

# Effects of Particle Filters and Selective Catalytic Reduction on Heavy-Duty Diesel Drayage Truck Emissions at the Port of Oakland

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## S Supporting Information

**ABSTRACT:** Effects of fleet modernization and use of diesel particle filters (DPF) and selective catalytic reduction (SCR) on heavy-duty diesel truck emissions were studied at the Port of Oakland in California. Nitrogen oxides (NO<sub>x</sub>), black carbon (BC), particle number (PN), and size distributions were measured in the exhaust plumes of ~1400 drayage trucks. Average NO<sub>x</sub>, BC, and PN emission factors for newer engines (2010–2013 model years) equipped with both DPF and SCR were 69 ± 15%, 92 ± 32%, and 66 ± 35% lower, respectively, than 2004–2006 engines without these technologies. Intentional oxidation of NO to NO<sub>2</sub> for DPF regeneration increased tailpipe NO<sub>2</sub> emissions, especially from older (1994–2006) engines with retrofit DPFs. Increased deployment of advanced controls has further skewed emission factor distributions; a small number of trucks emit a disproportionately large fraction of total BC and NO<sub>x</sub>. The fraction of DPF-equipped drayage trucks increased from 2 to 99% and the median engine age decreased from 11 to 6 years between 2009 and 2013. Over this period, fleet-average BC and NO<sub>x</sub> emission factors decreased by 76 ± 22% and 53 ± 8%, respectively. Emission changes occurred rapidly compared to what would have been observed due to natural (i.e., unforced) turnover of the Port truck fleet. These results provide a preview of more widespread emission changes expected statewide and nationally in the coming years.



## INTRODUCTION

Heavy-duty diesel trucks are a major source of nitrogen oxides (NO<sub>x</sub>) and diesel particulate matter (PM) emissions in the United States.<sup>1,2</sup> These emissions contribute to fine particulate matter (PM<sub>2.5</sub>) and ozone air quality problems,<sup>3,4</sup> and may lead to adverse health effects for exposed individuals.<sup>3,5–7</sup> Black carbon (BC) is a potent absorber of solar radiation and comprises the majority of diesel PM mass emissions.<sup>8</sup> Recent studies have suggested control of diesel BC emissions as a strategy to help mitigate global warming.<sup>9,10</sup>

PM and NO<sub>x</sub> emission standards have been established nationally to limit emissions from heavy-duty diesel trucks. Current standards are typically met using exhaust after-treatment control technologies. Trucks with 2007 and newer engines are equipped with a diesel particle filter (DPF), and trucks with 2010 and newer engines also include selective catalytic reduction (SCR) systems for NO<sub>x</sub> control. DPFs can be installed as retrofits on older engines that are already in use.<sup>11</sup>

Previous studies have shown that DPFs can reduce PM mass emissions from heavy-duty diesel engines by >90%.<sup>12–14</sup> Trapped carbon particles are oxidized to regenerate the filter either passively, by continuous reaction with nitrogen dioxide (NO<sub>2</sub>) that is formed by catalytic oxidation of exhaust nitric oxide (NO), or actively, for example by periodic injection of fuel. The intentional conversion of NO to NO<sub>2</sub> in passively

regenerated systems leads to increased primary NO<sub>2</sub> emissions and higher NO<sub>2</sub>/NO<sub>x</sub> emission ratios.<sup>13,15–17</sup> These emissions changes are of concern because NO<sub>2</sub> is toxic and increased primary NO<sub>2</sub> emissions promote ozone formation. Another concern is that DPF-related reductions in overall particle mass emissions may favor increased homogeneous nucleation rather than condensation of gases onto existing particle surfaces, thereby increasing formation of ultrafine particles (UFP) and total particle number (PN) emissions.<sup>12,18,19</sup> UFP (diameters <0.1 μm) can induce inflammatory and oxidant stress responses that have been linked to cardiovascular disease and mortality.<sup>20–22</sup> The increases in NO<sub>2</sub> and UFP emissions are both associated with high catalytic loading within the DPF and high exhaust temperatures.<sup>13,18</sup>

In California, the phase-in and use of DPFs has been greatly accelerated for drayage trucks, which are commonly used for short-haul freight transport at ports and rail yards. Over a three-year period between January 2010 and December 2012, all drayage trucks were required to be equipped with DPFs, either via retrofit or engine replacement.<sup>23</sup> Table S1 of the Supporting Information (SI) presents the schedule for required changes to

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the truck fleet in more detail. Emissions from California drayage trucks have been evaluated as this fleet modernization program has been implemented.<sup>17,24–26</sup> At the Ports of Los Angeles and Long Beach in Southern California, the drayage fleet was almost entirely replaced with new trucks, so the mean age of trucks decreased from 12.7 years to 2.5 years between 2008 and 2010.<sup>17</sup> Associated emissions reductions observed for carbon monoxide, NO<sub>x</sub>, and exhaust opacity were 30, 48, and 54%, respectively.<sup>17</sup> In contrast to the Southern California ports where truck replacement predominated, there was significant retrofitting of DPFs on older drayage trucks at the Port of Oakland. Dallmann et al.<sup>24</sup> reported a 41% reduction in NO<sub>x</sub> and a 54% reduction in BC emissions between 2009 and 2010 after pre-1994 trucks were banned and trucks with 1994–2003 engines were either retrofitted or replaced with newer equipment. The BC reductions resulted primarily from increased use of DPFs, whereas NO<sub>x</sub> reductions were attributed to fleet modernization, as the newer engines met more stringent NO<sub>x</sub> emission standards. The initial round of changes to the drayage truck fleet at the Port of Oakland led to an increased proportion of trucks with 2004 and newer engines, as well as a reduction in mean engine age from 11.0 to 8.3 years.<sup>24</sup>

The current study builds on previous work at the Port of Oakland and features new field measurements including additional pollutants not previously measured, namely NO<sub>2</sub>, PN, and particle size distributions. Also, emission factors for individual trucks in the current study were linked to engine attributes through transcribed license plate data. This linkage makes it possible to compare emissions across different control technology groups, in addition to quantifying changes in fleet-average emission factors over time.

## MATERIALS AND METHODS

Truck emissions were measured in November 2011 and March 2013 near the Port of Oakland. Following Dallmann et al.,<sup>24</sup> pollutant concentrations in the exhaust plumes of individual trucks were measured from an instrumented van that was positioned on an overpass. Westbound trucks heading toward the Port drove underneath on a major access road (SI Figure S1). The roadway at this location is level, and trucks were observed to be accelerating from a traffic light ~50 m before the sampling point or cruising at a speed of ~30 mph. Exhaust/ambient air mixtures sampled above the roadway were delivered to the van via a flexible aluminum duct, as shown in SI Figure S2. Concentrations of CO<sub>2</sub>, NO<sub>x</sub>, NO, BC, PN, and particle size distributions were measured at 1 Hz or faster, using instruments listed in SI Table S2. A video camera at roadway level recorded truck license plates, which were later transcribed and matched with data in California's Drayage Truck Registry, including engine model year and DPF retrofit status.

A sample pollutant concentration time series showing peaks associated with three trucks that drove by in succession is presented in SI Figure S3. Pollutant concentration peaks were integrated to calculate fuel-based emission factors, expressed in units of amount of pollutant emitted per kg of fuel burned, using a carbon balance method:<sup>27</sup>

$$E_p = \frac{\int_{t_1}^{t_2} ([P]_t - [P]_{t_1}) dt}{\int_{t_1}^{t_2} ([CO_2]_t - [CO_2]_{t_1}) dt} \frac{44}{12} w_c \quad (1)$$

The emission factor for pollutant P ( $E_p$ ) is calculated over the time interval  $t_1 \leq t \leq t_2$ , with  $t_1$  and  $t_2$  determined

independently by the inflection points of each peak to account for the fact that instruments operated with different response times. The numerator and denominator respectively represent the baseline-subtracted peak areas for pollutant P and CO<sub>2</sub>. When [P] and [CO<sub>2</sub>] have mass concentration units (e.g.,  $\mu\text{g m}^{-3}$ ), the ratio compares the relative abundances of pollutant P and CO<sub>2</sub> present in the exhaust. The weight fraction of carbon in diesel fuel ( $w_c = 0.87$ ) is used to convert emission factors from per mass of carbon to mass of fuel burned,<sup>27</sup> and the factor of 44/12 converts CO<sub>2</sub> to carbon mass. This carbon balance assumes that all fuel carbon is converted to CO<sub>2</sub> during combustion, with negligible emissions of CO and VOC relative to emitted CO<sub>2</sub>.<sup>16</sup> NO<sub>2</sub> emission factors for each truck were computed as the difference of NO<sub>x</sub> and NO emission factors, which were measured simultaneously using two separate chemiluminescent analyzers. NO<sub>x</sub> emission factors were calculated using the molecular weight of NO<sub>2</sub>.

Emission factors were computed for trucks when the peak CO<sub>2</sub> concentration rose more than 7% above baseline roadway concentrations, following Dallmann et al.<sup>24</sup> The baseline was taken to be the concentration measured just prior to the passage of a truck, with the timing determined from the roadway level video. Emission factors were computed only when the CO<sub>2</sub> peak could be definitively attributed to a single truck. Thus, no plume analyses were attempted when multiple trucks drove by at the same time or in close succession. In cases where CO<sub>2</sub> plume capture was successful but without clearly detectable peaks for other pollutants, near-zero values of emission factors were still computed, as illustrated in SI Figure S3.

The PN emission factors reported below were derived from an ultrafine, water-based condensation particle counter (CPC), as noted in SI Table S2. Normalized particle size distributions were measured using a fast mobility particle sizer (FMPS) to estimate size-resolved PN emission factors:

$$\Delta E_{PN} = \frac{\Delta N}{N} E_{PN} \quad (2)$$

Particle number concentrations measured in each size bin at the leading side of the particle number concentration peak,  $\Delta N$ , were baseline-subtracted and normalized to the total particle number concentration,  $N$ . The product of this normalized size distribution and the FMPS-derived PN emission factor,  $E_{PN}$ , gives the particle emission rate in each size bin in units of  $10^{15}$  particles emitted per kg of fuel burned.

The configuration of the particle sampling instruments used in this study is described in the SI and shown in SI Figure S4. An in-line dilution system was used to avoid exceeding the concentration limits of the CPCs used to measure PN concentrations. The dilution rate was actively monitored during the study. An aerosol photoacoustic absorption spectrometer was used in conjunction with an aethalometer to measure BC concentrations. The former instrument aided in postprocessing the aethalometer data to minimize the influence of the aethalometer's filter loading artifact, as described in the SI. Prior to field measurements, the full suite of instruments was staged and tested in the laboratory. In this assessment, we verified the NO<sub>2</sub> conversion efficiency of the chemiluminescent NO<sub>x</sub> analyzers, identified a time response issue with a CO<sub>2</sub> analyzer used in prior studies at the Port of Oakland, and verified the CO<sub>2</sub> analyzer used in the current study did not suffer from the same issue. Additionally, we evaluated a sampling artifact of the FMPS in which an artificial increase in

**Table 1. Average Emission Factors ( $\pm$  95% Confidence Interval) for Heavy-Duty Diesel Drayage Trucks Characterized by Engine Control Technology and Engine Model Year<sup>a</sup>**

fleet or truck category	range of engine model years	median engine model year	number of trucks <sup>c</sup>	NO <sub>x</sub> (g kg <sup>-1</sup> )	NO <sub>2</sub> (g kg <sup>-1</sup> )	NO <sub>2</sub> /NO <sub>x</sub> emission ratio	BC (g kg <sup>-1</sup> )	PN (10 <sup>15</sup> particles kg <sup>-1</sup> )
<b>2009 Fleet<sup>b</sup></b> (2% DPF, 0% SCR)	1970–2009	1997	169–172	32.6 $\pm$ 2.3	1.11 $\pm$ 0.58	0.034 $\pm$ 0.018	1.15 $\pm$ 0.19	N/A
<b>2011 Fleet</b> (54% DPF, 2% SCR)	1994–2011	2004	359–378	18.0 $\pm$ 1.2	2.10 $\pm$ 0.39	0.117 $\pm$ 0.023	0.67 $\pm$ 0.14	3.59 $\pm$ 0.81
<b>2013 Fleet</b> (99% DPF, 9% SCR)	1994–2013	2007	960–1005	15.4 $\pm$ 0.9	2.84 $\pm$ 0.22	0.184 $\pm$ 0.018	0.28 $\pm$ 0.05	2.47 $\pm$ 0.48
<b>Retrofit DPF</b>	1994–2006	1998	390–401	26.0 $\pm$ 1.3	3.91 $\pm$ 0.38	0.150 $\pm$ 0.017	0.32 $\pm$ 0.06	2.61 $\pm$ 0.76
<b>No DPF</b>	2004–2006	2005	178–188	16.5 $\pm$ 1.7	0.56 $\pm$ 0.28	0.034 $\pm$ 0.018	1.11 $\pm$ 0.26	4.72 $\pm$ 0.97
<b>DPF</b>	2007–2009	2008	657–695	11.9 $\pm$ 0.9	2.68 $\pm$ 0.27	0.225 $\pm$ 0.029	0.26 $\pm$ 0.06	2.52 $\pm$ 0.62
<b>DPF + SCR</b>	2010–2013	2011	93–99	5.1 $\pm$ 1.2	1.14 $\pm$ 0.27	0.221 $\pm$ 0.084	0.09 $\pm$ 0.04	1.59 $\pm$ 1.15

<sup>a</sup>Results shown in the last four rows are based on combined data from 2011 and 2013. <sup>b</sup>2009 emission factors are from Dallmann et al.<sup>24</sup> after adjustment to account for a CO<sub>2</sub> sampling artifact and consistent application of a time-dependent correction of the aethalometer, as described in the SI. The 2009 NO<sub>2</sub> emission factor was estimated based on the NO<sub>2</sub>/NO<sub>x</sub> emission ratio measured in this study in 2011 for trucks without DPFs, as indicated in the text. <sup>c</sup>The number of trucks used for each fleet or truck category analysis depended on the data available from each instrument; the maximum number in the given range corresponds to NO<sub>x</sub>, NO<sub>2</sub>, and NO<sub>2</sub>/NO<sub>x</sub> calculations and the minimum number typically refers to UFP. The sample size for BC analysis generally falls in the middle of the range.

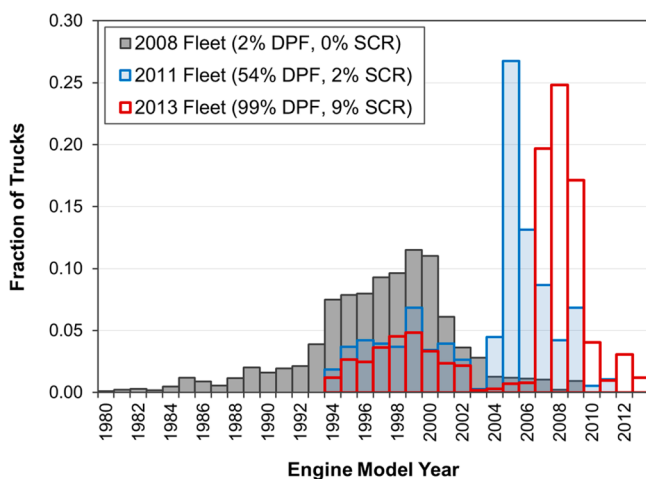
UFP less than 10 nm was reported during periods of rapidly decreasing PN concentrations, which subsequently guided our use of the data from this instrument. These instrument evaluations and related issues are discussed in greater detail in the SI.

## RESULTS AND DISCUSSION

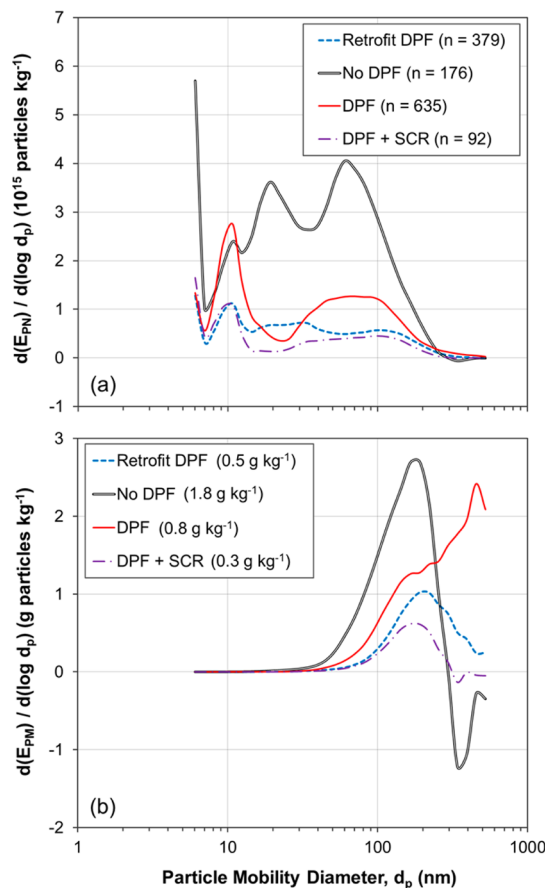
**Port Truck Age Distribution.** The age distribution of trucks operating at the Port of Oakland changed dramatically over a short period of time, as shown in Figure 1. In 2008, the median engine age for Port trucks was 11 years, and only 2% of trucks had 2007 or newer engines equipped with DPFs.<sup>28</sup> By early 2013, 99% of trucks were equipped with DPFs, 9% had 2010 or newer engines with both DPF and SCR systems, and median engine age decreased to 6 years.

**Average Emission Rates.** Fleet-average emission factors for Port trucks are presented in Table 1. Emission factors measured previously in 2009<sup>24</sup> are compared to those measured in 2011 and 2013. Also, emission factors from the 2011 and

2013 measurement campaigns were together disaggregated into four truck categories based on engine model year and installed emission controls. Results are reported in Table 1 and shown in Figures 2 and 4, and SI Figures S9 and S10 for (1) 1994–2006



**Figure 1.** Distribution of heavy-duty diesel truck engine model years at the Port of Oakland prior to California's Drayage Truck Regulation in 2008<sup>28</sup> and after phased implementation of the regulation in 2011 and 2013. The model year distribution from 2008 is based on the truck chassis; some engines may be one year older than the chassis.



**Figure 2.** Characteristic particle (a) number and (b) mass emission rate distributions for each emission control technology, based on combined 2011 and 2013 data. The particle mass emission factor estimated from each size distribution is noted in the figure legend. Note that data above  $\sim$ 200 nm in (b) are not reliable, given low particle number concentrations in this size range as shown in (a).

engines with retrofit DPFs, (2) 2004–2006 engines without DPFs, (3) 2007–2009 engines with DPFs, and (4) 2010–2013 engines with DPFs and SCR. Unless explicitly labeled as a retrofit, DPF and SCR controls were installed as original equipment at the time of manufacture. In Table 1 and elsewhere, uncertainty ranges represent 95% confidence intervals and model years refer to the engine, not the truck chassis.

**Nitrogen Oxides.** Due to fleet modernization and associated decreases in median engine age, the fleet-average  $\text{NO}_x$  emission factor decreased by  $53 \pm 8\%$  between 2009 and 2013 (Table 1). The  $\text{NO}_2/\text{NO}_x$  emission ratio in 2009 was not measured, but was assumed to be similar to that for 187 trucks without DPFs measured in 2011 (Table 1). A baseline  $\text{NO}_2$  emission factor for the 2009 fleet was estimated by applying this  $\text{NO}_2/\text{NO}_x$  ratio of  $0.03 \pm 0.02$  to the measured fleet-average  $\text{NO}_x$  emission factor. The  $\text{NO}_2/\text{NO}_x$  emission ratio increased from 0.03 to 0.18 between 2009 and 2013 as use of DPFs on Port trucks became universal.

$\text{NO}_2/\text{NO}_x$  emission ratios were highest for newer trucks with DPFs, with or without SCR systems, but engines with SCR had lower absolute  $\text{NO}_2$  and  $\text{NO}_x$  emission rates (Table 1, SI Figure S9). The  $\text{NO}_2$  emission rate for trucks with SCR systems was comparable to the low value determined for the pre-DPF truck fleet measured in 2009. This highlights the important role of SCR in mitigating the undesired increase in primary  $\text{NO}_2$  emissions associated with the use of DPFs to control exhaust PM emissions.

**Black Carbon.** Between 2009 and 2013, fleet-average BC emission factors decreased by  $76 \pm 22\%$  (Table 1). BC emission factors for older trucks with retrofit DPFs and 2007–2009 trucks originally equipped with DPFs were similar (Table 1, SI Figure S10). The newest trucks with 2010+ engines equipped with both DPFs and SCR had the lowest BC emission factors. Relative to modern trucks (2004–2006 engines) without these emission controls, trucks with pre-2010 engines equipped with DPFs emitted  $74 \pm 30\%$  less BC. The newest trucks (2010+ engines) emitted  $92 \pm 32\%$  less BC than the 2004–2006 trucks, which is consistent with prior laboratory studies of DPF effectiveness.<sup>12–14</sup> As the newest trucks enter into Port service, BC emissions could decrease to  $\sim 10\%$  of 2009 levels, with little if any increase in primary  $\text{NO}_2$  emissions.

**Particle Number.** The PN emission rate measured for 178 trucks without DPFs is used here as a reference value to approximate baseline conditions in 2009 (Table 1). Relative to this baseline of  $(4.7 \pm 1.0) \times 10^{15}$  particles  $\text{kg}^{-1}$ , there was a  $47 \pm 25\%$  reduction in the fleet-average PN emission rate by 2013, when DPFs were required on all Port trucks. Trucks with 2010+ engines had the lowest PN emission rates, emitting one-third the number of particles per kg of fuel burned compared to trucks without DPFs (Table 1, SI Figure S10).

PN emission factors presented above are based on total particle number concentrations measured with an ultrafine water-based CPC. As presented in SI Figure S11 and Table S3, results were highly correlated ( $R^2 = 0.86$ ) but 30% higher, on average, than PN emission factors for the same trucks calculated from measurements made using an ultrafine butanol-based CPC. This difference could be due to CPC sensitivity to particle composition that depends on the condensing fluid (i.e., water versus butanol), or due to other differences in CPC design.<sup>29</sup> PN emission factors derived from ultrafine water-based CPC and FMPS measurements were not

as well correlated ( $R^2 = 0.49$ ). On average, emission factors based on the ultrafine water-based CPC were 80% higher than those based on the FMPS. The lower values derived from FMPS measurements may in part be because the ultrafine CPC measures particles as small as 2.5 nm, whereas the low cutoff of the FMPS is 5.6 nm. This finding agrees with Jeong and Evans,<sup>30</sup> who noted that ultrafine water-based CPC measurements of PN concentration exceed FMPS measurements. In contrast, Zimmerman et al.<sup>31</sup> found that the FMPS can overstate PN concentrations when measuring emissions from high-emitting vehicles at high time resolution.

Emission factor-weighted particle size distributions were used to derive a characteristic particle number emission profile for each truck category. Measured size distributions for each truck were weighted by corresponding FMPS-derived PN emission factors. As shown in Figure 2, particle emissions ranging in size between 5.6 and  $\sim 300$  nm were measured, with a majority occurring in the ultrafine mode below 100 nm. Particle size distributions for all four groupings of trucks include an apparent sharp increase in the smallest size bin of the FMPS. We present these data as measured, though it is unclear if they are truly indicative of a peak in the number concentration of particles smaller than the lower sizing limit of the FMPS.

Figure 2 shows that the average size distribution for all trucks without DPFs was trimodal, including broad peaks around 10, 20, and 80 nm. Overall, DPFs appear to be most effective in reducing the emission rate of particles larger than  $\sim 15$  nm. On average, the emission rates of such particles from trucks without filters were approximately 3.5 times those from DPF-equipped trucks. These results indicate that use of DPFs on drayage trucks for controlling particle mass does not increase the emission factor of nucleation mode particles, which was a potential concern raised in other studies.<sup>12,18</sup> DPFs on trucks with 2007 and newer engines typically include active filter regeneration systems (e.g., periodic injection of unburned fuel to oxidize trapped particles). Nucleation is likely to occur during such active regeneration events,<sup>18</sup> with increased emissions of  $<30$  nm particles.<sup>32</sup> In this study, the emission factor of  $\sim 10$  nm particles from 2007 to 2009 DPF-equipped engines was 2.5 times the levels measured from both older truck engines with retrofit DPFs and 2010+ engines equipped with DPFs and SCR.

**Particle Mass.** Since direct measurements of PM mass were not made during this study, the size-resolved FMPS particle count data was used to estimate mass emissions. Assuming spherical particles with a density of  $1 \text{ g cm}^{-3}$  across the entire particle size range, PN distributions were converted into mass emission distributions. The PM emission factor for each truck category could ideally be estimated from the integrated area under each respective mass emission rate distribution. However, low number concentrations in the larger size ranges result in noise in the upper size bins that is magnified when number concentrations are converted to mass concentrations, as seen in Figure 2b. Therefore, PM emission factors corresponding to each truck category were determined assuming log-normal distributions and doubling the area to the left of the apparent peak value of each mass emission rate distribution. This peak in the mass emission distribution was typically around 200 nm. Recent studies indicate that additional particle mass exists beyond the upper size limit of the FMPS for diesel exhaust.<sup>33,34</sup> Therefore, the PM emission factors derived from FMPS measurements and reported in Figure 2b may understate the true PM emission rates. The estimated PM

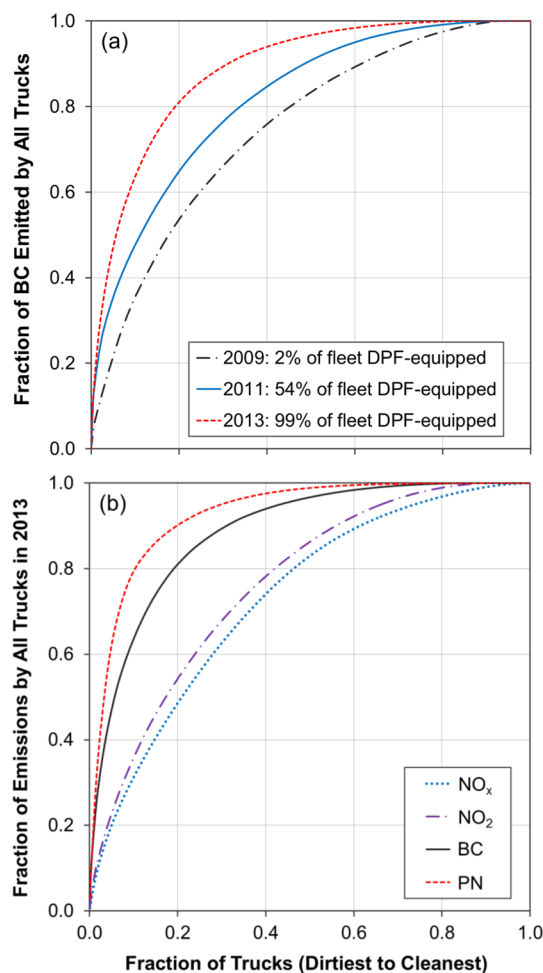
emission factor for 2010+ engines equipped with both DPFs and SCR was  $\sim 86\%$  lower than that found for 2004–2006 engines without these emission controls. This decrease in PM emissions is a little smaller than the 92% decrease found for BC (Table 1). Similarly, the average reduction in estimated PM emission factor for all DPF-equipped trucks compared to trucks without filters ( $\sim 72\%$ ) was slightly lower than that found for BC (80%).

**Pollutant Relationships.** As shown in SI Figure S12, the highest emitters of BC tended to have low emissions of UFP and  $\text{NO}_2$ —and vice versa—regardless of the type or vintage of emission control equipment. Such a relationship between BC and PN has been observed previously.<sup>27</sup> This result is consistent with the hypothesis that UFP formation is suppressed when large amounts of particle surface area are available, such that condensation onto existing particle surfaces is favored over nucleation to form UFP.<sup>19</sup> Likewise, the relationship between BC and  $\text{NO}_2$  has been reported previously,<sup>16</sup> and is the expected result of well-functioning DPF systems, which reduce BC mass emissions while deliberately oxidizing NO to  $\text{NO}_2$  to aid in filter regeneration.

**Emission Factor Distributions.** As fleet-average emission factors have decreased over time, emission factor distributions have become increasingly skewed, such that a small fraction of the fleet is responsible for an increasing fraction of total emissions. As shown in Figure 3 and SI Figure S13, particle-related emission factor distributions are more skewed than those for nitrogen oxides. In 2013, the highest emitting 10% of trucks were responsible for 65% of total BC and 80% of total PN, compared to only 32% of total  $\text{NO}_x$  emissions (Figure 3b). The skewness of  $\text{NO}_x$  emission factor distributions is increasing, though, and this trend is likely to continue as the number of engines equipped with SCR increases in future years (SI Figure S13a).

Emission factor distributions are shown separately for each engine model year, as measured in 2011 and 2013, in Figure 4. Trucks equipped with DPF and SCR systems not only had the lowest BC and  $\text{NO}_x$  emission factors, but also showed the least amount of variability in measured emission rates. The upper range of measured emission rates for many individual engine model years increased in 2013 relative to 2011, suggesting possible degradation or failure of some installed emission control systems over time. Our analysis identified two DPF-equipped trucks as the highest BC emitters in 2013 (Figure 4a). These trucks had emission factors of  $\sim 10 \text{ g BC kg}^{-1}$ , significantly higher than the 2013 fleet-average of  $0.28 \pm 0.05 \text{ g kg}^{-1}$  and approximately double the emission rate of next highest-emitting truck. These two high-emitting trucks represented 0.2% of the total number of trucks measured, but were responsible for 7% of total BC emissions (Figure 3b). This analysis also shows that trucks with 2007–2009 engines frequently emit  $\text{NO}_x$  at levels that are similar to what is observed from older trucks, even though the average emission rate for older trucks is approximately twice as high (Table 1 and Figure 4b). In summary, even though average emissions of BC and  $\text{NO}_x$  have decreased, some newer trucks were observed to emit BC and  $\text{NO}_x$  at high levels.

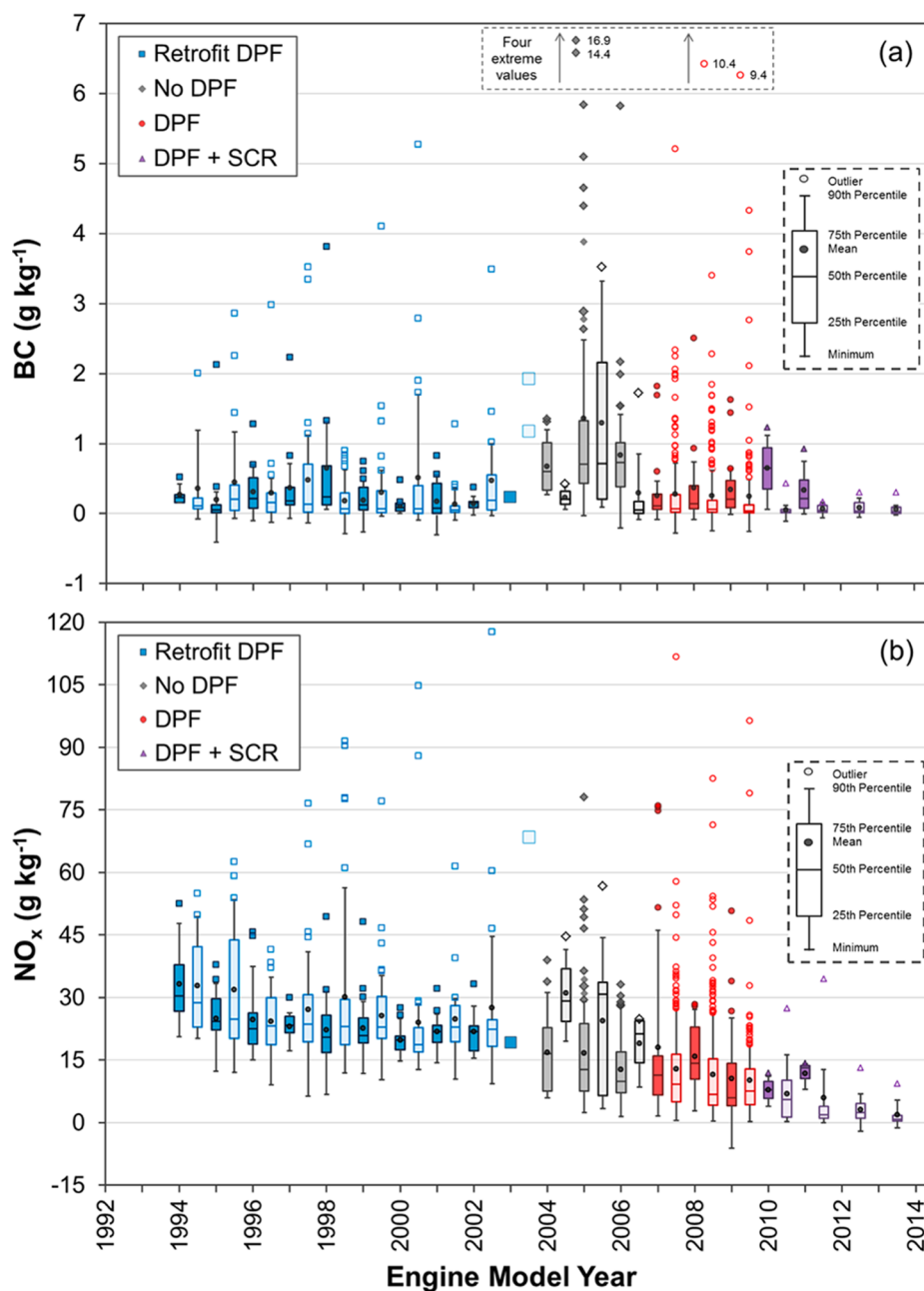
Identification and follow-up actions leading to repair of high-emitting trucks may be needed to help ensure that emission control systems remain in good working order, and to extend the early success in emission control efforts reported here. For instance, if the top 10% of BC emitters from the 2013 fleet were removed (Figure 3b), then fleet-average BC emissions



**Figure 3.** Cumulative emission factor distributions for (a) BC over time and (b) multiple pollutants in 2013, with trucks ranked from highest to lowest in terms of emission factors.

would decrease from  $0.28 \pm 0.05$  to  $0.11 \pm 0.01 \text{ g kg}^{-1}$ . The trucks that comprise this high emitting subfleet had an average BC emission factor of  $1.80 \pm 0.10 \text{ g kg}^{-1}$ , which was approximately six times the 2013 fleet-average value. A number of the trucks included in the top 10% were measured multiple times in this study, and 64% of the repeat measurements were also included in the top 10% of BC emissions. This suggests that the high emitter problem for BC is more often chronic rather than intermittent in nature. If all repeat measurements of BC by trucks classified as in the dirtiest 10% of the 2013 fleet are included, the average BC emission factor of  $1.36 \pm 0.10 \text{ g kg}^{-1}$  remains much higher than the overall fleet average. Elimination of these high-emitting trucks through repair or replacement would further increase fleet-average BC reductions measured in this study from  $76 \pm 21\%$  (Table 1) to  $90 \pm 22\%$ .

**Emissions Variability.** Differences in operating conditions can influence pollutant emission rates. This variability can be studied in the laboratory using different driving cycles, but laboratory testing is costly and generally limited to a small sample size. In-use emission evaluations as in the current study, on the other hand, can assess the emission performance of thousands of trucks under real-world conditions. These measurements provide emissions snapshots, though, and may not capture relevant variability in emissions. In the current study, we used repeat measurements of trucks that drove by

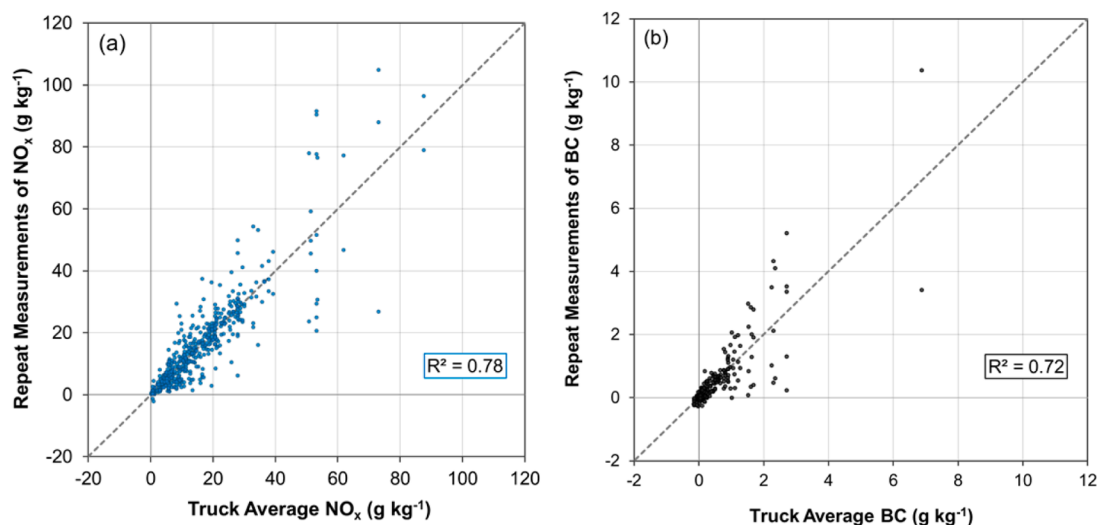


**Figure 4.** Distribution of (a) BC and (b)  $\text{NO}_x$  emission factors across engine model years for each individually measured truck. The truck categories as measured in 2011 are shown in shaded boxes and whiskers, and those measured in 2013 are shown in transparent boxes and whiskers. The larger number of outliers for 2013 measurements does not reflect a greater fraction of higher emitting trucks, but is instead the result of generally larger sample sizes during that campaign (Table 1). Also, note that there are four extreme outliers for the BC distribution that exceed the range shown.

multiple times to characterize emissions variability at our sampling location.

Repeat measurements of emissions from 207 individual trucks are plotted in Figure 5 and SI Figure S14 against corresponding average emission factors for each truck. Scatter about the indicated 1:1 line is due to variability in emission factors. Emissions rates for  $\text{NO}_x$  and BC were found to vary less than  $\text{NO}_2$  and PN. Measurement uncertainties contribute to variability in  $\text{NO}_2$  emission factors especially, as  $\text{NO}_2$  was calculated by difference (i.e.,  $\text{NO}_2 = \text{NO}_x - \text{NO}$ ). While fleet-average results for PN can still be evaluated, variability in emissions of this pollutant limits the usefulness of single snapshot measurements to characterize emissions from individual trucks.

**Emissions Representativeness.** Measurements made in this study do not include trucks traveling at highway speeds, where engine load and exhaust temperatures are high. This is relevant because these parameters can affect emission control system performance. For example, SCR systems are ineffective when exhaust temperature is low, which can occur during cold starts and at low load/low speed.<sup>35</sup> However,  $\text{NO}_x$  emissions from the SCR-equipped trucks in this study were very low (Figure 4b), which suggests that SCR systems were likely functioning when emissions were sampled. Increased UFP emissions from DPF-equipped trucks have been reported during highway driving when exhaust temperatures were high and during active DPF regeneration events.<sup>18,32</sup> Active filter regeneration can also increase emitted PM mass.<sup>32</sup> In this



**Figure 5.** Repeat (a)  $\text{NO}_x$  and (b) BC measurements for 207 individual trucks, with each individual measurement plotted on the vertical axis against the corresponding average emission factor for each truck on the horizontal axis. Repeatability of the measurement is indicated by the degree of scatter of data points about the dashed 1:1 line.

study, exhaust temperatures were not measured and it was not possible to determine the extent to which filters were actively regenerating.

**Acceleration of Emissions Reductions.** Emission reductions observed in this study at the Port of Oakland over  $\sim 3.5$  years are nearly double the 39 and 30% reductions in BC and  $\text{NO}_x$  emission factors measured for trucks at the nearby Caldecott Tunnel over a period of 9 years.<sup>8</sup> Trucks using the Caldecott Tunnel were not subject to any retrofit/replacement requirements during the period from 1997 to 2006 considered by Ban-Weiss et al.<sup>8</sup> Emission reductions at the Port have clearly occurred at a pace well beyond what can be achieved by natural fleet turnover alone. Programs requiring accelerated replacement of older trucks now extend beyond ports and rail yards to include heavy-duty trucks operating anywhere in California, regardless of origin or destination. Results of these local, accelerated changes at the Port of Oakland therefore provide a preview of how diesel truck emissions are likely to change across the state in the next few years, as well as nationally as larger numbers of newer trucks with advanced emission control systems enter into service.

## ■ ASSOCIATED CONTENT

### 📄 Supporting Information

The Supporting Information (SI) includes additional details about the sampling location and method, laboratory assessments of sampling artifacts, and supplementary results, as specified in the manuscript. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b01117.

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### Notes

The authors declare no competing financial interest.

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