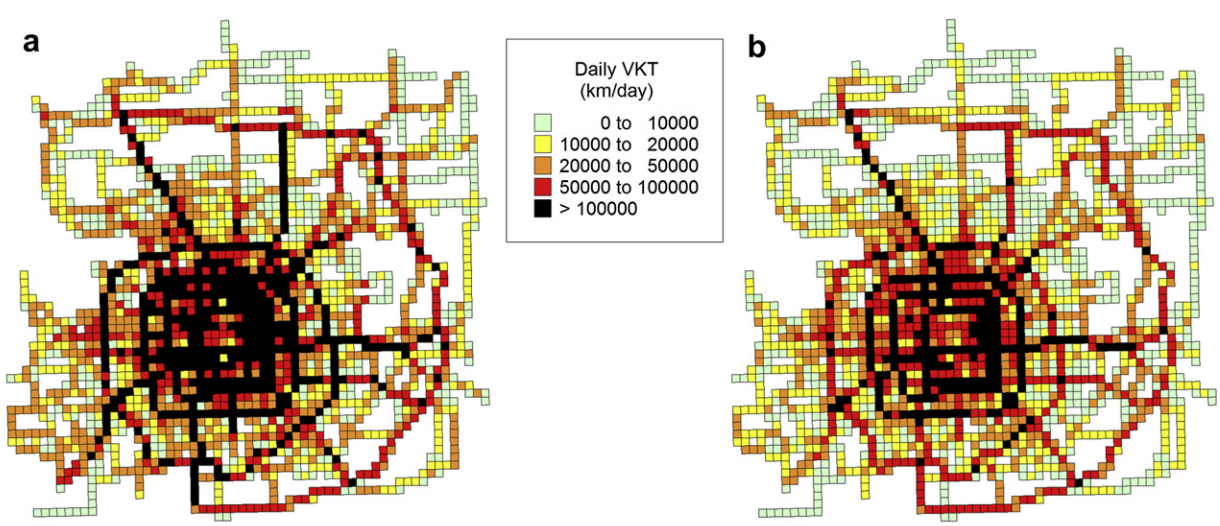

Fig. 6. Daily VKT for urban Beijing before (a) and during (b) the Olympics.

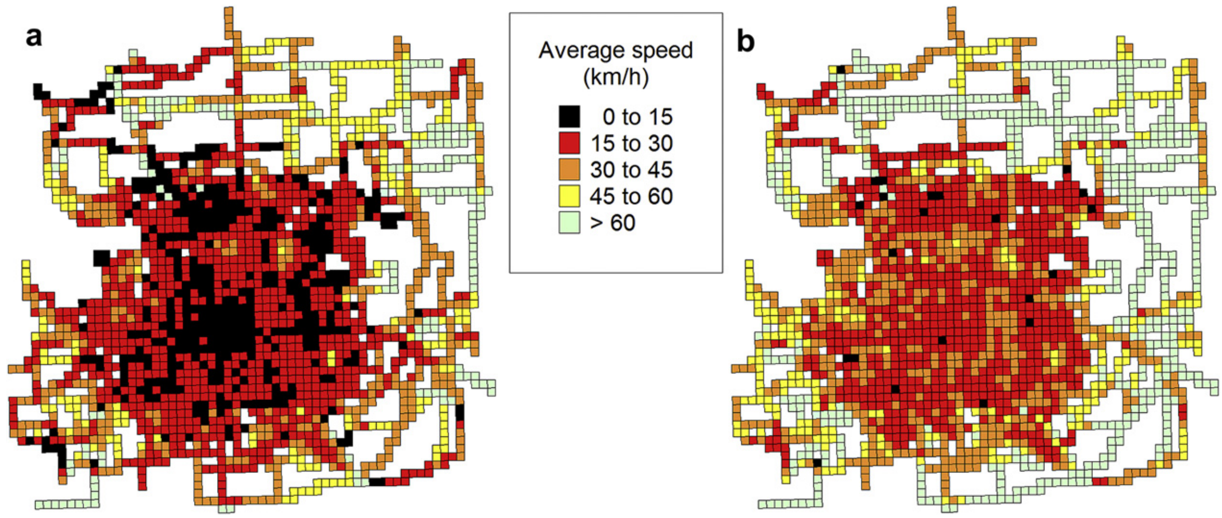

Fig. 7. Daily average speed for urban Beijing before (a) and during (b) the Olympics.

based on continuous video taping from the crossover above the road. Hourly data for CO and NO_x concentrations were provided by Thermo 48i and 42i, respectively, at both sites along the sidewalks. A portable weather station was set up near the air quality monitoring instruments to record second-by-second ambient temperature, wind speed, wind direction, humidity and atmospheric pressure.

Line-source dispersion models are usually used for the calculation of air quality based on known theoretical relationships between emissions, meteorology parameters and air pollutant concentrations. Street pollution models like OSPM (Oanh et al., 2008; Palmgren et al., 1999) and CALINE4 (Gramotnev et al., 2003) have been combined with curbside air quality measurements to estimate in-situ emission intensity or emission factors. For the dispersion of non-reactive or slowly reactive vehicle exhaust gases at short distances, chemical transformations can be disregarded. Eq. (2) may be used for calculations of hourly emissions from traffic, provided that both receptor and background concentrations are available from in-field monitoring.

$$Q = \frac{(C_r - C_{bg})}{F_d} \quad (2)$$

where C_r and C_{bg} are the receptor concentration with the contribution from road traffic and the background concentration from sources other than motor vehicles in the specified road link, Q is the traffic emissions at the road link, and F_d is a factor describing dispersion processes under certain meteorological conditions. In this study, only those monitoring data with the wind direction perpendicular or nearly perpendicular to the road were selected for CALINE4 simulation. Thus, in this case the difference between the monitored concentrations at both sides of the road can be used as the indicator of the direct contribution from the road traffic (Oanh et al., 2008). The dispersion factor F_d is given by a line-source pollution model, in our case, CALINE4. The model was originally developed for calculating CO concentrations (in ppm) from a road (Benson, 1992). A scaling factor has been applied in this study to adapt CALINE4 for NO_x. The inputs of the model include road geometry, meteorological parameters (wind speed, wind direction and its standard deviation, temperature, atmospheric stability class and mixing height), background concentration, and receptor information. The model also requires the input of road link emission intensity, which becomes the target for reverse application of CALINE4 in this study.

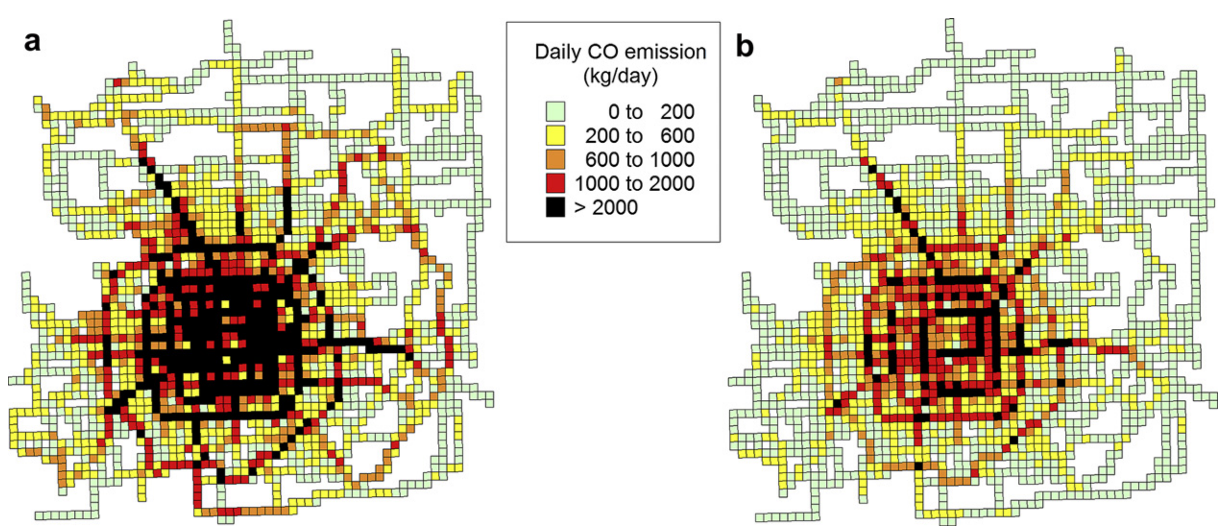

Fig. 8. Grid-based daily vehicle emission inventory for CO in urban Beijing before (a) and during (b) the Olympics.

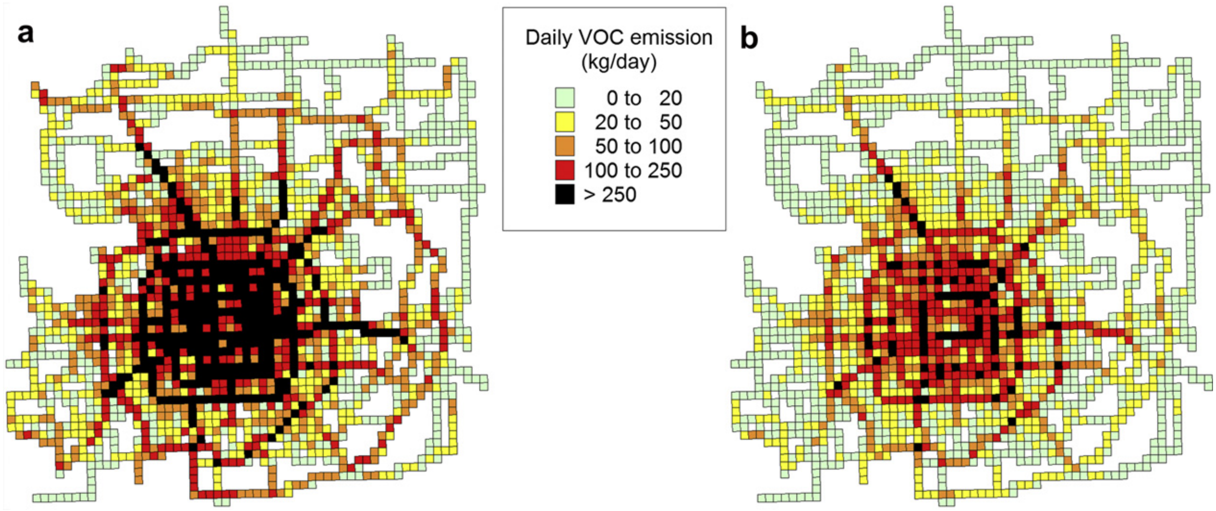

Fig. 9. Grid-based daily vehicle emission inventory for VOC in urban Beijing before (a) and during (b) the Olympics.

Considering the possible systematic errors in the line-source dispersion model, the reduction ratio instead of the absolute value of derived emission intensity has been used in this study for further analysis. The emission reduction ratio derived from curbside monitoring was compared with those achieved from the bottom–up inventory modeling to show the emission reduction benefits of the transportation control measures.

3. Results and discussion

3.1. *Traffic flow effect*

Fig. 4 shows the reduction ratio in daily traffic flows for each vehicle category from continuous traffic monitoring at 132 road links before and during the Olympics. Vehicle categories other than taxis and buses show a significant decrease in traffic flow due to the temporary traffic control measures. HDT had the highest reduction ratio because of the strict traffic intervention measures on its operational area and on yellow labeled vehicles. Increasing bus and taxi flow has been observed at some road links inside the downtown area or close to the Olympic venues.

The flow change at the curbside monitoring sites was also shown in Fig. 4. Daily flow of LDV and HDT has been reduced by 30.1% and 53.8%, respectively, during the Games. The flow of taxis and buses has been increased by 29.6% and 9.8%, respectively. The monitoring sites are close to the main Olympic venues, which could be the reason for higher public transportation demand. Two Olympic-specific lanes and increasing trips to the Olympic Park have also counteracted the effect of traffic control. Fig. 5 shows the weekday hourly flow monitored at the North 4th Ring Road. Hourly flow data has shown that most traffic reduction was achieved during the daytime. Traffic flow between midnight and 3:00 shows a temporarily slight increase because the municipal government issued a supplemental rule suspending license-based traffic control measures during these three hours.

Daily VKT and average speed distributions derived from the transportation simulation platform are shown in Figs. 6 and 7. Total urban VKT has been reduced by 32.0% during the Games. The average speed weighed by grid VKT has been increased from 25 km h^{-1} to 37 km h^{-1} during the Games. It has been found that a significant proportion of the grids are located in the speed bins lower than 30 km h^{-1} in downtown areas before the Games.

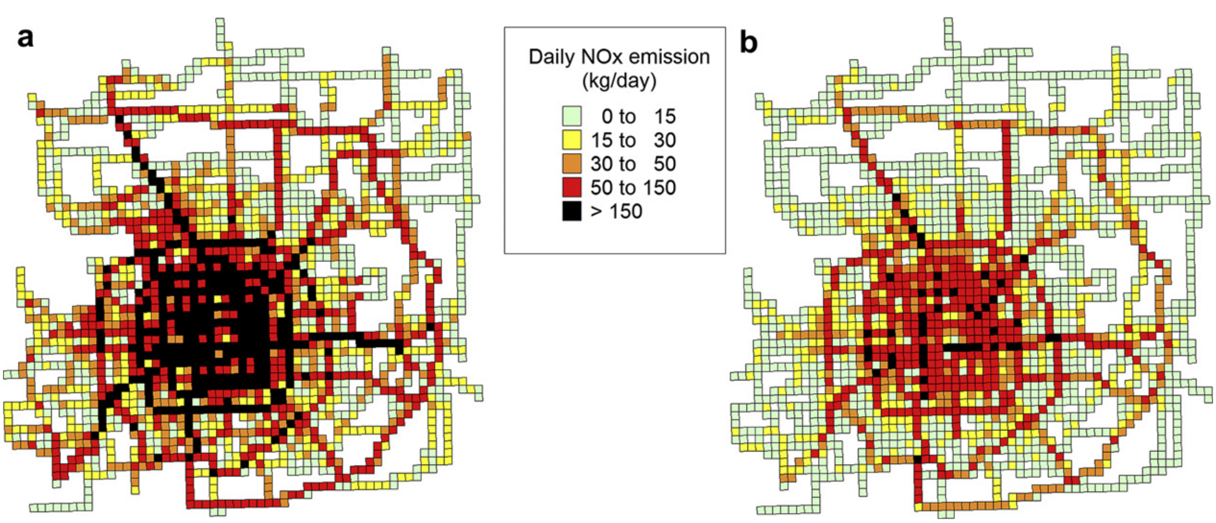

Fig. 10. Grid-based daily vehicle emission inventory for NO_x in urban Beijing before (a) and during (b) the Olympics.

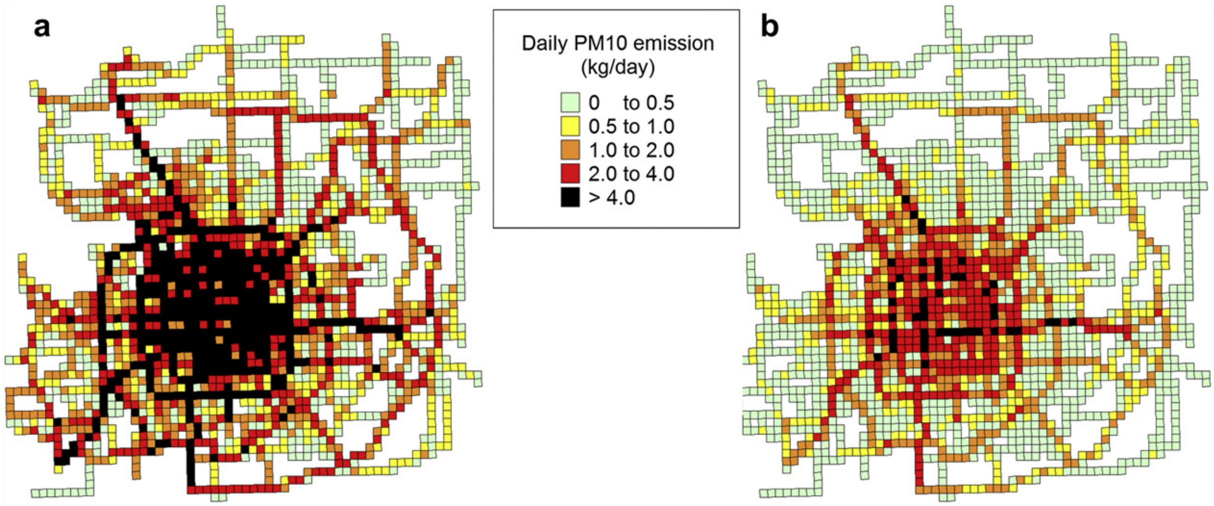

Fig. 11. Grid-based daily vehicle emission inventory for PM_{10} in urban Beijing before (a) and during (b) the Olympics.

3.2. Bottom–up emission inventory

Based on the grid-based vehicle activities acquired from the calibrated transportation simulation platform and the speed-dependent emission factors acquired from MOBILE5b-China, the bottom–up methodology described in Eq. (1) was used to develop mobile source emission inventories. The grid-based vehicle emission inventories for CO, VOC, NO_x and PM_{10} in the Beijing urban area before and during the Olympic Games are shown in Figs. 8–11, respectively.

The figures show that the distribution of vehicle emissions in Beijing's urban area are more concentrated in the urban core area with higher population density and travel demand. The radial arterials and exit highways with heavy traffic also contribute to high emission intensity in these grids. Grid-based emissions can be aggregated to calculate the total vehicular emissions. Table 3 shows a comparison between the total urban vehicle emissions before and during the Games.

Table 3
Daily urban motor vehicle emissions of Beijing in tons before and during the 2008 Olympics.

	VOC	CO	NO_x	PM_{10}
Before the Olympics	371	2993	282	15.9
During the Olympics	165	1293	153	7.7
Emission reduction	55.5%	56.8%	45.7%	51.6%

Improved traffic efficiency and reduced fleet average age helped Beijing achieve a higher mobile source emission reduction than lower VKT. More significant reductions have been found in VOC and CO emissions because they are more sensitive to average speed as shown in Fig. 2. Based on the daily grid-based inventory before the Olympics, trucks have contributed 21.6% and 40.3% of total motor vehicle NO_x and PM_{10} emissions in urban Beijing, respectively. Because of the higher contributions of trucks to PM_{10} emissions, strict controls on them during the Olympic Games achieved a higher reduction in total PM_{10} emissions than NO_x emissions.

3.3. Emission intensity at the North 4th Ring Road

Fig. 12 shows hourly average downwind CO and NO_x concentration monitored at the North 4th Ring Road site before and during the Olympics. Receptor CO and NO_x concentration was reduced by 31.2 ± 7.4% and 34.9 ± 13.9%, respectively. The largest CO reduction

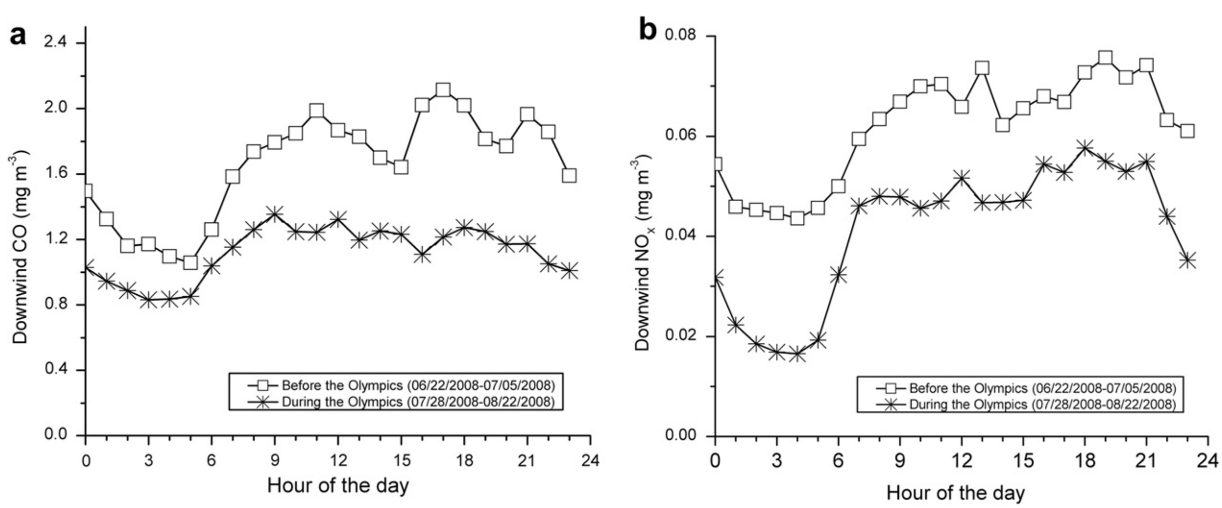

Fig. 12. Hourly average downwind CO (a) and NO_x (b) concentrations monitored at the North 4th Ring Road before and during the Olympics.

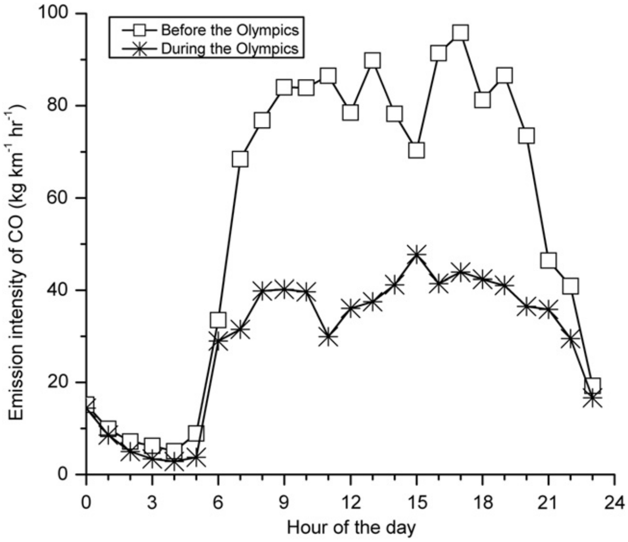

Fig. 13. Hourly CO emission intensity at the North 4th Ring Road.

(~42%) was observed from 16:00 to 19:00, one of the two rush-hours. The largest NO_x reduction (~59%) was observed during the midnight, which may be mainly attributed to the sharp decrease of diesel truck emission at night. Long before the beginning of the Olympics, the Beijing Traffic Management Bureau was already enforcing a routine traffic control regulation that trucks were only allowed to operate inside the 4th Ring Road between 23:00 and 6:00. Trucks were the most important NO_x and PM contributor at night before the Olympics. The banning of yellow labeled vehicles during the Olympics affected diesel trucks the most on its traffic flow and average emission factors among all vehicle categories, especially at night. This resulted in a higher reduction in NO_x than CO during the midnight.

The Beijing Environmental Protection Bureau (EPB) reports air pollution level of PM_{10}, SO_2 and NO_2 in Beijing through its public domain (http://www.bjee.org.cn/api/). As the Beijing EPB does not provide CO and NO_x data, we used the air pollution index (API) of NO_2 for comparison. The average API of NO_2 in Beijing was reduced by 46.2% during this same period. The reduction level is somewhat higher than our NO_x monitoring results (34.9% reduction on average); however, both results show that the NO_x emission reductions during the Olympic Games are significant.

CO and NO_x emission intensity has been derived from curbside air quality monitoring with the reverse application of the CALINE4 software package. Fig. 13 shows hourly CO emission intensities before and during the Olympic event derived from curbside air quality monitoring. A higher reduction was also observed in the daytime. Table 4 lists the daily emission intensities derived from the monitoring at the North 4th Ring Road site. CO and NO_x emissions have been reduced by 44.5% and 49.0%, respectively. As a comparison, daily CO and NO_x emission intensity calculated from grid modeling at the cell where curbside monitoring site locates was reduced by 51.0% and 50.1%, respectively, during the Games. The reduction ratio agrees well between the emission intensity derived from grid modeling and field monitoring.

Table 4
Emission intensity derived from reverse modeling at the North 4th Ring Road before and during the Olympics.

	Unit	Before the Olympics		During the Olympics	
		CO	NO_x	CO	NO_x
Daily emission intensity	$kg\ km^{-1}\ day^{-1}$	1473.4	71.4	817.7	36.4
Daily traffic flow	$vehicle\ day^{-1}$	242 761		189 760	

4. Conclusions

Our estimation of the grid-based emission inventories has found that motor vehicle emissions of VOC, CO, NO_x and PM_{10} inside urban Beijing during the 2008 Olympics have been reduced by 55.5%, 56.8%, 45.7% and 51.6%, respectively, as compared to the emission inventory before the Olympics. The effectiveness of transportation control measures adopted during the 2008 Olympics has been demonstrated. The co-effects of traffic flow reduction, traffic congestion improvement and the banning of high emitting vehicles have helped reduce the direct emissions from motor vehicles by more than one half. Curbside emission intensity derived from air quality monitoring further confirms that such co-effects have magnified the emission reduction benefit from VKT reduction. The experience gained in achieving good air quality during the Olympics suggests that besides vehicle technology improvement, the traffic system can also be improved to attain lower total emissions. Such strategies may include travel demand management and improvement of the public transportation system.

For a city with a rapid growth of its private motor vehicles, traditional macro-scale emission inventory methodology based on vehicle population and macro-scale activity parameters like annual mileage per vehicle may cause a substantial error when estimating traffic emissions in Beijing. A bottom–up methodology which integrates a traffic demand model calibrated with annual traffic monitoring may provide a more reliable inventory in a fast-changing city like Beijing.

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