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

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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 NOₓ 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 NOₓ 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 NOₓ from motor vehicles results in the same reduction in surface O₃ as elimination of 25,631 t of VOCs. Thus, controlling NOₓ 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 (NOₓ) and volatile organic compounds (VOCs), play an important role in regional climate, human health (Zhang et al. 2006; Wu et al. 2008) and vegetation (Feng et al. 2003; Wang and Maierrell 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 NOₓ 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...
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 40–80% of VOCs and 45–60% of NOx 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 NOx 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 NOx 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.

<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
<th>VOC (%)</th>
<th>NOx (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor vehicles</td>
<td>Gasoline passenger car</td>
<td>46</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Light duty gasoline truck</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heavy-duty gasoline truck</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Motorcycle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other sources</td>
<td>Petrol evaporation</td>
<td>23</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Industrial processes</td>
<td>–</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Coal consumption</td>
<td>–</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Biogenic emissions</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Source: adapted from Hao et al. (2005) and Wang and Li (2002)
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 NOx 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 NOx concentration, respectively.

So, if all the VOCs and NOx from motor vehicle emissions were eliminated, the surface O3 would decrease to $O_3'$ described in Equation 4 as follows:

$$O_3' = k P W P W_{vv}$$  \hspace{1cm} (4)

where $O_3'$ is the surface O3 concentration when VOCs and/or NOx emissions change.

The contribution of motor vehicles to surface O3 can be estimated from Equation 5:

$$C_m = 1 - \frac{O_3'}{O_3}$$  \hspace{1cm} (5)

where $C_m$ is the contribution of motor vehicle emissions to surface O3.

**Table 3 Weighting for different VOCs and NOx emission sources**

<table>
<thead>
<tr>
<th>Source</th>
<th>Emission</th>
<th>Proportion</th>
<th>Amount (t)</th>
<th>Contribution (G)</th>
<th>Weight</th>
<th>Year</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor vehicles</td>
<td>VOCs</td>
<td>0.46 ($P_{v1}$)</td>
<td>84772</td>
<td>0.62</td>
<td>1.35</td>
<td>2002</td>
<td>Lu et al. 2006</td>
</tr>
<tr>
<td></td>
<td>NOx</td>
<td>0.35 ($P_{n1}$)</td>
<td>118118</td>
<td>0.74</td>
<td>2.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other sources</td>
<td>VOCs</td>
<td>0.54 ($P_{v2}$)</td>
<td>159900</td>
<td>0.58</td>
<td>0.70</td>
<td>1999</td>
<td>Hao et al. 2005</td>
</tr>
<tr>
<td></td>
<td>NOx</td>
<td>0.65 ($P_{n2}$)</td>
<td>160300</td>
<td>0.26</td>
<td>0.40</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Determination of the exponents A and B**

The exponents $A$ and $B$ represent $O_3$ sensitivity to VOCs and NOx – defined formally as the percentage change in $O_3$ divided by the percentage change in emissions of VOCs or NOx. 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 NOx emissions than to VOC emissions, the modelled ozone sensitivity to NOx ranged from 0.09 to 0.63, while the sensitivity to NOx ranged from −0.17 to 0.43 (Delucchi and McCubbin 1996).

In Beijing, due to a VOCs/NOx ratio above 100, $O_3$ is more sensitive to NOx 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 NOx 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 NOx (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.
Variations in surface ozone in different scenarios

Eliminating the same percentage or amount of NOx 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 NOx 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 NOx 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 NOx emissions from motor vehicles have higher weights than from ambient VOCs and NOx, and from O3 than other sources (Hao et al. 2005). Thus, the weights of different emission sources of VOCs and NOx 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 NOx emissions from motor vehicles is the most effective way to control surface O3 pollution in the study area.

ACKNOWLEDGEMENTS

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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>VOC elimination</th>
<th>NOx elimination</th>
<th>Surface ozone reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ratio (%)</td>
<td>Volume (t)</td>
<td>Ratio (%)</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>20%</td>
<td>7.4</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>20%</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>0%</td>
<td>2.5</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>10,000</td>
<td>1.1</td>
</tr>
<tr>
<td>5</td>
<td>10,000</td>
<td>0</td>
<td>0.4</td>
</tr>
</tbody>
</table>


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