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Contribution of motor vehicle emissions to surface ozone in urban areas: A case study in Beijing

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Key words: Surface ozone, air pollution, motor vehicle emissions, source contribution, Beijing

SUMMARY

Surface ozone (O₃) pollution, a critical environmental challenge facing government agencies at all levels, is becoming more and more serious in China, especially in rapidly developing urban areas like Beijing. However, in China, few studies have evaluated the contribution of various pollution sources to surface O₃, e.g. motor vehicles. In this paper, we combined a non-linear model with an analysis of motor vehicle emissions of NO_x and VOCs in an integrated approach to estimate the contribution of motor vehicle emissions to surface O₃. The model showed that, in urban areas of Beijing in 2000, the contribution of motor vehicle emissions to surface O₃ was 45.9%, and that elimination of 20.0% of motor vehicle emissions will lead to a 7.4% reduction in surface O₃, while elimination of 20.0% of NO_x or VOC emissions from motor vehicles will result in a 5.0% and 2.5% decline, respectively, in surface O₃. In addition, elimination of 10,000 t of NO_x from motor vehicles results in the same reduction in surface O₃ as elimination of 25,631 t of VOCs. Thus, controlling NO_x emissions from motor vehicles is an effective way to control surface O₃ pollution in the study area.

INTRODUCTION

Surface ozone (O₃), a secondary pollutant produced from photochemical reactions involving nitrogen oxides (NO_x) and volatile organic compounds (VOCs), plays an important role in regional climate, human health (Zhang *et al.* 2006; Wu *et al.* 2008) and vegetation (Feng *et al.* 2003; Wang and Mauzerall 2004; Wang *et al.* 2005a, 2007; Tu *et al.* 2007). By the middle of this century, urban air pollutants will increase surface O₃ by at least 25%, and could be two to three times higher in China (Long *et al.* 2005). With rapid economic development and

unprecedented changes in land use, anthropogenic emissions of NO_x and VOCs have doubled during the past 11 years in China, and have reached the same level as in the USA and Europe (Elliott *et al.* 1997; Aunan *et al.* 2000; Wang *et al.* 2007). Due to tremendous efforts to control stationary pollution sources and to move heavy industries from urban areas in large Chinese cities in the past 20 years, stationary source pollutant emissions have steadily declined. However, with the acceleration of urbanisation and continuous enlargement of city

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Table 1 Growth of GDP, population and motor vehicles in Beijing

Category	1995	2000	2005
GDP (billion Yuan)	150.8	316.1	688.6
Population (10,000)	1251.1	1363.6	1538.0
Motor vehicles (10,000)	80.4	136.5	246.1

size, city traffic demands and motor vehicles are rapidly rising, therefore the share of motor vehicle emissions in urban air pollution has increased (Wang *et al.* 2005b). In recent years, motor vehicle emissions have accounted for 40–90% of VOCs and 45–60% of NO_x emissions in typical Chinese cities (Walsh 2007).

Beijing has an urban area of 1040 km² and a population of more than 10 million. With the rapid growth of GDP and population, motor vehicles in Beijing nearly doubled every 5 years between 1995 and 2005 (Table 1). At present, mobile sources contribute 64% of NO_x and 52% of VOCs emissions (Walsh 2007). One of the more detrimental consequences of such rapid growth in vehicle volumes is the impact on the environment, particularly on air quality. Episodes of high surface O₃ concentrations now occur frequently at many monitoring stations in Beijing in summer. The highest hourly concentration was 384 µg/m³ in 1998, 2.4 times the second grade of the National Ambient Air Quality Standard (160 µg/m³). Surface O₃ has become the main pollutant on 25% of the monitoring days in Beijing (Liu *et al.* 2005).

In China, few studies have been carried out on the contribution of motor vehicle emissions to surface O₃. In the USA and Europe, a non-linear model has been used to connect NO_x and VOCs emissions to surface O₃ concentrations to estimate the contribution of motor vehicle emissions (Schwing *et al.* 1980; Murphy *et al.* 1999). Here, we investigate the relationship between motor vehicle emissions and surface O₃, and extend the non-linear model proposed by Delucchi and McCubbin (1996) to evaluate the contribution of motor vehicle emissions to surface O₃ in urban areas of Beijing in 2000. We also discuss surface O₃ variations in different scenarios of motor vehicle emission eliminations to examine effective ways to reduce surface O₃.

METHODOLOGY

Model description

The simplest way to model non-linear O₃ formation is to assume a universal non-linear relationship between O₃ levels and VOC and NO_x emissions (Merz *et al.* 1972; Schwing *et al.* 1980; Delucchi and McCubbin 1996). The equation is shown as follows:

$$Ozone = k \cdot (VOCs)^A \cdot (NO_x)^B \quad (1)$$

where *Ozone* is the concentration of surface O₃; *k* is a constant; *VOCs* and *NO_x* represent the emission amounts of VOCs and NO_x, respectively; exponents *A* and *B* represent the sensitivity of surface O₃ to VOCs and NO_x, respectively.

Because different sources of VOC and NO_x emissions have different contributions to VOCs and NO_x concentrations, weights are assigned to different emission sources to reflect this importance. So Equation 1 can be rewritten as Equation 2:

$$Ozone = k \cdot \left(\sum_{i=1}^n P_{vi} \cdot W_{vi} \right)^A \cdot \left(\sum_{i=1}^n P_{ni} \cdot W_{ni} \right)^B \quad (2)$$

where *P_{vi}* and *P_{ni}* represent the percentage of VOCs and NO_x, respectively, from source *i*; *W_{vi}* and *W_{ni}* weigh the contribution of source *i* to VOCs and NO_x, respectively.

In this paper the sources are divided into two groups: motor vehicles and other sources (for detail see Table 2). Therefore, Equation 2 can be further rewritten as Equation 3:

$$Ozone = k \cdot (P_{v1} \cdot W_{v1} + P_{v2} \cdot W_{v2})^A \cdot (P_{n1} \cdot W_{n1} + P_{n2} \cdot W_{n2})^B \quad (3)$$

Table 2 Emission sources and related proportions of VOCs and NO_x in Beijing

Source	Type	VOCs (%)	NO _x (%)
Motor vehicles	Gasoline passenger car	46	35
	Light duty gasoline truck		
	Heavy duty gasoline vehicle		
	Motorcycle		
Other sources	Petrol evaporation	23	–
	Industrial processes	–	27
	Coal consumption	–	26
	Biogenic emissions	–	–

Source: adapted from Hao *et al.* (2005) and Wang and Li (2002)

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where P_{v1} and P_{v2} are the percentage of VOCs emission from motor vehicles and from other sources, P_{n1} and P_{n2} are the percentage of NO_x emissions from motor vehicles and from other sources, W_{v1} and W_{v2} weigh the contribution of motor vehicles and other sources to VOCs concentration, W_{n1} and W_{n2} weigh the contribution of motor vehicles and other sources to NO_x concentration, respectively.

So, if all the VOCs and NO_x from motor vehicle emissions were eliminated, the surface O_3 would decrease to *Ozone'*, described in Equation 4 as follows:

$$\text{Ozone}' = k \cdot (P_{v2} \cdot W_{v2})^A \cdot (P_{n2} \cdot W_{n2})^B \tag{4}$$

where *Ozone'* is the surface O_3 concentration when VOCs and/or NO_x emissions change.

The contribution of motor vehicles to surface O_3 can be estimated from Equation 5:

$$Cm = 1 - \frac{\text{Ozone}'}{\text{Ozone}} \tag{5}$$

where *Cm* is the contribution of motor vehicle emissions to surface O_3 .

Estimation of weights for VOCs and NO_x from different sources

The weights for motor vehicle emissions and other source emissions for VOCs and NO_x concentrations are defined in Equation 6, adapted from Lu *et al.* (2006) and Hao *et al.* (2005) (Table 3).

$$W_i = \frac{Cb_i}{E_i} \tag{6}$$

where W_i is the weight for VOCs or NO_x emissions from source *i* to VOCs or NO_x concentrations; Cb_i is the contribution of source *i* to VOCs or NO_x concentrations; *E* is VOCs or NO_x emissions from source *i*.

Determination of the exponents A and B

The exponents *A* and *B* represent O_3 sensitivity to VOCs and NO_x – defined formally as the percentage change in O_3 divided by the percentage change in emissions of VOCs or NO_x . Wang and Li (2002) reported that if VOCs from motor vehicle emissions were eliminated in 2000, surface O_3 would decrease by 15.2% in urban areas of Beijing. Based on these data, exponent *A* was estimated to be 0.19 from Equations (3), (4) and (5). In areas of the US, where ozone is more sensitive to NO_x emissions than to VOCs emissions, the modelled ozone sensitivity to VOCs ranged from 0.09 to 0.63, while the sensitivity to NO_x ranged from –0.17 to 0.43 (Delucchi and McCubbin 1996). In Beijing, due to a VOCs/ NO_x ratio above 100, O_3 is also more sensitive to NO_x emissions than to VOC emissions (Ma and Zhang 2000). This suggests that in the non-linear function of Beijing, exponent *B* is larger than exponent *A*. Typically, O_3 sensitivity to VOCs or NO_x emissions is between 0.2–0.7 (Delucchi and McCubbin 1996). This suggests that exponent *B* is mostly 0.20 to 0.43. Therefore, the average value, 0.32, was chosen for exponent *B* in our model.

RESULTS

Contribution of motor vehicle emissions to surface ozone

Using the non-linear model based on proportion and weight for VOCs and NO_x (Table 3), the contribution of motor vehicle emissions to surface O_3 was estimated to be 45.9% in urban areas of Beijing in 2000.

Table 3 Weighting for different VOCs and NO_x emission sources

Source	Precursor	Emission		Contribution (Cb)	Weight	Year	References
		Proportion	Amount (t)				
Motor vehicles	VOCs	0.46 (P_{v1})	84772	0.62	1.35 (W_{v1})	2002	Lu <i>et al.</i> 2006
	NO_x	0.35 (P_{n1})	118118	0.74	2.11 (W_{n1})		
Other sources	VOCs	0.54 (P_{v2})	139000	0.38	0.70 (W_{v2})	1999	Hao <i>et al.</i> 2005
	NO_x	0.65 (P_{n2})	163000	0.26	0.40 (W_{n2})		

Table 4 Surface ozone variations through different scenarios of elimination of VOCs and/or NO_x from motor vehicle emissions

Scenario	VOCs elimination		NO _x elimination		Surface ozone reduction (%)
	Ratio (%)	Volume (t)	Ratio (%)	Volume (t)	
1	20		20%		7.4
2	0		20%		5
3	20		0%		2.5
4		0		10,000	1.1
5		10,000		0	0.4

Variations in surface ozone in different scenarios

Eliminating the same percentage or amount of NO_x from motor vehicle emissions would result in higher reduction in surface O₃ than that of VOCs (Table 4). Further analysis shows that eliminating 10,000 t of NO_x from motor vehicle emissions results in the same reduction in surface O₃ as eliminating 25,631 t of VOCs (Table 4).

DISCUSSION

Based on the above estimates, the share of surface O₃ from motor vehicle emissions in urban areas of Beijing was nearly 50% in 2000. Our results also show that elimination of NO_x from motor vehicle emissions could result in higher surface O₃ reductions than that of VOCs. Due to the lower emission height and concentrated spatial distribution, VOCs and NO_x emissions from motor vehicles have higher weights than from ambient VOCs and NO_x, and from O₃ than other sources (Hao *et al.* 2005). Thus, the weights of different emission sources of VOCs and NO_x were integrated into the non-linear model, providing more reasonable results than those derived from linear functions (Mao *et al.* 2001). Moreover, due to the fewer parameters in

the simple non-linear model, it is more suitable for dealing with incomplete data in areas like Beijing. However, this non-linear model is actually so simple that it might give considerable uncertainties or errors due to the lack of any meteorological or chemical detail. The deficiency in this study was that the estimation of exponent *B* was obtained not from a local study of Beijing, but from studies of US urban areas. Due to lack of surface O₃ monitoring data, the results could not be validated in this paper. Despite the limitations, this study suggests that in rapidly developing urban areas in China, like Beijing, motor vehicles have become the dominant contributor to surface O₃, and that eliminating NO_x emissions from motor vehicles is the most effective way to control surface O₃ pollution in the study area.

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