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# Investigating Real-World Emissions of China's Heavy-Duty Diesel Trucks: Can SCR Effectively Mitigate $NO_x$ Emissions for Highway Trucks?

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## ABSTRACT

The Euro IV emission standards for heavy-duty diesel vehicles require a substantial reduction in $NO_x$ emissions, spurring the introduction of selective catalytic reduction (SCR) systems. However, previous studies have found unsatisfactory control of $NO_x$ emissions for SCR-equipped urban buses, which has raised concern among policy-makers and researchers regarding the capability of SCR adopted by heavy-duty diesel trucks (HDDTs) in real-world applications. This study tested sixteen HDDTs in China between 2010 and 2014, including six SCR-equipped Euro IV HDDTs using a portable emissions measurement system (PEMS). On-road emission measurement results show no significant difference in $NO_x$ emissions between Euro II and Euro III HDDTs. In contrast, we observed a substantial reduction in real-world $NO_x$ emissions, as low as 25.4 g kg-fuel$^{-1}$, for six SCR-equipped HDDTs (Euro IV) compared with those without SCR systems (Euro II and Euro III), providing an overall reduction of ~50%. However, real-world brake-specific $NO_x$ emission factors for the SCR-equipped HDDTs were higher by ~45% than the lab test limit of 3.5 g kWh$^{-1}$ due to off-cycle $NO_x$ emissions, indicating the importance of introducing real-world emission test requirements for HDDTs. Due to the introduction of SCR systems, distinctive impacts from real-world operating conditions are observed for HDDTs. For example, fuel-based $NO_x$ emission factors steadily decrease as the vehicle speed increases due to higher exhaust temperatures, which improve the efficiency of SCR systems.

***Keywords:*** Heavy-duty diesel trucks; $NO_x$ emission; PEMS; SCR.

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## INTRODUCTION

Heavy-duty diesel vehicles (HDDVs) have been identified as one of the most important contributors to air pollution, health impacts and climate change (Johnson *et al.*, 2009; Wu *et al.*, 2011; Silverman *et al.*, 2012; Bond *et al.*, 2013; Zhang *et al.*, 2013; Wu *et al.*, 2014) and have contributed to an ascending trend in China's total anthropogenic $NO_x$ emissions (Richter *et al.*, 2005; Wu *et al.*, 2012; Zhao *et al.*, 2013). Due to the severe environmental problems related to $NO_x$ emissions, China's "Twelfth Five-Year Plan (2011–2015)" set a clear goal of mitigating total $NO_x$ emissions by 10% over five years (NPC, 2011). More recently, China's State Council released the "Action Plan for Air Pollution Prevention and Control" in September 2013, containing the strictest control measures in recent years (State Council, 2013), which was followed by the release of local action plans at provincial or city levels (e.g., Beijing, Zhang *et al.*, 2014a). HDDVs are key targets for $NO_x$ emission control because of their high emission factors and vehicle-specific use intensity. According to the official report released by the MEP (2012), total $NO_x$ emissions from on-road vehicles in China were 6.4 Tg in 2011, 67% of these emissions were contributed by HDDVs (including public transit buses, highway trucks and coach buses). Moreover, Wu *et al.* (2012) estimated that the total $NO_x$ emissions of the national HDDV fleet in 2009 exceeded the amount provided in the

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official report based on a large sample of HDDVs tested with on-road emission measurement by ~1.0 Tg. Even for megacities, such as Beijing and Guangzhou, which are pioneers for controlling vehicle emissions in China (Zhang *et al.*, 2013, 2014a), their annual reduction in vehicle emissions of $NO_x$ has been significantly lower than for other pollutants (e.g., CO, THC and $PM_{2.5}$) over recent years. Zhang *et al.* (2014a) warned that the mitigation of $NO_x$ emissions from gasoline vehicles is partially offset by increased $NO_x$ emissions from HDDVs due to their unsatisfactory real-world $NO_x$ emission controls. Therefore, it is urgently necessary to strengthen the control of real-world $NO_x$ emissions from China's HDDVs through effective technology measures and policy interventions, in particular for heavy-duty diesel trucks (HDDTs), which account for a large portion of China's HDDV fleet (MEP, 2012).

From the perspective of China's vehicle emission control history, the Euro IV (equivalent to China IV) emission standards for HDDVs were first planned for implementation in 2010. The most significant advancement originating from the Euro IV standards is that selective catalytic reduction (SCR) would become a prevailing after-treatment technology to control exhaust $NO_x$ emissions. However, the promulgation of the Euro IV emission standards for HDDVs was postponed by the MEP until July 2013 for several reasons (Zhang *et al.*, 2014a). For example, a sufficient supply of low-sulfur fuel that complied with the Euro IV standards (e.g., 50 ppm or lower) was limited to major cities (e.g., Beijing and Shanghai) and unavailable nationwide (Zhang *et al.*, 2010; Yue *et al.*, 2015). Furthermore, the shortage of urea (e.g., AdBlue) filling facilities discouraged its use. In China, several previous on-road studies using portable emission measurement systems (PEMS) have reported real-world $NO_x$ emissions of Euro I to Euro III diesel trucks (Liu *et al.*, 2009; Huo *et al.*, 2012; Wu *et al.*, 2012). In Beijing, recent on-road studies evaluated SCR-equipped Euro IV and Euro V urban diesel buses and reported unexpectedly high real-world $NO_x$ emissions due to their low exhaust temperatures under congested driving conditions and low loads (Wu *et al.*, 2012; Fu *et al.*, 2013; Zhang *et al.*, 2014b). Therefore, there is considerable uncertainty in the control of $NO_x$ emissions for Euro IV HDDVs and in-use PEMS measurement programs are needed (Lowell and Kamakaté, 2013; Vlachos *et al.*, 2014). Considering the very large population and different operating conditions of trucks compared urban busses and that very few studies have been conducted on SCR-equipped HDDTs in China, it is important to investigate real-world $NO_x$ emissions for diesel trucks in China equipped with SCR systems.

This paper aims to provide policy-makers with a timely investigation of real-world $NO_x$ emissions from modern diesel trucks in China, particularly for SCR-equipped Euro IV trucks. We employed a PEMS to obtain high temporal resolution emission profiles for sixteen HDDTs, covering emission standard categories ranging from Euro II to Euro IV. We calculated the $NO_x$ emission factor for each vehicle as a weighted average of various road types (e.g., urban roads, suburban roads and freeways) to explore the impacts of tightened emission standards and real-world operating conditions. With a focus on SCR-equipped HDDTs, this study provides the analysis of major factors (e.g., road type, vehicle speed, and load mass) affecting $NO_x$ emissions for Euro IV highway trucks.

## METHODS

### *Experimental Section*

On-road emission tests were performed in Beijing and Guangdong between 2010 and 2014. The tested vehicles, including five Euro II HDDTs, five Euro III HDDTs and six Euro IV HDDTs (see Table 1), were recruited from local freight companies. Each vehicle tested has been properly maintained and serviced. In recent years, individual truck weights in China's truck fleet have significantly increased (Wu *et al.*, 2016). For example, more than 82% of total truck sales had gross vehicle weights (GVWs) exceeding 19 tons in 2009. Moreover, for tractors, nearly 98% of total sales had GVWs exceeding 25 tons. Therefore, we tested three tractors (i.e., IV-1, IV-2 and IV-3) with GVWs exceeding 25 tons. Heavier Euro IV HDDT samples would result in relatively high fuel consumption and $NO_x$ emission when developing emission inventories for China's truck fleet. Euro II and Euro III HDDTs are not equipped with advanced after-treatment devices to control $NO_x$ emissions. In contrast, Euro IV trucks use urea-based SCR systems and on-board diagnostic (OBD) equipment. In particular, these SCR systems adopt vanadium-based catalysts that have a higher tolerance to sulfur (e.g., up to 350 ppm) than copper- or iron-based catalysts. In accordance with the requirement of the regulations regarding real-world emissions measurement (BEPB&BAQTS, 2013), market fuel from the certified refueling stations was used and the fuel quality complied with China III or China IV standard (see Table S1). The difference is mostly sulfur content (< 350 ppm for China III and < 50 ppm for China IV), which should be applicable to SCR devices (Walker *et al.*, 2004; Jiang *et al.*, 2010). All drivers were instructed to maintain their usual driving behaviors during the test trips.

To explore the impacts of operating conditions on vehicle emissions, the test routes for each truck included various typical road types that can be categorized into urban roads, suburban roads and freeways. The measurement duration of each test for each vehicle lasted more than 2 hours with a hot start, in which the measurements for each typical road category continued for more than 30 min to ensure adequate real-world vehicle driving data and emission profiles. Average vehicle speeds on urban roads, suburban roads and freeways were approximately 20 km $h^{-1}$, 50 km $h^{-1}$ and 70 km $h^{-1}$, respectively (see Table 2). In addition to driving conditions, load mass is another factor influencing real-world fuel consumption and emissions. Long-distance freight trucks in China often overload to increase their operation profit. Therefore, we set various load weights for the tested vehicles, ranging from 0.5 to 20.5 tons, which is illustrated in Table 2. These loads represent load rates ranging from less than 5% to approximately 120%. Among the tested HDDTs, five vehicle samples (i.e., II-1, II-2, III-1, III-2 and IV-1; see Table 2) were tested under two load mass conditions for comparison. Discrepancies in the average ambient

**Table 1.** Summary of tested diesel trucks.

| Vehicle No. [a] | Tested place [b] | Model year | Odometer ($10^3$ km) | GVW (tons) | Engine power rating (kW) | Fuel supply system | Emission standard | After-treatment |
|---|---|---|---|---|---|---|---|---|
| II-1 | Beijing | 2006 | ~600 | 20.2 | 132 | Mechanical pump | Euro II | None |
| II-2 | Beijing | 2007 | ~700 | 24.4 | 155 | Mechanical pump | Euro II | None |
| II-3 | Beijing | 2007 | 549 | 25.0 | 132 | Mechanical pump | Euro II | None |
| II-4 | Beijing | 2008 | ~500 | 25.0 | 132 | Mechanical pump | Euro II | None |
| II-5 | Beijing | 2007 | ~600 | 25.0 | 132 | Mechanical pump | Euro II | None |
| III-1 | Beijing | 2010 | 46.1 | 25.0 | 180 | Electronic unit pump | Euro III | None |
| III-2 | Beijing | 2008 | 123 | 20.1 | 162 | Electronic unit pump | Euro III | None |
| III-3 | Beijing | 2010 | 58.7 | 25.0 | 180 | Electronic unit pump | Euro III | None |
| III-4 | Beijing | 2010 | 178 | 25.0 | 155 | High-pressure common rail | Euro III | None |
| III-5 | Beijing | 2012 | 60.1 | 25.0 | 156 | High-pressure common rail | Euro III | None |
| IV-1 [c] | Guangdong | 2009 | 41 | 45.8 | 283 | Electronic unit injector | Euro IV | SCR [d] |
| IV-2 [c] | Guangdong | 2009 | ~40 | 38.3 | 254 | Electronic unit injector | Euro IV | SCR [d] |
| IV-3 [c] | Guangdong | 2009 | ~40 | 45.8 | 283 | Electronic unit injector | Euro IV | SCR [d] |
| IV-4 | Beijing | 2013 | 24.1 | 20.4 | 180 | High-pressure common rail | Euro IV | SCR [e] |
| IV-5 | Beijing | 2014 | 138 | 25.0 | 180 | High-pressure common rail | Euro IV | SCR [e] |
| IV-6 | Beijing | 2014 | 180 | 25.0 | 180 | Electronic unit pump | Euro IV | SCR [f] |

Note: [a] Roman numeral and Arabic numeral refer to the emission stage and the vehicle number, respectively. For example, II-1 means the 1st tested truck complying with Euro II; [b] On road emission were performed in plains of Beijing and Guangdong province; [c] The three Euro IV HDDTs were recruited from local freight companies and were operating in a demonstration program for Euro IV HDDVs in the Guangdong province; [d] vanadium-based SCR catalyst, model SCRV020, manufactured by Cummins; [e] vanadium-based SCR catalyst, model SCRV021, manufactured by Cummins; and [f] vanadium-based SCR catalyst, model 1208010-43A, manufactured by First Automobile Works (FAW).

**Table 2.** Average vehicle speed, load mass and fuel consumption for the tested trucks.

| Vehicle No. | Average vehicle speed (km $h^{-1}$) | | | Total distance (km) | Distance percentage (%) | | | Load mass [a] (tons) | Load mass/rated load (%) | Fuel consumption (L/100 km) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Urban roads | Suburban roads | Freeways | | Urban roads | Suburban roads | Freeways | | | |
| II-1 | 15.8 | 51.2 | 70.4 | 76.7 | 15 | 35 | 50 | 6.5 | 64 | 23.2 |
| | 16.7 | 52.7 | 70.8 | 75.3 | 13 | 38 | 49 | 12.5 | 123 | 24.9 |
| II-2 | 19.4 | 52.2 | 66.8 | 77.0 | 14 | 37 | 49 | 6.5 | 45 | 21.2 |
| | 17.4 | 51.9 | 67.8 | 74.3 | 13 | 36 | 51 | 12.5 | 86 | 23.1 |
| II-3 | 21.7 | 47.7 | 73.1 | 111.6 | 10 | 26 | 64 | 0.5 | 3.4 | 17.7 |
| II-4 | 23.9 | 49.5 | 72.8 | 67.5 | 15 | 34 | 51 | 0.5 | 3.4 | 18.9 |
| II-5 | 21.6 | 52.6 | 73.1 | 79.7 | 15 | 40 | 45 | 0.5 | 3.4 | 19.4 |
| III-1 | 22.2 | 47.7 | 72.0 | 71.3 | 17 | 35 | 48 | 6.5 | 44 | 20.0 |
| | 19.6 | 50.2 | 68.1 | 73.0 | 16 | 36 | 48 | 12.5 | 85 | 20.1 |
| III-2 | 18.0 | 50.6 | 69.4 | 78.9 | 15 | 36 | 49 | 6.5 | 64 | 25.0 |
| | 22.4 | 46.1 | 66.3 | 77.8 | 20 | 33 | 47 | 12.5 | 124 | 25.1 |
| III-3 | 16.6 | 44.1 | 69.5 | 75.6 | 18 | 34 | 48 | 0.5 | 3.4 | 20.0 |
| III-4 | 16.4 | 48.0 | 75.5 | 77.9 | 20 | 31 | 49 | 0.5 | 3.4 | 20.1 |
| III-5 | 21.9 | 49.3 | 67.7 | 84.2 | 14 | 30 | 56 | 0.5 | 3.6 | 18.8 |
| IV-1 | 19.2 | 48.7 | 68.3 | 72.0 | 14 | 38 | 48 | 10.5 | 27 | 33.5 |
| | 22.6 | 48.4 | 69.5 | 110.5 | 9 | 39 | 52 | 20.5 | 53 | 41.3 |
| IV-2 | 22.1 | 47.0 | 65.4 | 117.6 | 10 | 41 | 49 | 20.5 | 66 | 47.6 |
| IV-3 | 23.8 | 50.3 | 64.0 | 115.3 | 9 | 55 | 36 | 20.5 | 53 | 42.8 |
| IV-4 | 16.8 | 45.1 | 71.0 | 83.2 | 24 | 30 | 46 | 1.5 | 15 | 20.5 |
| IV-5 | 21.5 | 45.4 | 68.5 | 81.8 | 24 | 37 | 39 | 1.5 | 10 | 23.1 |
| IV-6 | 20.8 | 46.1 | 66.1 | 83.2 | 24 | 29 | 47 | 1.5 | 10 | 20.8 |

Note: [a] The load mass was estimated based on the mass of the PEMS, the weight of the driver and the mass of the artificial load, among which the sum of PEMS mass and driver weight is ~0.5 tons.

temperature, relative humidity and air pressure between each comparison test pair were within 5°C, 10% and 1 mbar, respectively, to eliminate impacts from environmental conditions on vehicle emissions.

A PEMS (SEMTECH-DS, Sensors Inc.) was applied to measure on-road emissions of gaseous pollutants for the diesel trucks. SEMTECH-DS employed a non-dispersive ultraviolet (NDUV) module for separate measurement of exhaust NO and $NO_2$ concentrations. Moreover, a heated flame ionization detector (HFID) measured the total hydrocarbon (THC) content, and a non-dispersive infrared (NDIR) analyzer was employed to measure CO and $CO_2$ concentrations (Liu *et al.*, 2009; Wu *et al.*, 2012). To ensure measurement accuracy, the analyzers were zero and span calibrated before each test. Real-time exhaust flow rates were recorded via an exhaust flow meter (SEMTECH-EFM). Instantaneous vehicle speed and location information (longitude, latitude and altitude) were recorded using a GPS receiver integrated into the SEMTECH-DS. Moreover, the vehicle interface module of the SEMTECH-DS can record real-time signals regarding the engine operation mode (e.g., engine speed, torque and power) for the six Euro IV diesel trucks equipped with OBD systems.

### *Data Processing*

Emission rates (unit in g $s^{-1}$) for each HDDT were collected at one-second intervals in this study. We first calculated distance-based emission factors (g $km^{-1}$) of all gaseous pollutants (e.g., $NO_x$, CO, THC, and $CO_2$) by road type for each individual vehicle based on the instantaneous emission rate profiles and driving conditions:

$$EF_{dist.,i,j} = \frac{3600 \times \sum_1^t ER_{i,j}}{\sum_1^t v_i} \tag{1}$$

where, $EF_{dist.,i,j}$ is the average distance-based emission factor for road type i and pollutant j, g $km^{-1}$; $t$ is the total test time on road type i, s; $ER_{i,j}$ is the instantaneous emission rate for road type i and pollutant j, g $s^{-1}$; and $v_i$ is the instantaneous vehicle speed for road type i, km $h^{-1}$.

To eliminate effects of vehicle size (e.g., engine power rating and/or GVW) between each of the tested trucks, we also calculated the fuel-based emission factor for better comparison with a carbon balance method (Wu *et al.*, 2012; Zhang *et al.*, 2014c):

$$EF_{fuel,i,j} = \frac{EF_{dist.,i,j} \times W_C \times 1000}{0.273 \times EF_{dist.,i,\mathrm{CO_2}} + 0.429 \times EF_{dist.,i,\mathrm{CO}} + 0.866 \times EF_{dist.,i,\mathrm{THC}}} \tag{2}$$

where $EF_{fuel,i,j}$ is the average fuel-based emission factor for road type i and pollutant j, g kg-$fuel^{-1}$; $W_C$ is the carbon mass ratio in diesel fuel, i.e., 0.866 (Zhang *et al.*, 2014b, c); and $EF_{dist.,i,CO_2}$, $EF_{dist.,i,\mathrm{CO}}$ and $EF_{dist.,i,\mathrm{THC}}$ are the average distance-based emission factors for $CO_2$, CO and THC, respectively, for road type i, g $km^{-1}$.

To eliminate the impacts of driving conditions on each HDDT sample, we further weighted the overall average emission factors for the tested vehicles based on their emission factors for various road types:

$$EF_j = 0.55 \times EF_{f,j} + 0.25 \times EF_{sub,j} + 0.2 \times EF_{urb,j} \tag{3}$$

where $EF_j$ is the weighted average emission factor for pollutant j, g kg-$fuel^{-1}$ or g $km^{-1}$; and $EF_{f,j}$, $EF_{sub,j}$ and $EF_{urb,j}$ are the average emission factors of pollutant j for freeways, suburban roads and urban roads, respectively, g kg-$fuel^{-1}$ or g $km^{-1}$. We referred to the local standard DB11/965-2013 of Beijing (BEPB&BAQTS, 2013) for the recommended weighting coefficients.

## RESULTS AND DISCUSSION

### *Real-World $NO_x$ Emissions Associated with Tightened Emission Standards*

Fig. 1 presents the weighted $NO_x$ emission factors for the tested HDDTs. The weighted fuel-based $NO_x$ emission factors are 49.1 ± 11.4, 47.9 ± 17.7 and 25.4 ± 3.3 g kg-$fuel^{-1}$, respectively, for Euro II to Euro IV HDDTs. Little reduction in $NO_x$ emissions from Euro II to Euro III HDDTs is observed. Furthermore, a wide range in fuel-based $NO_x$ emission factors for Euro II and Euro III HDDTs, i.e., from 27 to 67 g kg-$fuel^{-1}$, are identified. This finding might be attributed to several factors, including different engine technologies, emission control strategies, load masses and maintenance performances (Almén and Erlandsson, 2011; Ligterink *et al.*, 2012; Carrese *et al.*, 2013). In contrast, for the six Euro IV HDDTs equipped with urea-SCR systems, their fuel-based $NO_x$ emission factors on real roads are significantly lower, by an average of approximately 50%, than those without SCR systems. To compare with the emission standard limits (units in g $kWh^{-1}$), we also derived real-world brake-specific $NO_x$ emission factors for the six Euro IV HDDTs based on the engine operation data. For the Euro II and Euro III HDDTs, we applied engine combustion efficiency values of 209 and 206 g-fuel $kWh^{-1}$, respectively (CRAES, 2010), to convert between the different units. The real-world brake-specific $NO_x$ emission factors for Euro II, III and IV HDDTs, which are listed in Table 3, are higher than their corresponding laboratory emission limits (i.e., 7.0, 5.0 and 3.5 g $kWh^{-1}$ for Euro II, III and IV HDDTs based on laboratory engine bench tests, respectively) by 47%, 97% and 45%, respectively, similar to the gaps between real-world emissions and regulatory limits previously reported by Wu *et al.* (2012).

Nevertheless, a recent investigation revealed that numerous counterfeit HDDTs are available in China's market, which claims to meet the Euro IV standard with SCR systems. However, no SCR systems or urea tanks can be found on these trucks (CCTV, 2014). These counterfeit Euro IV HDDTs have been determined to have emission performances similar to Euro III HDDTs or even older models. Consequently, more stringent inspections during the conformity of production and enhanced in-use emission testing compliance programs (e.g., PEMS and remote sensing regulation) for Euro IV HDDVs are urgently needed in China.

Published studies regarding real-world $NO_x$ emissions of HDDVs are summarized in Table 3 from a broad review of the literature. There have been very few studies, and only two of them measured the Euro IV trucks in China including this study. In the current study, the focus of the investigation

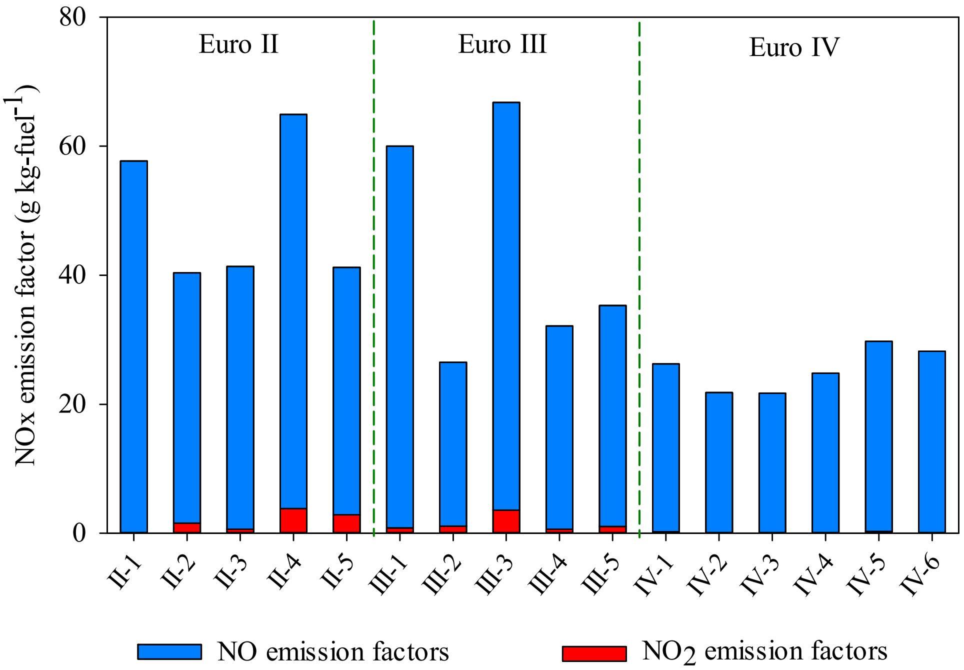

**Fig. 1.** Weighted fuel-based $NO_x$ emission factors for each tested HDDT. The emission factors are the test results for low loads, when trucks were tested with varying load mass. Specific load mass information is given in Table 2. $NO_x$ is presented as the sum of NO and $NO_2$, which are also shown separately.

**Table 3.** Summary of real-world $NO_x$ emissions for the HDDVs tested using PEMS.

| | $NO_x$ emission factors | |
|---|---|---|
| | g kg-fuel$^{-1}$ | g kWh$^{-1}$ |
| Beijing and Guangdong, China; Trucks (This study) | 49.1 ± 11.4 (Euro II) | 10.26 ± 2.38 [a] (Euro II) |
| | 47.9 ± 17.7 (Euro III) | 9.86 ± 3.64 [a] (Euro III) |
| | 25.4 ± 3.3 (Euro IV) | 5.08 ± 0.66 (Euro IV) |
| Beijing, China; Trucks (Wu *et al.*, 2012) | 47.3 ± 11.8 (Euro I) | |
| (GVW > 12 tons) | 36.6 ± 16.1 (Euro II) | |
| | 45.9 ± 5.6 (Euro III) | |
| Xi’an, China; Trucks (Liu *et al.*, 2009) | ~48 (37–60) (Euro II) | |
| (mostly GVW< 5 tons) | ~50 (44–58) (Euro III) | |
| Five cities in China; Trucks (Huo *et al.*, 2012) | 44 ± 25 (Euro II) | |
| | 51 ± 15 (Euro III) | |
| | 36 ± 11 (Euro IV) [b] | |
| Beijing, China; Buses (Wu *et al.*, 2012) | 46.0 ± 16.0 (Euro II) | |
| | 46.6 ± 4.1 (Euro III) | |
| | 41.7 ± 6.1 (Euro IV) | 6.6 and 9.5 for two Euro IV buses |
| Beijing, China; Buses (Liu *et al.*, 2011) | | 7.86 and 11.05 for two Euro III buses |
| | | 6.88 and 7.08 for two Euro IV buses |
| Beijing, China; Buses (Fu *et al.*, 2013) | | 9.61~12.44 (Euro IV) |
| Beijing, China; Buses (Zhang *et al.*, 2014b) | 30.0 (Euro V) | 5.6 (Euro V) |
| EU; Trucks (Bonnel *et al.*, 2011) | | 4.7 (3.1–8.5) (Euro IV) |
| Netherlands; Trucks (Ligterink *et al.*, 2009) | | 8.4 (city) and 7.1 (freeway) for Euro III; |
| | | 6.5 (city) and 2.6 (freeway) for Euro V; |
| Sweden; HDDTs [c] (Erlandsson *et al.*, 2008) | | 4.80 (Euro IV) |
| US; HDDTs (Krishnamurthy *et al.*, 2007) | | 4.3–5.1 (MY 2002) [d] |
| US; HDDTs (Johnson *et al.*, 2009) | | 3.80’ average of in-use NTE events (MY 2004) [d] |

Note: [a] Brake-specific emission factors are converted based on an assumed engine efficiency of 209 g-fuel kWh$^{-1}$ for Euro II trucks and 206 g-fuel kWh$^{-1}$ for Euro III trucks; [b] average $NO_x$ emission factor of two Euro IV trucks tested in Jinan, Shandong, in 2011; [c] net vehicle weight is 15 tons, and the vehicles were equipped with exhaust gas recirculation (EGR) systems; and [d] MY 2002 and MY 2004 in the US are comparable to the Euro IV standards.

was on their performance in terms of controlling $NO_x$ emissions. Similar to previous PEMS test results (Liu *et al.*, 2009; Huo *et al.*, 2012; Wu *et al.*, 2012), we added new on-road evidence of the unsuccessful $NO_x$ emission control for pre-Euro IV HDDVs due to the absence of effective after-treatment devices (e.g., SCR systems) and a strong in-use inspection program. Furthermore, Wang *et al.* (2012) employed a mobile platform to measure on-road $NO_x$ emissions of 440 chased trucks in Beijing and Chongqing and found that the median fuel based $NO_x$ emission factors were 40–50 g kg-fuel$^{-1}$, highly coincident with PEMS test results. Krishnamurthy *et al.* (2007) identified a trade-off between higher fuel economy and controlling $NO_x$ emissions under real-world conditions. Unfortunately, fuel economy is one of the most important concerns for truck manufacturers and owners; thus, without an effective in-use compliance program, $NO_x$ emissions can easily run out of control.

For SCR-equipped trucks (Euro IV), the average $NO_x$ emission factor (i.e., 25.4 ± 3.3 g kg-fuel$^{-1}$) is comparable to previous test results in the EU and US for trucks complying with Euro IV or similar emission standards (Erlandsson *et al.*, 2008; Johnson *et al.*, 2009; Bonnel *et al.*, 2011). Previous studies have indicated only small emission reductions for Euro IV buses equipped with urea-SCR systems compared with Euro III buses (Liu *et al.*, 2011; Wu *et al.*, 2012; Fu *et al.*, 2013). Low exhaust temperatures (below 200°C during most of the operating time) under congested urban driving conditions and low loads result in unsatisfactory performance of SCR systems, which has also been shown for Euro IV and Euro V HDDVs in low-speed urban driving circumstances (Ligterink *et al.*, 2009; Carslaw *et al.*, 2011; Velders *et al.*, 2011). Unlike the operating conditions of urban buses, higher driving speeds and loads for the tested SCR-equipped trucks lead to significantly higher exhaust temperatures, which activate the SCR systems. This condition facilitated the effectiveness for SCR to convert $NO_x$ to $N_2$. In the following section, additional analysis on the impacts of real-world operating conditions is provided.

Direct $NO_2$ emissions (i.e., primary $NO_2$) from modern diesel vehicles are of significant concern due to their oxidation potential to aggravate secondary pollution, e.g., ozone. We present separate primary NO and $NO_2$ emission factors in Fig. 1. The averaged primary $NO_2$ emission factors for Euro II, Euro III and Euro IV HDDTs are 1.8 ± 1.6, 1.7 ± 1.2 and 0.1 ± 0.1 g kg-fuel$^{-1}$, respectively, indicating that the average fractions of primary $NO_2$ in total $NO_x$ are 3.7%, 3.5% and 0.4%. This finding agrees well with previous results for Euro III (3.2%) and Euro IV (1.0%) buses (Wu *et al.*, 2012). Lower primary $NO_2$ emissions from Euro IV HDDTs might be attributed to the introduction of SCR systems, without the combined use of a diesel oxidation catalyst (DOC) and a diesel particle filter (DPF). Therefore, the primary $NO_2$ fraction for Euro IV HDDTs is lower than those in other geographical regions (e.g., EU) because the application of DOC and DPF systems would cause concern regarding the increased primary $NO_2$ fraction (e.g., up to 50%) (Carslaw *et al.*, 2011; Hu *et al.*, 2012; Velders *et al.*, 2011). Upcoming Euro VI emission standards for HDDVs, which are scheduled to be implemented no later than 2017 in Beijing (probably two or three years later for nationwide implementation), will set very stringent limits on mitigate diesel particle emissions and will promote broad application of DOC and DPF systems. The real-world primary $NO_2$ emissions of Euro VI HDDVs must be monitored when DOC and DPF systems become widely available in the market.

### *Impact of Driving Conditions and Load Mass on $NO_x$ Emissions*

Table 4 summarizes the fuel-based $NO_x$ emission factors for the tested HDDTs associated with emission standards and road types. For HDDTs without SCR systems (Euro II and Euro III), little variation in the fuel-based $NO_x$ emission factors is found among the three different roads (average of 45–52 g kg-fuel$^{-1}$). This finding indicates that for HDDTs without SCR systems, the impacts of driving conditions on $NO_x$ emissions are consistent with the trend in fuel consumption. However, the pattern for HDDTs with SCR (Euro IV) is very different. A significant decrease in the fuel-based $NO_x$ emission factors for HDDTs with SCR systems is found because their average speeds increase from urban roads (~20 km h$^{-1}$) to freeways (~70 km h$^{-1}$). Fig. 2 presents the average fuel-based $NO_x$ emission factors according to instantaneous speed bins, which clearly shows the same trend as in Table 4. For HDDTs without SCR systems, the average fuel-based $NO_x$ emission factors are not sensitive to changes in vehicle speed. However, for HDDTs with SCR systems, fuel-based $NO_x$ emissions are reduced from ~55 g kg-fuel$^{-1}$ under extremely congested conditions (e.g., 0–10 km h$^{-1}$) to approximately 20 g kg-fuel$^{-1}$ on freeways.

Similar to Velders *et al.* (2011) and Verbeek *et al.* (2010), our study also identifies how driving conditions (e.g., road type and vehicle speed) are related to the real-world performance of SCR systems. If the average emission level of Euro III HDDTs is seen as the baseline, the $NO_x$ emission reductions for SCR-equipped Euro IV HDDTs are 18%, 49% and 58% on urban roads, suburban roads and freeways, respectively, which is because exhaust temperatures at low

**Table 4.** $NO_x$ emission factors for all tested HDDTs associated with emission standards and road types.

| Emission standard | Fuel-based emission factors (g kg-fuel$^{-1}$) | | |
|---|---|---|---|
| | Urban roads | Suburban roads | Freeways |
| Euro II | 47.2 ± 14.68 | 47.6 ± 10.68 | 50.5 ± 10.83 |
| Euro III | 51.7 ± 16.04 | 49.5 ± 21.48 | 45.8 ± 17.84 |
| Euro IV | 42.4 ± 12.08 | 25.2 ± 3.63 | 19.2 ± 3.19 |

Note: Average vehicle speeds on urban roads, suburban roads and freeways were approximately 20 km h$^{-1}$, 50 km h$^{-1}$ and 70 km h$^{-1}$, respectively.

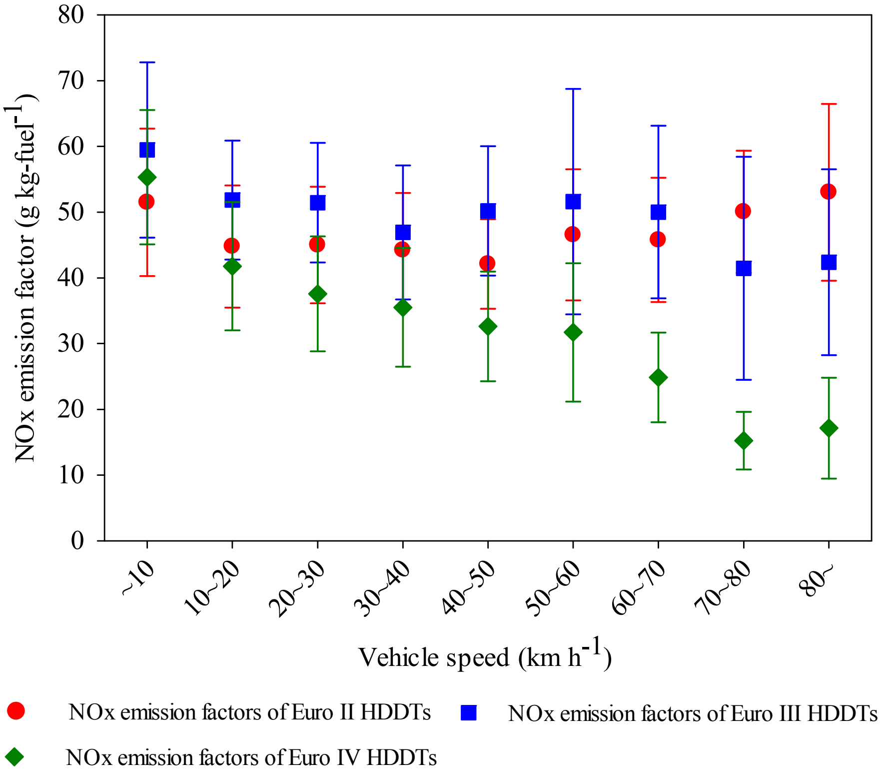

**Fig. 2.** Fuel-based $NO_x$ emission factors for the tested HDDTs in various vehicle speed bins.

speeds might be too low for proper functioning of SCR systems. A similar conclusion has been previously identified as the major reason for poor $NO_x$ emission control performance in Euro IV diesel buses (Wu *et al.*, 2012; Fu *et al.*, 2013). Alternatively, using the OBD-derived engine combustion efficiency, the brake-specific $NO_x$ emission factors for the Euro IV HDDTs are 8.5 g $kWh^{-1}$, 5.0 g $kWh^{-1}$ and 3.8 g $kWh^{-1}$ on urban roads, suburban roads and freeways, respectively. As a result, only the brake-specific $NO_x$ emission factors on freeways are close to the emission limit (3.5 g $kWh^{-1}$). Similar findings have also been reported based on real-world PEMS studies in Europe (Velders *et al.* 2011; Lowell and Kamakaté, 2013). A more effective in-use compliance program, e.g., the real-world emission test regulation, is required to control off-cycle emissions (Lowell and Kamakaté, 2013), especially for modern HDDVs using advanced after-treatment devices (e.g., SCR systems). Consequently, in the development of a high-resolution vehicle emission inventory for future scenarios that has a considerable penetration of advanced HDDVs with SCR systems, we suggest that the impacts from driving conditions should be carefully considered in the spatial allocation process associated with different road types (Zheng *et al.*, 2014).

Five representative HDDTs were selected from the sixteen tested trucks to explore the real-world $NO_x$ emission change with load mass. Due to larger individual emissions difference in each group meeting Euro II and Euro III HDDTs (see Fig. 1), one high emission and one low emission trucks were picked up. However, the average $NO_x$ emission factors were similar for the six Euro IV HDDTs, thus only one were selected to analyze the impact of load mass. Fig. 3 presents the fuel-based $NO_x$ emission factors under high and low loads. The high load mass is equal to around twice the low load mass, but unlike four Euro II and III HDDTs, the low and high loads of the Euro IV HDDT were higher, because of its large vehicle size. In general, the fuel consumption for all five HDDTs increases by 1–9% (see Table 2) under high loads compared to low loads. For HDDTs without SCR systems (Euro II and Euro III), the fuel-based $NO_x$ emission factors increase by 1–31% for a doubling in the load mass, which is because higher engine loads generally increase the combustion temperature, thereby enhancing $NO_x$ formation (Almén and Erlandsson, 2011).

For the HDDT with SCR (i.e., IV-1) in this study, the fuel consumption also increases under higher loads. However, unlike the HDDTs without SCR systems, the $NO_x$ emission factor under high loads is approximately 22 g kg-fuel$^{-1}$, a reduction of 18% relative to low loads. Lowell and Kamakaté (2013) also reported the same effect for Euro V diesel trucks with SCR systems, suggesting a $NO_x$ emission reduction of ~20% under a 100% load compared to a 50% load. We verified the measured exhaust temperatures using a thermocouple temperature probe integrated into the SEMTECH-EFM; the average temperature was found to increase from 199°C to 258°C for a doubling in the load mass. The higher temperatures enhance the efficiency of SCR systems (Fu *et al.*, 2013). Zhang *et al.* (2014b) also found that the use of on-board air-conditioning systems for SCR-equipped Euro IV diesel hybrid buses significantly increase real-world fuel consumption and resulted in better SCR performance due to higher exhaust temperatures. However, the HDDVs complying with the US 2010 standard

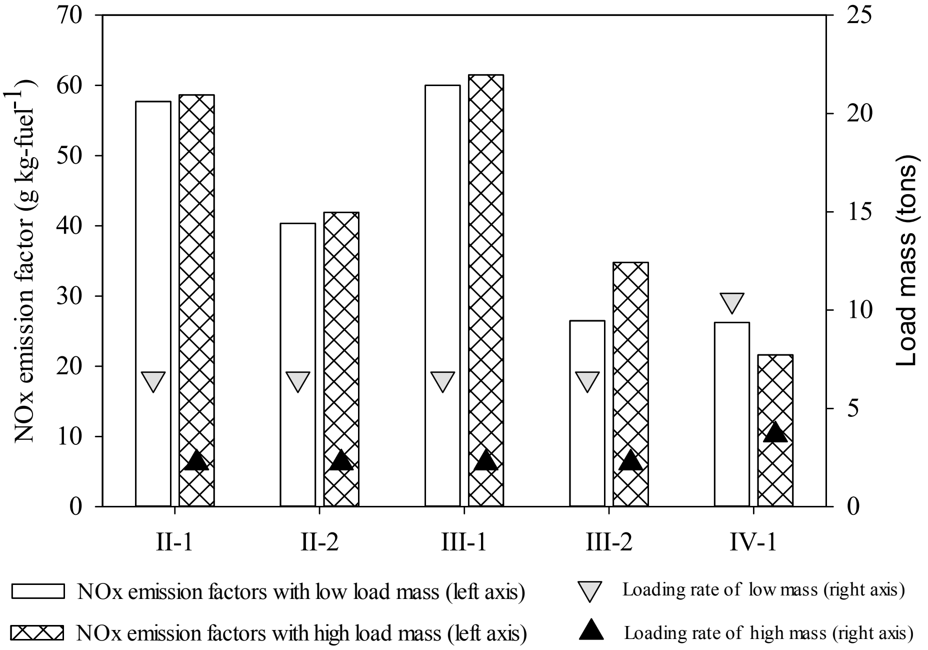

**Fig. 3.** Fuel-based $NO_x$ emission factors under high and low loads for five HDDTs (Note: Four Euro II and III HDDTs (i.e., II-1, II-2, III-1 and III-2) emission tests were performed in Beijing and One Euro IV HDDTs (i.e., IV-1) in Guangdong).

might achieve very low $NO_x$ emissions (e.g., lower than 1 g km$^{-1}$), although some challenges still remain under unfavorable operating conditions, which are associated with lower exhaust temperatures (e.g., low speed, idle conditions and low load mass) (Misra *et al.*, 2013; Spreen *et al.*, 2014).

## CONCLUSIONS

We measured real-world emissions of sixteen HDDTs complying with Euro II to Euro IV emission standards using a PEMS. The fuel-based $NO_x$ emission factors for all of the tested trucks were calculated based on emission profiles measured at one-second intervals. Furthermore, we analyzed the impacts of real-world operating conditions on $NO_x$ emissions, with a special focus on six HDDTs equipped with SCR systems.

The average fuel-based $NO_x$ emission factors for Euro II, III and IV HDDTs were 49.1 ± 11.4, 47.9 ± 17.7 and 25.4 ± 3.3 g kg-fuel$^{-1}$, respectively. We found no significant reduction in real-world $NO_x$ emissions as the emission standards tightened from Euro II to Euro III. In contrast, thanks to SCR systems, the average fuel-based $NO_x$ emission factors for the six SCR-equipped HDDTs (Euro IV) decreased by ~50% compared to HDDTs without SCR systems (Euro II and Euro III), and $NO_2$ emissions were also considerably lower for Euro IV HDDTs. These findings suggest a better performance of SCR systems for HDDTs relative to those installed in the urban bus fleet. However, we also found that the real-world brake-specific $NO_x$ emissions were higher than the emission limits by 47%, 97% and 45% for the tested Euro II, Euro III and Euro IV HDDTs, respectively, indicating a substantial gap between real-world emissions and laboratory-derived emission limits.

We also highlighted the importance of real-world operating conditions on $NO_x$ emissions for SCR-equipped HDDTs. For driving conditions, we found a significant decrease in the fuel-based $NO_x$ emission factors for SCR-equipped HDDTs with increased vehicle speeds, which differed from the findings for HDDTs without SCR systems. The fuel-based $NO_x$ emission factors for the six HDDTs with SCR systems on suburban roads and freeways were lower than those on urban roads by ~41% and ~55%, respectively. Our study provides first-hand data for further improvement in local vehicle emission inventories and policy-making related to controlling vehicle emissions in China.

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## SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

## REFERENCES

Almén, J. and Erlandsson, L. (2011). On-board exhaust emission measurement on heavy duty vehicles at different driving conditions. *SAE Technical Paper* 2011-01-2209

BEPB (Beijing Municipal Environmental Protection Bureau) and BAQTS (Beijing Municipal Administration of Quality and Technology Supervision) (2013). DB11/965-2013 Limits and Measurement Method of Emissions from Heavy Duty Vehicle (PEMS Method).

Bond, T.C., Doherty, S.J., Fahey, D.W., Forster, P.M., Berntsen, T., DeAngelo, B.J., Flanner, M.G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P.K., Sarofim, M.C., Schultz, M.G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S.K., Hopke, P.K., Jacobson, M. Z., Kaiser, J.W., Klimont, Z., Lohmann, U., Schwarz, J.P., Shindell, D., Storelvmo, T., Warren, S.G. and Zender, C.S. (2013). Bounding the role of black carbon in the climate system: A scientific assessment. *J. Geophys. Res.* 118: 5380–5552.

Bonnel, P., Kubelt, J. and Provenza, A. (2011). Heavy-duty engines conformity testing based on PEMS. EC-JRC Scientific and Technical Reports. http://publications.jrc.ec.europa.eu/repository/bitstream/JRC66031/reqno_jrc66031_lbna24921enn.pdf

Carrese, S., Gemma, A. and La Spada, S. (2013). Impacts of driving behaviours, slope and vehicle load factor on bus fuel consumption and emissions: A real case study in the city of Rome. *Procedia Soc. Behav. Sci.* 87: 211–221.

Carslaw, D., Beevers, S., Tate, J., Westmoreland, E. and Williams, M. (2011). Recent evidence concerning higher $NO_x$ emissions from passenger cars and light duty vehicles. *Atmos. Environ.* 45: 7053–7063.

CCTV (China Central Television) (2014). True China IV HDDTs are not available in Hebei province. http://money.163.com/14/0512/15/9S28G2BT002534NV.html.

CRAES (Chinese Research Academy of Environmental Sciences) (2010). Investigating China automobile energy saving and emission reduction, Research Report of the Special Project of Basic Work for National Science and Technology.

Erlandsson, L., Almen, J. and Johansson, H. (2008). Measurement of emissions from heavy duty vehicles meeting Euro IV/V emission levels by using on-board measurement in real life operation. Proceedings of 16th International Conference on Transport and Air Pollution, Graz, Austria.

Fu, M., Ge, Y., Wang, X., Tan, J., Yu, L. and Liang, B. (2013). $NO_x$ emissions from Euro IV busses with SCR systems associated with urban, suburban and freeway driving patterns. *Sci. Total Environ.* 452–453: 222–226.

Hu, J., Wu, Y., Wang, Z., Li, Z., Zhou, Y., Wang, H., Bao, X. and Hao, J. (2012). Real-world fuel efficiency and exhaust emissions of light-duty diesel vehicles and their correlation with road conditions. *J. Environ. Sci.* 24: 865–874.

Huo, H., Yao, Z., Zhang, Y., Shen, X., Zhang, Q. and He, K. (2012). On-board measurements of emissions from diesel trucks in five cities in China. *Atmos. Environ.* 54: 159–167.

Jiang L., Ge Y., Shah A., He, C. and Liu Z. (2010). Unregulated emissions from a diesel engine equipped with vanadium-based urea-SCR catalyst. *J. Environ. Sci.* 22: 575–581.

Johnson, K.C., Durbin, T.D., Cocker, D.R., Miller, W.J., Bishnu, D.K., Maldonado, H., Moynahan, N., Ensfield, C. and Larro, C.A. (2009). On-road comparison of a portable emission measurement system with a mobile reference laboratory for a heavy-duty diesel vehicle. *Atmos. Environ.* 43: 2877–2883.

Krishnamurthy, M., Carder, D.K., Thompson, G. and Gautam, M. (2007). Cost of lower $NO_x$ emissions: Increased $CO_2$ emissions from heavy-duty diesel engines. *Atmos. Environ.* 41: 666–675.

Ligterink, N., de Lange, R., Vermeulen, R. and Dekker, H. (2009). On-road $NO_x$ emissions of Euro-V trucks. TNO report, MON-RPT-033-DTS-2009-03840.

Ligterink, N.E., Tavasszy, L.A. and de Lange, R. (2012). A velocity and payload dependent emission model for heavy-duty road freight transportation. *Trans. Res. Part D* 17: 487–491.

Liu, H., He, K., Lents, J. M., Wang, Q. and Tolvett, S. (2009). Characteristics of diesel truck emission in China based on portable emissions measurement systems. *Environ. Sci. Technol.* 43: 9507–9511.

Liu, Z., Ge, Y., Johnson, K.C., Shah, A.N., Tan, J., Wang, C. and Yu, L. (2011). Real-world operation conditions and on-road emissions of Beijing diesel buses measured by using portable emission measurement system and electric low-pressure impactor. *Sci. Total Environ.* 409: 1476–1480.

Lowell, D. and Kamakaté, F. (2013). Urban off-cycle $NO_x$ emissions from Euro IV/V trucks and buses. The International Council on Clean Transportation (ICCT). http://www.theicct.org/sites/default/files/publications/ICCT_WP18_urban_Nox_emissions.pdf.

MEP (Ministry of Environmental Protection, P.R. of China) (2012) China vehicle emission control annual report (in Chinese).

Misra, C., Collins, J.F., Herner, J.D., Sax, T., Krishnamurthy, M., Sobieralski, W., Burntizki, M. and Chernich, D. (2013). In-use $NO_x$ emissions from model year 2010 and 2011 heavy-duty diesel engines equipped with aftertreatment devices. *Environ Sci. Techno.* 47: 7892–7898.

NPC (Nation People's Congress) (2011). 12th Five-Year Plan on national economic and social development (in Chinese). http://finance.people.com.cn/GB/14164290.html.

Richter, A., Burrows, J.P., Nüß, H., Granier, C. and Niemeier, U. (2005). Increase in tropospheric nitrogen dioxide over China observed from space. *Nature* 437: 129–132.

Silverman, D.T., Samanic, C.M., Lubin, J.H., Blair, A.E., Stewart, P.A., Vermeulen, R., Coble, J.B., Rothman, N., Schleiff, P.L. and Travis, W.D. (2012). The diesel exhaust in miners study: A nested case–control study of lung cancer and diesel exhaust. *J. Natl. Cancer Inst.* 104:855–868.

Spreen, J., Vonk, W. and Vermeulen, R. (2014). $NO_x$ and PM emissions of a Mercedes Citaro Euro VI bus in urban operation. TNO report, TNO 2014 R11307.

State Council (2013). Action Plan for Air Pollution Prevention and Control (in Chinese). http://www.gov.cn/zwgk/2013-

09/12/content_2486773.htm

Velders, G.J.M., Geilenkirchen, G.P. and de Lange, R. (2011). Higher than expected $NO_x$ emission from trucks may affect attainability of $NO_2$ limit values in the Netherlands. *Atmos. Environ.* 45: 3025–3033.

Verbeek, R., Vermeulen, R., Vonk, W. and Dekker, H. (2010). Real-world $NO_x$ emissions of Euro V vehicles. TNO Science and Technology Report, MON-RPT-2010-02777.

Vlachos, T.G., Bonnel, P., Perujo, A., Weiss, M., Villafuerte, P.M. and Riccobono, F. (2014). In-use emissions testing with portable emissions measurement systems (PEMS) in the current and future European vehicle emissions legislation: Overview, underlying principles and expected benefits. *SAE Int. J. Commer. Veh.* 7: 199–215.

Walker, A.P., Blakeman, P.G., Ilkenhans, T., Magnusson, B., McDonald, A.C., Kleijwegt, P., Stunnenberg, F. and Sanchez, M. (2004). The development and in-field demonstration of highly durable SCR catalyst systems. *SAE Technical Paper* 2004-01-1289.

Wang, X., Westerdahl, D., Hu, J., Wu, Y., Yin, H., Pan, X. and Zhang, M.K. (2012). On-road diesel vehicle emission factors for nitrogen oxides and black carbon in two Chinese cities. *Atmos. Environ.* 46: 45–55.

Wu, X., Wu, Y., Zhang, S., Liu, H., Fu, L. and Hao, J. (2016). Assessment of vehicle emission programs in China during 1998–2013: Achievement, challenges and implications. *Environ. Pollut.* 214: 556–567.

Wu, Y., Wang, R., Zhou, Y., Lin, B., Fu, L., He, K. and Hao, J. (2011). On-road vehicle emission control in Beijing: Past, present, and future. *Environ. Sci. Technol.* 45: 147–153.

Wu, Y., Zhang, S., Li, M., Ge, Y., Shu, J., Zhou, Y., Xu, Y., Hu, J., Liu, H., Fu, L., He, K. and Hao, J. (2012). The challenge to $NO_x$ emission control for heavy-duty diesel vehicles in China. *Atmos. Chem. Phys.* 12: 9365–9379.

Wu, Y., Yang, L., Zheng, X., Song, S., Li, J. and Hao, J. (2014). Characterization and source apportionment of particulate PAHs in the roadside environment in Beijing. *Sci. Total Environ.* 470–471: 76–83.

Yue, X., Wu, Y., Hao, J., Pang, Y., Ma, Y., Li, Y., Li, B. and Bao, X. (2015). Fuel quality management versus vehicle emission control in China, status quo and future perspectives. *Energy Policy* 79: 87–98.

Zhang, K., Hu, J., Gao, S., Liu, Y., Huang, X. and Bao, X. (2010). Sulfur content of gasoline and diesel fuels in northern China. *Energy Policy* 38: 2934–2940.

Zhang, S., Wu, Y., Liu, H., Wu, X., Zhou, Y., Yao, Z., Fu, L., He, K. and Hao, J. (2013) Historical evaluation of vehicle emission control in Guangzhou based on a multi-year emission inventory. *Atmos. Environ.* 76: 32–42.

Zhang, S., Wu, Y., Wu, X., Li, M., Ge, Y., Liang, B., Xu, Y., Zhou, Y., Liu, H., Fu, L. and Hao, J. (2014a). Historic and future trends of vehicle emissions in Beijing, 1998–2020: A policy assessment for the most stringent vehicle emission control program in China. *Atmos. Environ.* 89: 216–229.

Zhang, S., Wu, Y., Hu, J., Huang, R., Zhou, Y., Bao, X., Fu, L. and Hao, J. (2014b). Can Euro V heavy-duty diesel engines, diesel hybrid and alternative fuel technologies mitigate $NO_x$ emissions? New evidence from on-road tests of buses in China. *Appl. Energy* 132: 118–126.

Zhang, S., Wu, Y, Liu, H, Huang, R., Yang, L., Li, Z., Fu, L. and Hao, J. (2014c). Real-world fuel consumption and $CO_2$ emissions of urban public buses in Beijing. *Appl. Energy* 113: 1645–1655.

Zhao, B., Wang, S., Liu, H., Xu, J., Fu, K., Klimont, Z., Hao, J. and He, K., Cofala, J. and Amann, M. (2013). $NO_x$ emissions in China: Historical trends and future perspectives. *Atmos. Chem. Phys.* 13: 9869–9897.

Zheng, B., Huo, H., Zhang, Q., Yao, Z., Wang, X., Yang, X., Liu, H. and He, K. (2014). High-resolution mapping of vehicle emissions in China in 2008. *Atmos. Chem. Phys.* 14: 9787–9805.

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