On-road diesel vehicle emission factors for nitrogen oxides and black carbon in two Chinese cities

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A B S T R A C T

Nitrogen oxides (NOx) and black carbon (BC) emission factors (EF) of 440 on-road diesel trucks were determined by conducting on-road chasing studies in Beijing and Chongqing, China, in the winter 2010. NOx and BC EF distributions are reported. The median NOx EFs for trucks sampled on level roads in Chongqing and Beijing are 40.0 and 47.4 g kg-fuel −1, respectively. The median BC EFs are 1.1 and 0.4 g kg-fuel −1 in Chongqing and Beijing, respectively. In addition, a clear downward trend of BC EFs of on-road diesel trucks sampled in Beijing since 2008 is observed. Moreover, Beijing-registered trucks had the lowest BC EFs among the entire sample. These observations appear to reflect the effectiveness of emission standard and fuel quality standard implemented in Beijing (China IV) and nationwide (China III) in reducing BC (and likely overall particulate matter) emission. However, NOx EFs for Beijing-registered trucks did not show lower value than those from other regions. Unlike black carbon, there is no clear correlation between emission controls and NOx emissions from the sampled on-road trucks. Further analysis shows that trucks with high BC EFs do not usually have high NOx EFs, and vice versa, indicating that the current emission standards implemented in Beijing and nationwide have only limited impact on NOx emissions control. Therefore, effective multi-pollutant control strategies and in-use compliance programs are imperative to reduce the overall emissions from the transportation sector.

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1. Introduction

The transportation sector has gradually become a dominant contributor to the already high air pollution levels in China due to the rapid growth in vehicle population (Fu et al., 2001; Hao et al., 2000, 2001; Walsh, 2007). In large Chinese cities such as Beijing, Shanghai and Guangzhou, emissions of nitrogen oxides (NOx) from motor vehicles accounted for 41%—70% of total urban NOx pollution in 2002 (Yi et al., 2007). Diesel and gasoline exhaust was shown to account for 8% of fine particulate matter (PM2.5) in Beijing on annual basis in 2000 (Zheng et al., 2005) and 15% during the summer time in 2004 (Song et al., 2007).

Environmental impacts associated with vehicular emissions are tremendous. NOx act as precursors to photochemical formation of ozone (O3) which can exacerbate chronic respiratory diseases and cause short-term reductions in lung function (Bernard et al., 2001). NOx also contributes to the secondary formation of PM2.5 (Harrison et al., 1997; He et al., 2001; Tan et al., 2009). PM2.5 exposure is associated with serious human health impacts, including increased rates of hospitalization and death (Mar et al., 2005; Pope and Dockery, 2006; Schwartz and Neas, 2000). Black carbon, a major PM component, is reported to be the second strongest contributor, after carbon dioxide (CO2), to current global warming (Ramanathan and Carmichael, 2008), and also affects the large-scale circulation and hydrologic cycle with significant regional climate effects (Menon et al., 2002).

To reduce the impact of vehicle emissions on urban air quality, China has launched a series of vehicle emission control measures and policies, including adoption of European Union-like emission standards for new vehicles, improving fuel quality, and banning heavy emitters from urban Beijing. Stage I and II emission standards (i.e., China I, China II) were promulgated on April 16, 2001, and Stage III, IV, and V emission standards for Chinese vehicles (i.e., China III, China IV and China V) on May 30, 2005. China II, III, and IV emission
standards are essentially equivalent to Euro II, III, and IV emission standards, respectively, in regulating emission rates of vehicle engines for gaseous pollutants including carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM) (GAQSIQPRC, 2001, 2005). Table 1 presents the emission limits specified in China I–V standards, and the typical technologies adopted to meet those standards. The actual dates of compliance with those emission standards and fuel quality standards are listed in Table 2. According to Ministry of Environmental Protection (MEP) of China, total NOx emission control (i.e., from various sectors such as the power industry, the cement industry and transportation) was introduced in the “The Twelfth Five-year Plan”, which aims to reduce total NOx emission in China by 10% from 2010 to 2015 (http://www.gov.cn/zwgk/2011-09/07/content_1941731.htm). Effective implementation of total NOx emission control requires accurate NOx emission inventories.

Emission factors (EFs), expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant, are useful in assessing vehicular emissions and form the basis of emission inventories. Recently, Portable Emission Measurement Systems (PEMS) were employed by researchers to quantify emission factors of on-road diesel vehicles in Beijing, with the emission control requirements of vehicles or engines to meet the standards. NOx emission standards were issued as part of China I to China V standards but the effectiveness in NOx reduction is still uncertain (He et al., 2010). BC is an important component of diesel particulate matter (PM). In this paper, we are not directly addressing effectiveness of China emission control for PM, but instead, we report BC as a PM indicator.

Primary objectives of this study were to 1) characterize on-road NOx emissions of Chinese diesel vehicles and 2) to compare NOx and BC EFs of diesel trucks from different regions in China using the refined on-road chasing method developed in Wang et al. (2011). We conducted on-road measurements in two cities, Beijing and Chongqing, and sampled 440 on-road diesel trucks in total. As the capital of China and the host city of the 29th Olympic Games, the city of Beijing is a pioneer in implementation of stringent vehicle emission control measures during the past decade. Chongqing, located approximately 1500 km southwest of Beijing in the Sichuan Basin, is the largest municipality in terms of population (~32 million) in China. On-road emissions studies are rare in Chongqing. The results from our study will provide scientific basis for implementing total NOx emission control as well as multi-pollutant emission control regulations in China.

2. Methodology

2.1. Instrumentation

The mobile platform was a gasoline powered minivan (Wang et al., 2009, 2011; Westerdahl et al., 2009). Instruments were powered by two 12 V deep-cycle storage battery/inverters (providing a total of 500 W at 120 V). Air sampling was conducted through a side window. Particulate-phase air pollutants were sampled using flexible conductive tubing while NOx was sampled identification of heavy emitters and their disproportionate contribution to total on-road emissions, observation of lower BC EFs from trucks registered in Beijing, and a demonstration of the effectiveness of introducing lower emission diesel buses. This work significantly expanded the sample size compared to previous studies, performed with PEMS or more traditional dynamometer methods and the results reflected real-world emissions of diesel vehicles.

This paper describes the findings from our most recent field campaign on characterizing on-road EFs of Chinese diesel trucks conducted in December 2010, focusing on NOx and BC emission factors of Chinese diesel trucks. NOx emission standards were adopted to meet those standards. The actual dates of compliance with those emission standards and fuel quality standards are listed in Table 2. According to Ministry of Environmental Protection (MEP) of China, total NOx emission control (i.e., from various sectors such as the power industry, the cement industry and transportation) was introduced in the “The Twelfth Five-year Plan”, which aims to reduce total NOx emission in China by 10% from 2010 to 2015 (http://www.gov.cn/zwgk/2011-09/07/content_1941731.htm). Effective implementation of total NOx emission control requires accurate NOx emission inventories.

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Table 1

The emission limits in China I–V standards and the typical control technologies adopted by the vehicle or engine manufacturers to meet the standards.

<table>
<thead>
<tr>
<th>China I</th>
<th>China II</th>
<th>China III*</th>
<th>China IV</th>
<th>China V†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission limits for gasoline passenger cars (g/km)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>2.72</td>
<td>2.2</td>
<td>2.30</td>
<td>1.00</td>
</tr>
<tr>
<td>HC</td>
<td>–</td>
<td>0.20</td>
<td>0.15</td>
<td>–</td>
</tr>
<tr>
<td>NOx</td>
<td>–</td>
<td>–</td>
<td>0.15</td>
<td>0.08</td>
</tr>
<tr>
<td>HC + NOx</td>
<td>0.97</td>
<td>0.5</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Typical Technologies</td>
<td>EFI + TWC</td>
<td>EFI + TWC</td>
<td>OBD + EFI + TWC</td>
<td>OBD + EFI + TWC</td>
</tr>
<tr>
<td>Emission limits for heavy-duty diesel engines (g/kWh)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>4.5</td>
<td>4.0</td>
<td>2.1/5.45‡</td>
<td>1.5/4.0</td>
</tr>
<tr>
<td>HC</td>
<td>1.1</td>
<td>1.1</td>
<td>0.66/0.78</td>
<td>0.46/0.55</td>
</tr>
<tr>
<td>NOx</td>
<td>8.0</td>
<td>7.0</td>
<td>5.0/5.0</td>
<td>3.5/3.5</td>
</tr>
<tr>
<td>PM</td>
<td>0.36</td>
<td>0.15</td>
<td>0.10/0.16</td>
<td>0.02/0.03</td>
</tr>
<tr>
<td>Typical Technologies</td>
<td>TC</td>
<td>TC + IC</td>
<td>HPCR or EGR + DOC</td>
<td>OBD + HPCR + SCR or OBD + EGR + DPF</td>
</tr>
</tbody>
</table>

* China III includes the typical technologies: EI, electronic fuel injection; TWC: three-way catalyst; OBD: on-board diagnosis.
† China V will be implemented in Beijing in 2012.
‡ EFI: electronic fuel injection; TWC: three-way catalyst; OBD: on-board diagnosis.
using high density Teflon tubing. All sampling lines were situated with the inlets approximately perpendicular to the airflow outside the van. Self-pollution was not apparent upon inspection of the individual time series observations (Wang et al., 2011). Isokinetic sampling was not attempted because particles studied in this paper were in the submicron size range, and the Stokes number was in the range of $10^{-7}$ to $10^{-3}$, indicating that the effects of particle inertia and isokinetic sampling were not significant (Baron and Willeke, 2001; Wang et al., 2011). Instruments used for on-road measurements were as follows: a Vaisala CARBOCAP (Model GMP 343, Vaisala) measured CO$_2$ concentration using Non-Dispersive Infrared (NDIR) method; a Micro-Aethalometer (Model AE51, Magee Scientific) was employed to measure BC mass concentration by optical transmission analysis; a NO$_2$ converter (Model 401, 2B Technologies) connected with a NO monitor (Model 410, 2B Technologies) measured NO$_x$ concentration using Ultraviolet (UV) absorbance methods. In addition, a Fast Mobility Particle Sizer (FMPS, Model 3091, TSI Inc.) reporting particle number concentration and size distribution (5.6–560 nm) and a Q-Trak (Model 7565, TSI Inc.) reporting carbon monoxide, humidity and temperature were operated in the mobile platform. These instruments were selected because of their low power requirements, rapid response, proven ability to produce high quality data, and small size.

The recording time intervals of Micro-Aethalometer (BC), Vaisala CARBOCAP (CO$_2$), Q-Trak, and NO monitor (NO$_x$) were set to the lowest practical time resolution, which was 1 s for BC, 5 s for CO$_2$, and 10 s for CO and NO$_x$. Observations were then averaged to 10 s. The adoption of instruments with fast response enabled us to identify the corresponding pollutant data of the target vehicles more precisely. It was also flexible, allowing the selection of many different types of target vehicles. The operational strategy was to sample all trucks that appeared separated from others so that only one target vehicle was in front of the mobile platform with a minimal impact of other on-road vehicles. The suitability of the selection was confirmed upon review of the data with an objective of observing a clear signal above background. A digital camcorder was operated in the front seat of the van and recorded the traffic conditions continuously during the on-road measurements. The recorded video and written notes served to describe the on-road conditions and to identify the target vehicle for linkage with the monitoring data. Internal clocks of all instruments were synchronized to a portable computer, which also functioned as a data logger for the CARBOCAP, Micro-Aethalometer and NO$_x$ monitor. The license plate numbers of target vehicles and the speed of our mobile platform were recorded during the on-road measurements. The license plates include identification of the province of registration for each truck. All suitable trucks were sampled without reference to province of registration. It is possible, in principal, to obtain further information, such as registration date, engine model, emission standard, etc. from these license plate numbers. However, such data are not easily available in China. As a proof of concept, registration and engine information of 11 Chongqing trucks were obtained based on their license plate numbers. Road gradients were qualitatively determined during each chase event in Chongqing and were recorded on written notes and camcorder for further analysis.

In our study, BC concentrations reported by Micro-Aethalometer were adjusted after experiments to account for filter loading levels. Theories and methods of adjustment are presented in Wang et al. (2011).

2.2. Sampling routes and periods

The on-road chasing studies were conducted on the 6th Ring Expressway in Beijing and the Inner Ring Expressway in Chongqing. Sampling routes in the two cities are illustrated in Fig. 1. Dates, time, weather conditions, and the number of sampled diesel trucks for each field trip are listed in Table 3.

We sampled 192 diesel trucks in Beijing on five days from December 9th to December 17th 2010; 248 diesel trucks in Chongqing on five days from December 21st to December 27th 2010. Trucks in Beijing were all sampled on level gradient roads. However, Chongqing is a mountainous city. Measurements in Chongqing included level, uphill and downhill segments. 127 trucks were sampled on uphill gradient roads, 124 trucks were sampled on level gradient roads and 36 trucks were sampled on downhill gradient roads. Suitable data from downhill samples were less available than for uphill and level samples because plumes emitted from trucks on downhill segments were usually small. It was difficult to capture acceptable data from these plumes and observe significant signals on instruments in our protocol. The basic operational requirement for chase methods employed to date is that a clear CO$_2$ plume must be identified when following a single truck.

2.3. Emission factor calculations

The individual EFs are calculated based on the data collected during the on-road measurements. Carbon balance calculations are based on the fuel combustion process, relating the emission of carbon-containing species from vehicle exhaust to fuel consumption (Geller et al., 2005; Kirchstetter et al., 1999a,b; Stedman, 1989; Stedman et al., 1991). We consider CO$_2$, CO and BC as the primary carbonaceous products of the combustion process. We do not have
measurements of hydrocarbon (HC) gases. Neglecting HC should have a minor effect in our calculations since gas-phase carbonaceous products are usually dominated by CO2 (Ning et al., 2008; Yli-Tuomi et al., 2005). The fuel-based emission factors are calculated using the following equation:

\[
EF_p = \frac{\Delta[P]}{\Delta[CO_2] \times MW_{CO_2} + \Delta[CO] \times MW_{CO} + \Delta[BC] \times MW_{BC}}
\]

where \(\Delta[i] = [i] - [i]_b\), \(i = P, CO_2, CO\) and \(BC\); subscript 0 denotes the baseline value; \(EF_p\) is the fuel based emission factor of pollutant \(P\) in grams of pollutant emitted per kilogram of fuel consumed \((g \text{ kg}^{-1})\); \(\Delta[P]\) is the on-road concentration of pollutant \(P\) above the baseline, with the unit of grams per cubic meter of air \((g \text{ m}^{-3})\); \(\Delta[CO_2], \Delta[CO]\) and \(\Delta[BC]\) represent increases of CO2, CO and BC, with the unit of grams per cubic meter of air \((g \text{ m}^{-3})\); \(MW_i\) is the molecular weight of the \(i\)th species; \(\omega_c\) is the mass fraction of carbon in the fuel. For this protocol we assume homogeneous dilution of the species of interest; an assumption which is reinforced by the averaging of multi minute observations.

In our calculations, \(MW_{BC}, MW_{CO}, MW_{CO2}\) are taken to be 12, 28 and 44 g mol\(^{-1}\). NO\(_x\) was treated as NO2 equivalent with \(MW_{NO2}\) as 46 g mol\(^{-1}\) (GAQSIQPRC, 2005; USEPA, 2010). When calculating NO\(_x\) EFs, the impact of ambient air humidity and temperature was considered (Yanowitz et al., 2000). These ambient air factors influence engine emissions. The following formula is adopted to calculate the correction factor of NO\(_x\) concentration (Dodge et al., 2003; Lindhjem et al., 2004):

\[
k_{NO_x} = 1 + 0.00446(T - 25) - 0.018708(H - 10.71)
\]

\[
NO_{x,\text{corrected}} = \frac{NO_{x,\text{measured}}}{k_{NO_x}}
\]

where \(T\) is the ambient temperature in °C, \(H\) is the ambient water contenting-H\(_2\)O kg-dry-air\(^{-1}\). Ambient temperature and humidity data are downloaded from weather underground website (http://www.wunderground.com/) and shown in Table 3. The average \(k_{NO_x}\) in Chongqing and Beijing are 1.03 and 1.07, respectively.

The properties of diesel fuel were taken from a number of reports on Chinese fuel standards, according to which fuel density is reported to be approximately 0.85 and carbon content is 85.5% with an estimated 5% variability (BQTSB, 2007; GAQSIQPRC, 2003)

In this study, EF calculations are performed for individual diesel trucks in real traffic conditions on expressways in each area. This approach is described in detail by Wang et al. (2011). The observed on-road concentrations were first aggregated into 10-second averages. Average EFs were calculated for each vehicle that had been chased for at least one minute. Emitted pollutant concentrations were obtained by subtracting baseline concentration from real time concentration for each pollutant. EFs for each vehicle were derived based on the mean value of EFs during the periods when we were chasing individual target vehicles. For vehicles operating on multiple road gradients, EFs were derived based on mean value of corresponding segments (uphill, level, downhill) of chasing periods.

**Table 3** Sampling dates, times and routes of sampled trucks.

<table>
<thead>
<tr>
<th>Sampling date</th>
<th>Sampling time</th>
<th>Sampling area</th>
<th>Temp</th>
<th>RH</th>
<th>Vehicle sampled</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>%</td>
<td>Trucks</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Up(^a) Le Dn</td>
</tr>
<tr>
<td>2010-12-09</td>
<td>2:00pm–5:00pm</td>
<td>BJ 6th Ring Expwy(^b)</td>
<td>3–5</td>
<td>39–42</td>
<td>24</td>
</tr>
<tr>
<td>2010-12-11</td>
<td>1:30pm–5:30pm</td>
<td>BJ 6th Ring Expwy</td>
<td>0–2</td>
<td>24–32</td>
<td>56</td>
</tr>
<tr>
<td>2010-12-13</td>
<td>1:30pm–5:30pm</td>
<td>BJ 6th Ring Expwy</td>
<td>–5–3</td>
<td>19–24</td>
<td>54</td>
</tr>
<tr>
<td>2010-12-14</td>
<td>1:30pm–5:30pm</td>
<td>BJ 6th Ring Expwy</td>
<td>–4</td>
<td>22–24</td>
<td>45</td>
</tr>
<tr>
<td>2010-12-17</td>
<td>12:30pm–2:30pm</td>
<td>BJ 6th Ring Expwy</td>
<td>7–8</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total (Beijing): 192</td>
</tr>
<tr>
<td>2010-12-21</td>
<td>11:00am–3:30pm</td>
<td>CQ Inner Ring Expwy(^b)</td>
<td>8–14</td>
<td>44–71</td>
<td>37</td>
</tr>
<tr>
<td>2010-12-22</td>
<td>11:00am–3:00pm</td>
<td>CQ Inner Ring Expwy</td>
<td>8–9</td>
<td>66–76</td>
<td>58</td>
</tr>
<tr>
<td>2010-12-23</td>
<td>11:00am–3:00pm</td>
<td>CQ Inner Ring Expwy</td>
<td>9</td>
<td>76–82</td>
<td>59</td>
</tr>
<tr>
<td>2010-12-26</td>
<td>10:45am–2:30pm</td>
<td>CQ Inner Ring Expwy</td>
<td>5–6</td>
<td>81</td>
<td>53</td>
</tr>
<tr>
<td>2010-12-27</td>
<td>9:45am–1:00pm</td>
<td>CQ Inner Ring Expwy</td>
<td>2–8</td>
<td>66–87</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total (Chongqing): 248</td>
</tr>
</tbody>
</table>

\(^a\) Up: uphill segment; Le: level segment; Dn: downhill segment.

\(^b\) Beijing 6th Ring Expressway.

\(^c\) Chongqing Inner Ring Expressway.
Statistical hypothesis tests (t-test) were employed to investigate the statistical significance when comparisons between different datasets were conducted in this study.

3. Results and discussion

3.1. Descriptions of sampled vehicles

Properties of sampled vehicles in two cities are illustrated in Fig. 3, categorized by regions, vehicle classes and on-road speed. In Beijing, a majority (56%) of sampling trucks were registered in Beijing and Hebei provinces, whereas in Chongqing, 80% of sampling trucks are locally registered. The truck fleet was dominated by heavy duty diesel trucks (gross weight greater than 6 metric tons) in both cities as determined by visual characteristics. Speed distribution chart shows that most of sampling trucks were in the speed range of 60~70 km h$^{-1}$, and the average speed of trucks sampled in Beijing is 8% greater than that in Chongqing. In this paper, “trucks sampled in Beijing” came from more than 10 provinces, while “Beijing-registered trucks” only account for 17% of the trucks sampled in Beijing.

Fig. 2 presents an example of data observed during on-road chase studies. The figure demonstrates several important factors regarding the nature of event sampling that provided the data for emission factor calculations. The pollutant time series made up of 10 s data averages align well for the pollutants under study during the two chase events which are in excess of 2 min long for each. There is a stable baseline period between the two events; in this case this baseline was used for calculations. The nature of data from all monitors provides adequate time resolution to represent the two events. In this chase study, target vehicles were randomly selected thus collection of replicate measurements on vehicles was not attempted.

3.2. EFs of trucks on roads with different road gradients in Chongqing

Road gradient effects on NO$_x$ and BC emissions from heavy-duty diesels were investigated in our Chongqing field campaign because of the mountainous terrain in this city. We sampled 127 trucks on uphill roads and 124 trucks on level roads. 32 of them were on both uphill and level roads. The uphill/level ratios of emitted pollutant concentration for those 32 trucks are shown in Fig. 4a. NO$_x$ and BC EFs of 127 trucks on uphill roads and 124 trucks on level roads are shown in Fig. 4b and c, respectively. In Fig. 4, the centerline, top line and bottom line of each box refer to median, 75% percentile and 25% percentile value of samples, respectively. The whisker top and bottom refer to 90% and 10% percentile of samples, respectively. In Fig. 4a, median values of uphill/level ratios of NO$_x$ and BC concentrations are 1.7 and 2.2, respectively, indicating higher pollutant emissions on uphill roads. The median value of the uphill/level ratio of CO$_2$ concentration is 1.5, which is indicative of the greater fuel consumption of trucks on uphill roads because CO$_2$ dominates carbon emission and is proportion to fuel consumption (Ning et al., 2008; Yli-Tuomi et al., 2005). Null hypothesis analysis was performed for the uphill and level EF comparison of the 32 trucks. p values of the comparisons based on NO$_x$, BC and CO$_2$ are all less than 0.001, indicating statistical significance of the comparison results. In Fig. 4b and c, the median BC EF of trucks on uphill and level roads are 1.4 and 1.1 g/kg-fuel, respectively; the median NO$_x$ EF of trucks on uphill and level roads are 45.0 and 40.0 g/kg-fuel, respectively. In our study, the increase in fuel-based EFs due to higher road gradient is not as large as the distance-based EFs obtained by Rexeis et al. (2005) and Boulter et al. (2007). Both fuel consumption and emissions of trucks increase as road gradient increases, leading to moderate increase in fuel-based EFs.

As discussed earlier, most of trucks on downhill roads emitted smaller plumes that were difficult to detect cleanly as required by our protocol. Therefore, EFs of trucks on downhill roads are not listed in Fig. 4. The sample size of trucks on downhill roads (36 trucks) is much smaller than that on uphill (127 trucks) and level roads (124 trucks).

It is noted that vehicle speed also affects emission factors. However, nearly 70% trucks we sampled in Chongqing were operated in a relatively small speed range (40~70 km h$^{-1}$), and we did not identify a clear speed dependency in the emission factors from our dataset.

3.3. BC and NO$_x$ EFs of trucks sampled in Beijing and Chongqing

As shown in Fig. 3, trucks sampled in Beijing were primarily registered in five regions: Beijing, Hebei, Inner Mongolia, Shandong and Tianjin; trucks sampled in Chongqing were primarily registered in Chongqing. BC and NO$_x$ EFs of trucks registered in different regions are shown by box and whisker plots in Fig. 5. The centerline in each box refers to median value; bottom and top lines refer to the 1st quartile and 3rd quartile value, respectively; whisker bottom and top lines refer to the 10 percentile and 90 percentile of the sample. In Fig. 5a and b, vertical dash lines divide samples by their sampling regions: the left part of the dash line refers to trucks sampled in Beijing whereas the right part of the dash line refers to trucks sampled in Chongqing.

3.3.1. EF of diesel trucks registered in different regions

Shown in Fig. 5a, the median BC EF of Beijing-registered trucks is 0.20 g kg-fuel$^{-1}$. Furthermore, the mean BC EF of Beijing-registered trucks is 0.30 g kg-fuel$^{-1}$, which is 75% ($p < 0.001$) lower than that of trucks sampled in Beijing but registered in other regions; it is also 82% ($p < 0.001$) lower than that of trucks registered in Chongqing. This is possibly due to implementation of the more stringent emission standard implemented in Beijing than in other regions of China. As indicated in Table 2, China III standard for new registered vehicles were enforced from December 30, 2005 in Beijing but only from January 1, 2008 in other Chinese cities (Fung et al., 2010; Wu et al., 2011). If we assume the age distributions of on-road trucks are the same in every city, the earlier implementation date in Beijing suggests that China III diesel trucks account for a greater portion of the on-road fleet in Beijing than in other cities. Moreover, the improved fuel quality in the region may also contribute to the findings.

![Fig. 2. An example of time series data collected during chasing study on the 6th Ring Expressway in Beijing.](image-url)
In contrast, as shown in Fig. 5b, the median NO$_x$ EF of Beijing-registered trucks is not the lowest among entire samples. Furthermore, the mean NO$_x$ EF values for Beijing trucks are 15% ($p = 0.027$) lower than those from Hebei and 17% ($p = 0.033$) lower than those from Shandong, but findings from other regions do not reach statistical significance. This observation indicates that emission control measures, such as advanced emission standards and improved fuels implemented in Beijing, have very limited impacts.
on NOx emission. This finding is consistent with that presented by He et al. (2010), which characterized EFs of diesel vehicles in Beijing, Shenzhen and Xi’an, finding that NOx EFs of China III heavy duty diesel vehicles (HDDV) is greater than that of China I and II.

The median value of BC EFs of trucks sampled on level roads in Chongqing (right side of the vertical dash line in Fig. 5a) is greater than that of trucks sampled in Beijing (left side of the vertical dash line in Fig. 5a). As listed in Table 4, the median value of NOx EFs of trucks sampled in Beijing and Chongqing are 47.3 and 40.0 g kg-fuel−1, respectively; the median value of BC EFs of trucks sampled in Beijing and Chongqing are 0.4 and 1.1 g kg-fuel−1, respectively. The NOx EFs for trucks sampled in Beijing are comparable to the value reported in other studies conducted in China (Chen et al., 2007; He et al., 2010; Liu et al., 2008; Wang et al., 2001) and in USA (Ban-Weiss et al., 2008; Jimenez et al., 2000; Kirchstetter et al., 1999a,b; Yanowitz et al., 1998). These results are also listed in Table 4.

Lower BC EFs of trucks sampled in Beijing may be attributed to better fuel quality with much lower sulfur level in the Beijing area than in other areas in China as well as a possibly newer fleet composition (Fu et al., 2001; Hao et al., 2006; Katherine et al., 2006; Zhang et al., 2010). Hao et al. (2006) and Liu et al. (2008) show that fuel sulfur content significantly affects emissions of light duty gasoline vehicles (LDGV) and HDDV. Zhang et al. (2010) analyzed 107 diesel samples from fuel stations along highways in China. He found that majority of their diesel fuel samples contained sulfur ranging from 500 ppm to 2000 ppm, which was equivalent to pre-China II diesel vehicle fuel standard. Because no advanced fuel quality standards have been implemented on a nationwide basis in China since 2007, the sulfur contents of diesel fuel reported by Zhang et al. (2010) are likely representative of diesel fuel in Chongqing area. In Beijing, on the other hand, diesel fuel sulfur content must be less than 50 ppm to comply with the new China IV emission standard beginning in 2008 (Wu et al., 2011). It is likely

![Fig. 5. EFs of trucks registered indifferent regions. a: BC EF (log scale); b: NOx EF. BJ: Beijing; HB: Hebei; IM: Inner Mongolia; SD: Shandong; TJ: Tianjin; CQ: Chongqing.](image)

### Table 4

<table>
<thead>
<tr>
<th>Sample categories</th>
<th>Mean of samples (g kg-fuel−1)</th>
<th>Median of samples (1st quartile – 3rd quartile) (g kg-fuel−1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx, Chongqing Uphill</td>
<td>48.8</td>
<td>45.0 (36.1 – 58.0)</td>
</tr>
<tr>
<td>NOx, Chongqing, Level</td>
<td>42.1</td>
<td>40.0 (31.7 – 48.1)</td>
</tr>
<tr>
<td>NOx, Beijing, Level (2010)</td>
<td>50.5</td>
<td>47.2 (38.1 – 62.5)</td>
</tr>
<tr>
<td>BC, Chongqing Uphill</td>
<td>2.2</td>
<td>1.4 (0.7 – 2.3)</td>
</tr>
<tr>
<td>BC, Chongqing, Level</td>
<td>1.6</td>
<td>1.1 (0.7 – 1.6)</td>
</tr>
<tr>
<td>BC, Beijing, Level (2010)</td>
<td>1.1</td>
<td>0.4 (0.2 – 0.8)</td>
</tr>
<tr>
<td>BC, Beijing, Level (2009)</td>
<td>2.2</td>
<td>0.8 (0.4 – 1.7)</td>
</tr>
<tr>
<td>BC, HDDV in CA, USA</td>
<td>(Geller et al., 2005), road tunnel</td>
<td>0.78 ± 0.09</td>
</tr>
<tr>
<td>NOx, HDDV in Beijing</td>
<td>(He et al., 2010), PEMS</td>
<td>40.9 ± 11.4 (China I)a</td>
</tr>
<tr>
<td>NOx, HDDV in Shanghai</td>
<td>(Chen et al., 2007), PEMS</td>
<td>43.1 (Pre-China I)</td>
</tr>
<tr>
<td>NOx, HDDV in Guangzhou</td>
<td>(Wang et al., 2001), road tunnel</td>
<td>34 (Pre-China I)</td>
</tr>
<tr>
<td>NOx, HDDT in USA</td>
<td>(Jimenez et al., 2000), remote sensing</td>
<td>45 ± 2</td>
</tr>
<tr>
<td>NOx, HDDT in CO, USA</td>
<td>(Yanowitz et al., 1998), chase dynamometer</td>
<td>39 ± 2</td>
</tr>
<tr>
<td>NOx, HDDT in CA, USA</td>
<td>(Kirchstetter et al., 1999a,b), road tunnel</td>
<td>42 ± 5</td>
</tr>
<tr>
<td>NOx, MDDT/HDDT in CA, USA</td>
<td>(Ban-Weiss et al., 2008), tunnel</td>
<td>40 ± 3</td>
</tr>
</tbody>
</table>

a Diesel vehicle.
b Heavy duty diesel vehicle.
c Heavy duty diesel truck.
d Median duty diesel truck.
that fuel in many trucks is a mixture of diesel purchased in various locations.

### 3.3.2. BC EFs of diesel trucks sampled in Beijing from 2008 to 2010

BC EFs of diesel trucks sampled in Beijing in 2008, 2009 and 2010 are shown by box and whisker plots in Fig. 6. The median and mean BC EF of diesel trucks sampled in Beijing in 2010 is 0.4 g kg-fuel\(^{-1}\) and 1.1 g kg-fuel\(^{-1}\), respectively. The mean value is 52% \((p = 0.004)\) and 74% \((p = 0.030)\) lower than that we collected in 2009 and 2008 studies, respectively. In 2008, trucks sampled in Beijing were dominated by Beijing-registered trucks due to the restriction of non-Beijing trucks during our sampling period in that year; in 2009 and 2010, trucks sampled in Beijing are from more than 10 provinces. While the protocols employed in each of these studies are essentially identical, there was an instrumental difference between BC measurements made in 2008 and following studies. The time resolution of BC in 2008 was 1 min vs. 1 s (averaged to 10 s) in 2009 (Wang et al., 2009, 2011) and the present study. Since PM emission standard in Beijing are more stringent than nationwide standards, this downward trend in BC EFs may reflect the effectiveness of advanced vehicle emission standard (China III) implemented nationwide since 2008 (Wu et al., 2011).

### 3.3.3. Linking on-road EFs with registration data

Truck license plate numbers provide a way to obtain further information, such as truck registration date, engine model and emission standard for each truck on the road. However, this data is not readily available. As a proof-of-concept study, the initial registration information of 11 trucks sampled in Chongqing was acquired from governmental sources based on their license plate numbers for further analysis. EFs, initial registration dates and compiled emission standards of the 11 trucks are illustrated in Fig. 7.

A decreasing trend of BC EFs is observed from China I to China III emission standard among the 11 diesel trucks. However, a similar trend is not observed for NO\(_x\) EFs. This observation further indicates that advanced emission standards (i.e. China III) implemented might have limited impact on NO\(_x\) emissions. The reader is cautioned that this small sample does not represent the overall group of vehicles tested or the larger fleet. Further evaluations of the larger data set would prove valuable to reinforce the tentative observations.

New emission standards will be enforced in Beijing (China V) and other Chinese cities such as Chongqing (China IV) in 2012. As fuel economy and BC (and likely PM) emissions improve, the implementation of effective control technologies is critical for NO\(_x\) emission reduction.

### 3.4. EF distributions and high emitting diesel vehicles

Fig. 8 presents the EF distributions and the cumulative distributions (by assuming that the fuel consumption rates and vehicle mileage traveled are the same for all the sampled vehicles) of trucks sampled in Chongqing and Beijing. NO\(_x\) and BC EFs are grouped by different road gradient in Fig. 8. Median and mean values of EFs are represented by solid and dash lines in each subplot in Fig. 8, corresponding to the values listed in Table 4. Both NO\(_x\) and BC EFs of trucks show log-normal shapes except that a second mode is observed for BC EFs of trucks sampled in Beijing (Fig. 8h). Further analysis shows that Hebei-registered trucks dominate this mode, with BC EFs ranging between 2.9 and 9.9 g kg-fuel\(^{-1}\).

Cumulative distributions of truck emissions are presented in Fig. 8(c,f,i). On level roads, the top 10% highest emitting trucks are responsible for 17.5% NO\(_x\) emission and 43.0% BC emission in Chongqing, and 18.1% NO\(_x\) emission and 64.4% BC emission in Beijing. The 20% highest emitting trucks are responsible for 40.7% NO\(_x\) emission and 54.8% BC emission in Chongqing, and 31.9% NO\(_x\) emission and 76.9% BC emission in Beijing. The proportion of total BC emission attributed by high emitting trucks sampled in Beijing is similar as that we observed in the 2009 study (Wang et al., 2011). It should be noted that those findings are based on the sampled vehicles in our study.

Our results suggest that, while a small number of high BC emission trucks contribute disproportionately to the total BC emissions, high NO\(_x\) emission trucks do not dominate the total NO\(_x\) emissions. Furthermore, we observed that high BC emission trucks are usually not high NO\(_x\) emission sources and vice versa (Fig. 9). For example, the dash lines in Fig. 9 refer to the 90 percentile value of NO\(_x\) EF and BC EF of the entire sample. The median NO\(_x\) EF value of the 10% highest BC emission trucks (top-left area in Fig. 9) is 41.8 g kg-fuel\(^{-1}\), while the median NO\(_x\) EF value of entire sample is 43.8 g kg-fuel\(^{-1}\). The median BC EF value of the top 10% highest NO\(_x\) emission trucks (bottom-right area in Fig. 9) is 0.4 g kg-fuel\(^{-1}\), while the median BC EF value of entire sample is 0.6 g kg-fuel\(^{-1}\).

### 3.5. Implications

Our observations and analysis suggest the challenges in in-use, multi-pollutant control strategies for diesel trucks in China. First,
as described in Table 1, the control technologies to meet China II to III standards, such as turbo-charging (TC), intercooling (IC), high pressure common rail (HPCR), exhaust gas recirculation (EGR), and diesel oxidation catalysts (DOC), are primarily put in place to limit PM and HC emissions, with some improvements in NO\textsubscript{x} emissions. The upcoming China V and VI emission standards for heavy-duty diesel engines will focus on both NO\textsubscript{x} and PM controls, which requires selective catalytic reduction (SCR), fuel quality improvements and diesel particulate filters (DPF). Second, even though emission certification processes for new vehicles and engines have been strictly enforced since the implementation of China I emission standards, the government has only limited resources to ensure the conformity of production (COP). The in-use compliance (IUC), which is required with the implementation of China III (light-duty vehicles)/China IV (heavy-duty diesel engines) standards, has just been implemented, and can potentially reinforce vehicle emission controls. Third, in-use vehicle emission standards, which are assessed by annual inspections, are much less stringent than the new vehicle and engine emission standards (e.g. China I–V). Fourth, for in-use HDDVs, NO\textsubscript{x} emissions are much more difficult to control than PM because of two major reasons: (1) Fuel efficiency is one of the most important concerns for vehicle manufacturers and owners in the market place, and PM emissions and fuel consumption rates can be both reduced through combustion improvement while in contrast NO\textsubscript{x} emissions will increase due to PM-NO\textsubscript{x} trade-off effects (Jacobs et al., 2003; Maiboom et al., 2008); (2) Heavy PM emissions can be identified relatively easily by the smoke check required for in-use heavy-duty diesel vehicles, but there is no requirement of NO\textsubscript{x} emission test. So without effective COP and IUC programs, effective NO\textsubscript{x} emission control cannot be guaranteed even with strictly enforced new vehicle and engine certification processes, as the vehicle and engine manufacturers would have the incentive to risk the noncompliance for improving the fuel efficiency.

4. Conclusion

Emissions of 440 diesel trucks were sampled in Beijing and Chongqing, China, by employing the on-road chasing method developed in Wang et al. (2011). EFs for BC and NO\textsubscript{x} were calculated, and their EF distributions were reported. Median values of NO\textsubscript{x} EFs for trucks in Chongqing and Beijing are 40.0 and 47.4 g kg-fuel\textsuperscript{-1}, respectively, on level roads. These numbers are comparable to data
reported by other studies in China. Median values of BC EFs for trucks in Chongqing and Beijing are 1.1 and 0.4 g kg-fuel\(^{-1}\) on level roads. The lower BC EFs in Beijing may reflect the better fuel quality used in this region. Moreover, BC EFs of trucks in Beijing are compared with the data reported in our previous work. A clear downward trend is observed from 2008 to 2010, reflecting cumulative effects of improvements in fleet composition that has taken place since 2008. Further reduction in BC emission is expected from better fuel quality and replacement of old trucks in the future.

As a proof-of-concept, we acquired registration information of 11 trucks in Chongqing and investigated how information of registration date and engine model might improve our understanding of emissions vs. control status of trucks. A downward trend of BC EFs is observed from China I to China III trucks, indicating the effectiveness of emission standard enforced in Beijing and nationwide.

However, NO\(_x\) EFs for trucks from Beijing does not show lower values than trucks from other regions, despite improved fuel and a large proportion of trucks with newer emission standard. NO\(_x\) EFs of China III trucks did not show lower values than China I and II trucks for the 11 trucks with further engine information. Scatter plot between NO\(_x\) EFs and BC EFs illustrates that high BC emission trucks are usually not high NO\(_x\) emitters. These observations suggest that current emission standard implemented in Beijing and nationwide may have limited impacts on NO\(_x\) emission reduction, likely due to the ineffectiveness of current control technologies in NO\(_x\) reduction and lack of in-use compliance programs. It is challenging to reduce NO\(_x\) emission without reducing fuel efficiency by any means other than catalytic controls. These controls require considerable improvements in fuel quality in some regions of China. Therefore, multi-pollutant control strategies and in-use compliance programs are imperative when new emission standard and regulations are launched in China. Clearly, the inclusion of data regarding truck engine characteristics provides data that is very valuable to the interpretation of emissions data collected in chase studies.

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