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Traffic-related air pollution modeling during the 2008 Beijing Olympic Games: The effects of an odd-even day traffic restriction scheme

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ABSTRACT

An integrated urban air quality modeling system was applied to assess the effects of a short-term odd-even day traffic restriction scheme (TRS) on traffic-related air pollution in the urban area of Beijing (UAB) before, during and after the 2008 Olympic Games. Using traffic flow data retrieved from an on-line traffic monitoring system, concentration levels of CO, PM_{10}, NO_2 and O_3 on the 2nd, 3rd, 4th Ring Roads (RR) and Linkage Roads (LRs), the main roads distributed around the UAB, were predicted for the pre- (10th-19th, July), during- (20th July-20th September) and post-TRS (21st-30th, September) periods. A widely used statistical framework for model evaluation was adopted, the dependences of model performance on time-of-the-day and on wind direction were investigated, and the model predictions turned out reasonably satisfactory. Results showed that daily average concentrations on the 2nd, 3rd, 4th RR and LRs decreased significantly during the TRS period, by about 35.8, 38.5, 34.9 and 35.6% for CO, about 38.7, 31.8, 44.0 and 34.7% for PM_{10}, about 30.3, 31.9, 32.3 and 33.9% for NO_2, and about 36.7, 33.0, 33.4 and 34.7% for O_3, respectively, compared with the pre-TRS period. Hourly average concentrations were also reduced significantly, particularly for the morning and evening peaks for CO and PM_{10}, for the evening peak for NO_2, and for the afternoon peak for O_3. Consequently, both the daily and hourly concentration level of CO, PM_{10}, NO_2 and O_3 conformed to the China National Ambient Air Quality Standards Grade II during the Games. In addition, notable reduction of concentration levels was achieved in different regions of Beijing, with the traffic-related air pollution in the downwind northern and western areas relieved most significantly. The TRS policy was therefore effective in alleviating traffic-related air pollution and improving short-term air quality in Beijing during the Games.

1. Introduction

Beijing, the capital city of China and the host city of the 2008 Olympic Games, has a population of over 18 million and meanwhile suffers serious air pollution. Particularly, PM_{10}, with its high daily and annual concentrations on average, remained the primary air pollutant in Beijing since 2000 (Beijing EPB, 2009). The PM_{10} annual average concentration in Beijing has been staying at a high level, fluctuating around 160 $\mu g/m^3$ during the period of 2001–2006. Despite a decrease in the following two years as a result of various control measures, the annual average concentration in 2008 still exceeded 120 $\mu g/m^3$ (Beijing EPB, 2009), which was about 20% higher than the China National Ambient Air Quality Standards (CNAAQS) Grade II (100 $\mu g/m^3$) and six times the latest World Health Organization (WHO) Air Quality Guidelines (WHO, 2005). Of the major anthropogenic sources of atmospheric particulate matters in the mega cities (e.g. Beijing, Shanghai, Guangzhou) in China, on-road vehicular emissions is an important and perhaps the fastest growing one (Chan and Yao, 2008). Recent source apportionment studies have revealed that gasoline-related emissions (the combination of gasoline exhaust and gas vapor) contributed 52% of the volatile organic compound (VOC) emissions in Beijing in the summer time of 2005 (Song et al., 2007), and automobile contributed about 27% of the yearly average PM_{10} emissions in Beijing for the period of 2001–2003 (Zhang et al., 2007). Moreover, traffic congestion and traffic-related air pollution has been a serious issue in urban Beijing with the vehicle population increasing dramatically at a daily rate of over one thousand, reaching over 3.5 million by the end of 2008 (BTMB, 2008). The booming economic prosperity and substantial increase of vehicle population have resulted in the exponential growth of vehicular emissions of CO, PM_{10}, NO_x and VOC (Cai and Xie, 2007). A Sino-Italian environmental protection program based on Intelligent Traffic System and Traffic Air Pollution (ITS-TAP) monitoring system was launched between the Italian Ministry for the Environment and Territory and Beijing Municipal Government in 2005 (Mazzon, 2008), to improve effectively the air quality and traffic condition in Beijing. Moreover, the Beijing Municipal Government had committed to the international society that air quality in Beijing would be improved and be better than before, satisfying the CNAAQS and WHO Air Quality Guidelines during the 2008 Olympic Games. To fulfill the air quality commitment during the Games, the government implemented a list of stringent control measures for natural, industrial, agricultural, construction, biomass burning and

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residential emissions (Wang et al., 2009a). To reduce vehicular emissions, five particular control schemes were placed, including issuance of new automobile emissions standards; decommissioning of high emissions vehicles, buses and taxis; recovery of fuel vapors at gas stations and from tankers; banning of non-local heavy duty diesel trucks within the Beijing Administrative area; and control of emissions from small stationary diesel generators (COC, 2008). Particularly, an odd-even day traffic restriction scheme (TRS), a control measure that was demonstrated effective in Atlanta (Fang et al., 2009), was enforced for two months from 20th July to 20th September, 2008, to help ease congestion and improve air quality during the Olympics and Paralympics. Consequently, the UAB had a distinct characteristic of source emissions compared to usual periods, as emissions from sectors other than on-road vehicles were expected to decrease significantly, with on-road vehicles becoming the major source for air pollution in that particular period, due to their huge population even after the TRS policy was in effect. Different studies have been performed related to the air quality impact assessment of traffic control measures, such as a four-day traffic control experiment during the Sino-Africa Summit in 2007 (Westerdahl et al., 2009), on-road black carbon emission reduction (Wang et al., 2009a) and emission restrictions from various sectors including on-road vehicles (Wang et al., 2009b). As the control measures for sectors other than on-road vehicles were constantly in effect and remained the same for the pre-, during- and post-TRS periods, this study intends to seize this unique opportunity to study the effects of the TRS policy on traffic-related air pollution, by adopting an integrated urban-scale modeling system with online-monitored data of on-road traffic flows at a high temporal resolution of two seconds from the ITS-TAP system, and based on the analysis of the short-term variation of traffic-related air pollution in response to the TRS policy.

Geographical Information System (GIS)-based approach (Nejadkoorki et al., 2008), regression-based technique (Briggs et al., 2000) and land-use regression (LUR) model (Ryan and LeMasters, 2007) have been utilized to characterize traffic-related air pollution in urban areas. While these techniques proved applicable and particularly specialized in characterizing the spatial patterns and exposure and health effects of traffic-related air pollution, model-based simulation has been one of the major tools for air quality assessment, air pollution diagnosis and evaluation of pollution control policies at the urban, regional and global levels (Chiquetto and Mackett, 1995; Namdeo et al., 2002; Gokhale and Raokhande, 2008; Goncalves et al., 2009). ADMS-Urban, a well tested and intensively validated quasi-Gaussian dispersion air quality model developed by Cambridge Environmental Research Consultants, (Carruthers et al., 1994, 1999, 2000; CERC, 2009b), has been widely used for regulatory purposes in the UK (Bennett and Hunter, 1997; Riddle et al., 2004) and used in the investigation and assessment of air pollution mitigation and control strategies in many cities of China (McHugh et al., 2005). Moreover, ADMS-Urban has some features especially tuned to obtain best performance on urban areas (CERC, 2003), which is mostly due to the up to date parameterization of atmospheric boundary layer structure based on the Monin-Obukhov length and the boundary layer height, and is also due to the specific algorithms for the Gaussian concentration distributions in stable and neutral conditions, but non-Gaussian vertical distributions in convective conditions, to take into account the skewed structure of the vertical component of the turbulence. Furthermore, it is particularly convenient to set up on-road emissions, and to define the road source geometry and the output grids accurately, by means of the nested GIS tool (Arcview or Mapinfo). Thus, ADMS-Urban was adopted in this study to simulate and assess the effects of the TRS policy on traffic-related air pollution in the UAB before, during and after the 2008 Beijing Olympic Games. Firstly, the model performance was evaluated with the measurement data from a typical roadside air quality monitoring site. Subsequently, the ambient concentrations of CO, PM_{10}, NO_2 and O_3 at a height of 1.5 meters were calculated for the periods of pre-TRS (10th–19th July, 2008), during-TRS (20th July- 20th September, 2008) and post-TRS (21st-30th September, 2008), respectively, based on traffic flows on the dense network of the 2nd, 3rd and 4th Ring Roads (RR) and Linkage Roads (LRs, including major intercity expressways and intercity roads between RRs), followed by an investigation of the temporal and spatial variation of traffic-related air pollution in the UAB in response to the TRS policy.

2. Methods and data

2.1. Description of study domain, urban and background monitoring sites, and receptors

The study domain, the main UAB, covers the 2nd, 3rd and 4th RR, which were 32.7, 48.0 and 65.3 kilometers long, and had six, six to eight and eight lanes, respectively, as well as the major LRs mainly having eight lanes. These simulated roads were the main roads of UAB with the majority of traffic flows. About 62% of Beijing is mountainous area located in the west, the north and the northeast. Thus, the local wind field has a clear diurnal variation, with northeasterly and southeasterly winds dominating in the daytime and southeasterly wind dominating in the night. The Chegongzhuang (CGZ) air quality monitoring site, which was located five kilometers west of the West 2nd RR and was on a corner (geographical coordinates: 39°55'53"/N, 116°19'38"/E) of a crossroad where a five-lane North-South oriented street and a six-lane West-East oriented street intersected with high traffic flows, had a sampling height of about 4.5 meters from ground and had been well maintained with routine calibration of the measurement equipment by the Beijing Municipal Environmental Monitoring Centre during the Games as a traffic monitoring site. This site provided the model evaluation data of hourly concentrations of CO, $PM_{10,}$ NO_2 and O_3 for 10th-20th July and 10th-20th August, 2008. Moreover, to assure the accuracy of the model predictions, it is important to account for significant underlying, or 'background' levels of pollutants in the atmosphere, and to account for any sources of pollution that are not otherwise included in the model run. Therefore, we selected the background diurnal profiles of CO, PM_{10} and NO_2 for the whole evaluation period from Dingling (DL) air quality monitoring station, which was approximately 42 kilometers north from the CGZ air quality monitoring site and was in the suburban area with very few motor vehicles. For O_3, a major secondary air pollutant, we used the measurement data from Shangdianzi (SDZ) regional atmospheric background monitoring site, one of the four regional atmospheric background monitoring sites in China and located about 150 kilometers northeast of Beijing (40°39'/N, 117°07'/E). Measurement data from the SDZ background measurement site are free of influence by motor vehicles and represent the background characteristic of atmospheric constitutes in northern regions of China including Beijing (Liu et al., 2007). Due to the lack of the measurement data from this site for the summer in 2008, we have adopted the reported measurements in SDZ for the summer periods in 2004 (Liu et al., 2006a) and in 2006 (Liu et al., 2008) as a substitute, considering the generally accepted understanding of the relatively constant feature of background concentrations within a short time period. Finally, we used the averaged daily profiles for July, August and September based on the 2004 and 2006 data from SDZ as the background O_3. To reflect the variation of traffic-related air pollution in response to the TRS policy, 31 representative receptors located along the 2nd, 3rd and 4th RR and the LRs were chosen, where the hourly concentrations of CO, PM_{10}, NO_2 and O_3 were simulated for the pre-TRS, during-TRS and post-TRS periods. The study domain, which included the road network of Beijing, the locations of the CGZ, DL and SDZ air quality monitoring sites and the receptors representative of regions in different directions, is shown in Fig. 1.

2.2. ADMS-Urban model set up

Various parameters required determination for running ADMS-Urban. These parameters mainly included surface roughness, the