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Effects of Diesel Particle Filter Retrofits and Accelerated Fleet Turnover on Drayage Truck Emissions at the Port of Oakland

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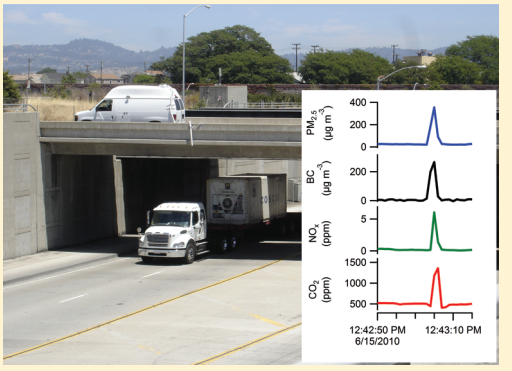
ABSTRACT: Heavy-duty diesel drayage trucks have a disproportionate impact on the air quality of communities surrounding major freight-handling facilities. In an attempt to mitigate this impact, the state of California has mandated new emission control requirements for drayage trucks accessing ports and rail yards in the state beginning in 2010. This control rule prompted an accelerated diesel particle filter (DPF) retrofit and truck replacement program at the Port of Oakland. The impact of this program was evaluated by measuring emission factor distributions for diesel trucks operating at the Port of Oakland prior to and following the implementation of the emission control rule. Emission factors for black carbon (BC) and oxides of nitrogen (NO_x) were quantified in terms of grams of pollutant emitted per kilogram of fuel burned using a carbon balance method. Concentrations of these species along with carbon dioxide were measured in the exhaust plumes of individual diesel trucks as they drove by en route to the Port. A comparison of emissions measured before and after the implementation of the truck retrofit/replacement rule shows a 54 ± 11% reduction in the fleet-average BC emission factor, accompanied by a shift to a more highly skewed emission factor distribution. Although only particulate matter mass reductions were required in the first year of the program, a significant reduction in the fleet-average NO_x emission factor (41 ± 5%) was observed, most likely due to the replacement of older trucks with new ones.



INTRODUCTION

Heavy-duty diesel trucks are a significant source of fine particulate matter ($PM_{2.5}$), black carbon (BC), and oxides of nitrogen (NO_x) emissions.[1,2] Diesel NO_x emissions are a precursor to secondary air pollutants including ozone, particulate nitrate, and nitric acid. Exposure to diesel PM has been associated with a variety of adverse health effects.[3,4] This is of particular concern to populations in close proximity to highly trafficked roadways,[5] including communities near major freight-handling facilities such as ports and rail yards.[6] Air quality impacts may be exacerbated by older trucks with higher pollutant emissions in drayage service at port and rail yards. For example, as shown in Figure 1 for the Port of Oakland as of late 2008, 17% of drayage trucks had 1993 or older model engines, and only 6% were 2004 or newer.[7]

Recognizing the air quality impacts of diesel truck emissions, the California Air Resources Board (CARB) implemented a drayage truck emission control regulation at ports and intermodal rail yards statewide that took effect in 2010 and will become increasingly stringent over time.[8] Unlike current national emission standards that require low emission levels from the new heavy-duty engines sold each year, the drayage truck regulation focuses on achieving reductions in emissions from older engines and accelerating turnover of the in-use truck fleet. Key features of CARB's regulation include (1) an outright ban on 1993 and older engine model years which are not suitable for retrofitting, (2) diesel particle filter (DPF) retrofit requirements for more recent engines, and (3) incentives to replace older trucks with 2007+ model year trucks that meet the most stringent exhaust PM emission standards currently in force. The retrofit schedule imposed by the regulation requires installation of DPF systems on trucks with 1994−2003 engine model years by 2010 and retrofits of 2004−06 truck engines in stages from 2010 to 2013. All drayage trucks are required to meet the 2007 engine emission standard by the end of 2013. This approach is expected to reduce exhaust PM emissions from drayage trucks much more rapidly than what could be achieved by relying on natural fleet-turnover alone. CARB estimates that by 2014 this program will reduce PM emissions from the state drayage truck fleet 86% from 2007 baseline levels.[9]

Various methods have been employed to investigate the air quality impact of port-related heavy-duty diesel truck activity in California, with most research efforts focused on the Ports of Los Angeles and Long Beach. Minguillon et al. applied source apportionment techniques to $PM_{2.5}$ samples collected in communities surrounding these ports and found that vehicular sources were the dominant contributor to measured $PM_{2.5}$ concentrations.[10] High levels of port-related diesel truck activity have also been linked to elevated diesel-related pollutant concentrations measured

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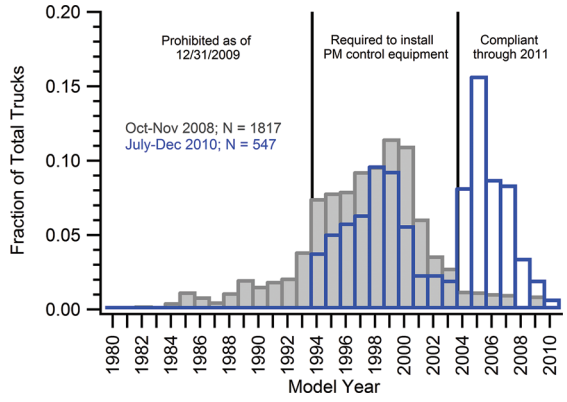

Figure 1. Port of Oakland drayage truck engine age distributions. The 2008 distribution is based on survey data collected by the Port of Oakland.[7] An analysis of compliance inspection records for Port trucks[35] was used to develop the 2010 distribution.

downwind of freeways and arterial roadways in the vicinity of the ports.[6] Remote sensing of individual diesel trucks operating at the Port of Los Angeles showed a 33% reduction in the fleet-average NO_x emission factor between 2008 and 2009.[11] This decrease was attributed to the introduction of new trucks into the port fleet in response to California's drayage truck control rule. A decrease in average plume opacity was also reported; however, the opacity measurement is difficult to relate to absolute PM mass emission rates. In contrast to programs at the Ports of Los Angeles and Long Beach, where truck replacement was the primary approach used to reduce emissions, both diesel particle filter retrofits and truck replacement were part of the response at the Port of Oakland in the San Francisco Bay area.

The use of DPF systems, installed as original equipment on new engines, or retrofit on older engines, is a key element in control of diesel PM emissions. All DPF systems use a filter (also referred to as a particle trap) to physically remove particles from the exhaust stream. There are various approaches to filter regeneration, whereby trapped carbonaceous particles are oxidized to prevent excessive particle accumulation and back-pressure in the exhaust system. In actively regenerated systems, the filter is heated (e.g., by electrical heating when trucks are parked at night, or by periodic injection of unburned diesel fuel while the engine is running) to promote the oxidation of trapped particles. In contrast, passively regenerated systems utilize catalysts to promote oxidation of trapped particles at lower temperatures. In these systems the filter is continuously regenerated during normal engine operation. In a commonly used approach, an oxidation catalyst is installed upstream of the filter to convert nitric oxide (NO) present in diesel exhaust to nitrogen dioxide (NO_2). NO_2 is then used as the oxidizing agent for filter regeneration.[12]

DPF systems have been shown to reduce PM mass emissions by >90%.[13−16] Systems utilizing oxidation catalysts are also capable of achieving similar reductions in carbon monoxide and hydrocarbon emissions.[14,15] DPF systems with high levels of catalytic loading have been shown to increase the NO_2/NO_x exhaust ratio,[15,17,18] which can exacerbate existing urban ozone and NO_2 air quality problems.[19,20] This may be of particular concern in the case where older engines with higher baseline NO_x emissions undergo DPF retrofit, creating the potential for high NO_2 emissions. Other concerns include the potential for formation of nitrated polycyclic aromatic hydrocarbons[21] and

Figure 2. Mobile laboratory parked on Bay Street overpass. Air sampling inlet is positioned above the vertical exhaust stacks of diesel trucks driving westbound on 7th Street toward the Port of Oakland.

questions regarding their effectiveness in reducing particle number emissions from diesel engines.[13,22]

The objectives of this study were to measure drayage truck emissions at the Port of Oakland and quantify emission changes due to the retrofit and renewal of the truck fleet in response to California's drayage truck rule. The results will inform those involved in California's drayage truck rule and elsewhere where measures to clean up port-related air pollution are being considered. Our results are also meaningful in light of California's plans to extend similar engine retrofit/replacement requirements to all heavy-duty trucks operating anywhere in the state.[23]

METHODS

Field Sampling Site. Measurements of exhaust emissions from diesel trucks driving to the Port of Oakland were made using a mobile laboratory equipped with a suite of pollutant analyzers. The mobile lab was positioned on the Bay Street overpass above 7th Street in West Oakland, as shown in Figure 2. The roadway below is a 4-lane arterial connecting the Port of Oakland with nearby Interstate 880 and West Oakland, and is characterized by high volumes of port-related truck activity. Truck exhaust was sampled above the westbound lanes of 7th Street, where trucks heading toward the Port were observed to be cruising at steady speed or accelerating from a traffic light ~50 m to the east. The roadway grade is level around the location where truck emissions were measured.

Truck emissions were measured on selected weekdays during November 2009 and June 2010, before and after the implementation of the drayage truck rule. Pre-1994 engines were banned from the port effective January 1, 2010. Retrofit or replacement of 1994−2003 engines was also required on the same schedule. However, backlogs in retrofitting trucks with DPFs led to deadline extensions of several months; the retrofit work was ~95% complete by June 2010.[24]

Air Pollutant Measurements. From the mobile laboratory parked on the overpass above 7th Street, an air sampling line was extended over the edge of the bridge and down directly (~1−3 m) above the vertical exhaust stacks of trucks driving below. During sampling, air was drawn continuously through 8 m of flexible

aluminum ducting (7.6 cm diameter) to a manifold located inside the mobile laboratory. A portion of the flow through the manifold was drawn through short (<1 m) Teflon and conductive silicone sampling lines to gas- and particle-phase pollutant analyzers, respectively.

Analyzers were operated with 1-s time resolution in order to measure rapidly changing pollutant concentrations when trucks passed by. Pollutant measurements included a nondispersive infrared gas analyzer for CO_2 (LI-COR, Lincoln, NE; model LI-820); a chemiluminescent analyzer for NO_x (ECO Physics, Ann Arbor, MI; model CLD-64); an Aethalometer for BC (Magee Scientific, Berkeley, CA; model AE-16); and an aerosol photometer (TSI, Shoreview, MN; model DustTrak II 8530) equipped with a size-selective impactor inlet for quantifying $PM_{2.5}$. A condensation particle counter (TSI, Shoreview, MN; model 3007) was included in the suite of instrumentation deployed during field sampling. However, particle concentrations in the exhaust plumes of sampled trucks often exceeded the upper limit of the instrument (10^5 particles cm^{-3}), preventing the quantification of particle number emissions. CO_2 and NO_x concentrations were logged using a laptop computer, while BC and $PM_{2.5}$ concentrations were logged internally by the respective analyzers and downloaded at the end of each sampling day. Internal clocks for all instruments were synchronized prior to the start of measurements each day. A video camera was used to record vehicle activity on 7th Street to identify times when individual trucks passed by the sampling site.

The Aethalometer used in this study measures light attenuation through a filter on which particles deposit. BC mass concentration is calculated from light-attenuation measurements using a mass-specific attenuation cross-section specified by the manufacturer. Previous studies have shown that this attenuation coefficient is not constant with filter loading, and consequently the Aethalometer incorrectly reports lower BC mass concentrations as the filter becomes increasingly loaded.[25,26] This effect is especially pronounced for the highly absorbing aerosols typical of diesel exhaust. A relationship developed by Kirchstetter and Novakov to account for this effect was used to adjust raw BC concentrations[26]

$$\mathrm{BC} = \frac{\mathrm{BC_0}}{0.88\exp(-\mathrm{ATN}/100) + 0.12} \quad (1)$$

where BC and BC_o refer to corrected and raw BC concentrations, respectively, and ATN is the instrument-reported attenuation. This correction has previously been applied to Aethalometer measurements of BC in the exhaust of diesel vehicles, and time-integrated adjusted BC concentrations were shown to be in agreement with measurements of BC determined by thermal-optical analysis of simultaneously collected $PM_{2.5}$ samples.[27]

The DustTrak aerosol photometer used to measure $PM_{2.5}$ concentrations is an optical instrument in which light scattered by particles is measured and converted to a mass concentration using an empirical calibration factor. The amount of light scattered by an aerosol is a function of particle number concentration, size distribution, and chemical composition. The factory calibration for the DustTrak is derived using a standard test dust, which consists of minerals rather than carbon particles.[28] $PM_{2.5}$ mass concentrations based on the mineral dust-derived calibration factor were measured during this study; this may result in systematic bias for diesel exhaust $PM_{2.5}$ emissions that consist mainly of carbon particles and that often include a high BC mass fraction. Therefore, when presenting $PM_{2.5}$ emission factors, the focus is on the relative change in emissions between the November 2009 and June 2010 sampling periods rather than on absolute $PM_{2.5}$ emission factors.

Data Analysis. The recorded video was analyzed to determine exact times when trucks passed by the air sampling inlet. Pollutant measurements including CO_2 were used to calculate BC, $PM_{2.5}$, and NO_x emission factors for individual trucks. A peak in measured CO_2 concentration with a rise of at least 7% above baseline levels was used to indicate successful capture of an exhaust plume from a passing truck. This threshold was selected based on a sensitivity analysis of the baseline CO_2 concentrations (~500 ppm) measured at our sampling location and corresponds to three times the relative standard deviation (noise) in the baseline CO_2 signal. Emission factors were not calculated for trucks with CO_2 peaks below this threshold. When multiple trucks passed the sampling inlet in rapid succession, the emissions from individual trucks were not resolvable. Rather an emission signature from a combined group of trucks was measured, as described in more detail below.

Corresponding peaks in CO_2, BC, $PM_{2.5}$, and NO_x concentration time series indicated the co-occurrence of these species in an exhaust plume. BC, $PM_{2.5}$, and NO_x emission factors were calculated for individual trucks with valid plume measurements using a carbon balance method. In this approach, concentrations of pollutants measured in the exhaust plume are normalized to concentrations of CO_2, the main carbon-containing species present in diesel exhaust. Knowledge of the weight fraction ($w_c = 0.87$) of carbon in diesel fuel allows for the calculation of fuel-specific emission factors with units of g pollutant emitted per kg of fuel burned.[27,29]

$$\mathrm{EF}_p = \frac{\int_{t_1}^{t_2} ([P]_t - [P]_{t_1})\,\mathrm{d}t}{\int_{t_1}^{t_2} ([\mathrm{CO_2}]_t - [\mathrm{CO_2}]_{t_1})\,\mathrm{d}t} w_c \quad (2)$$

Here, EF_P is the emission factor for pollutant P. The interval $t_1 \leq t \leq t_2$ represents the time period that instruments were sampling the exhaust plume of an individual truck. This time window characterizes the peak width and is typically 4−10 s. $([P]_t - [P]_{t_1})$ is the baseline-subtracted concentration ($\mu g\ m^{-3}$) of pollutant P at time t, and similarly for $[CO_2]$ (mg C m^{-3}).

In a previous application of this method to characterize BC and particle number emission factors for heavy-duty diesel trucks, t_1 and t_2 were determined by identifying inflection points to the left and right of the CO_2 concentration peak, respectively.[27] A similar method was used here with peak widths determined individually for all species to account for differences in the time response of individual instruments to the exhaust plume. Concentrations of additional carbon-containing compounds in exhaust plumes (e.g., carbon monoxide, volatile organic compounds) were not measured in this study, and are thus excluded from the denominator of eq 2. These species are typically present in relatively low concentrations relative to CO_2 in diesel exhaust,[30] therefore only a small positive bias (<5% for most trucks) in emission factor calculations is expected due to omission of these species.

RESULTS AND DISCUSSION

Truck Activity. Truck activity was similar during the November 2009 and June 2010 sampling periods, when truck volumes averaged 250 and 230 per hour, respectively (Table 1).

Approximately 85% of observed trucks consisted of a tractor with an attached trailer or chassis trailer and container. The remaining trucks consisted of tractors without an attached trailer and tractors with an unloaded chassis trailer. Other than selection of a Port-focused sampling site, no further attempts were made as part of this study to identify and separate port trucks from other trucks that are not subject to the drayage truck emission control rules. However, a recent survey of truck activity on 7th Street indicates the majority (~70%) of trucks passing the sampling location used in this study are drayage trucks.[7]

Plume Captures. Figure 3 shows three examples of baseline-subtracted pollutant concentration time series recorded when trucks drove by our sampling location. Note that clear peaks are seen in the concentrations of all measured species in Figure 3a and c, indicating that the passing trucks emitted significant quantities of NO_x, BC, and $PM_{2.5}$. In contrast, Figure 3b corresponds to the passage of a truck with low particulate matter emissions, as evidenced by clearly defined peaks in concentrations of CO_2 and NO_x but not BC and $PM_{2.5}$. The relative frequency of successful truck plume captures with no measurable accompanying $PM_{2.5}$ and BC emissions increased to 11 and 16%, respectively, in June 2010 from 2 and 5% in November 2009. This increase is consistent with cleaner trucks in the later sampling period.

The double peaks shown in Figure 3c resulted from two trucks passing the sampling inlet in close succession. During all sampling periods, there were frequent instances of multiple trucks passing by the sampling site simultaneously (i.e., two trucks driving side-by-side in the westbound lanes) or in rapid succession. These truck-cluster events resulted from the high levels of port-related truck activity on 7th Street and the grouping of trucks at nearby traffic lights. In these cases, plumes for individual trucks were not resolvable and emission factors were instead calculated for each cluster. Combined emissions from 384 trucks were observed in 100 clustered events during November (representing 44% of the total truck sample). During June, emissions from 626 trucks were observed in 181 clustered events (23% of the total truck sample).

As noted above, emission factors were not calculated for trucks when measured CO_2 concentrations did not rise clearly above baseline levels. The percentage of unsuccessful plume captures was greater during June sampling (61% of 2687 trucks) compared to November (36% of 863 trucks). As shown in Table 1, average wind speeds were approximately two times higher in June than in November. Higher wind speeds contributed to more rapid dilution of exhaust plumes during June sampling, and this likely explains the higher percentage of unsuccessful plume captures. Although increased wind speeds during June sampling led to a lower rate of successful captures, the dilution for successful plume captures was similar for both sampling periods. This is indicated by a similar mean rise in CO_2 peak concentrations above baseline levels for successful captures during each sampling period (191 ± 31 ppm and 196 ± 23 ppm for November 2009 and June 2010 sampling, respectively). The difference in temperature and relative humidity between sampling periods (see Table 1) is not expected to significantly impact measured emission factors. Temperature and humidity effects on the formation of NO_x in

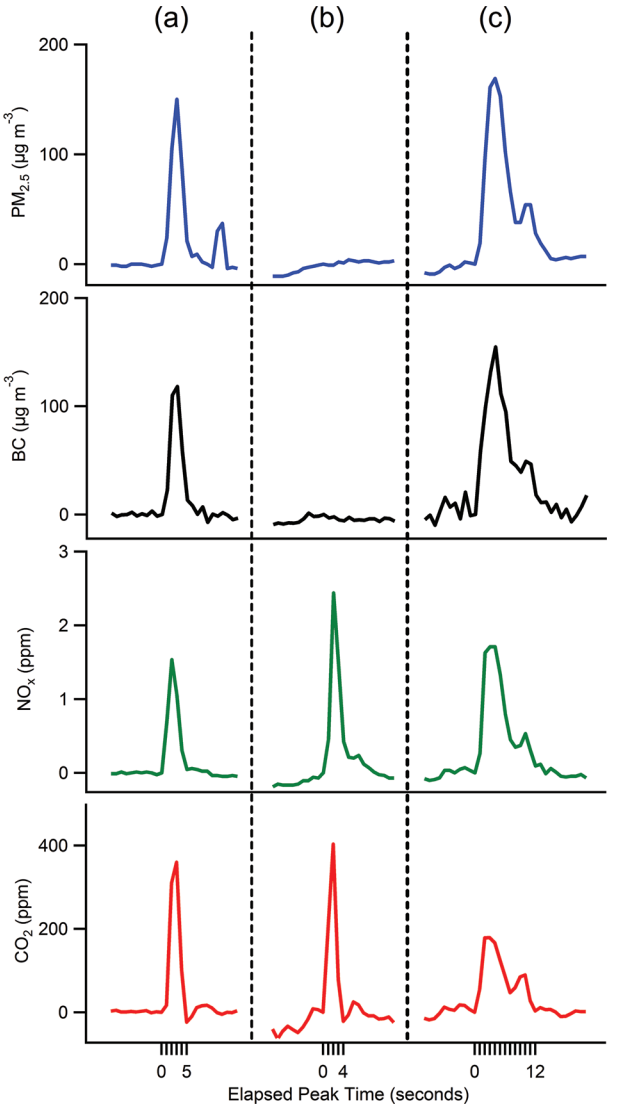

Figure 3. Baseline-subtracted concentrations of $PM_{2.5}$, BC, NO_x, and CO_2 in the exhaust plumes of (a) a representative truck, (b) a truck with low BC and PM emissions, and (c) two trucks passing the sampling inlet in close succession.

Table 1. Meteorological and Truck Sample Size Data

sampling date	sampling time	temperature[a] (°C)	relative humidity[a] (%)	wind speed[a] (m s^{-1})	total trucks	individually resolved truck plumes N (%)	trucks with combined plumes N (%)	trucks with no plume capture[b] N (%)
11/19/2009	12:00−15:30	13	56	2.4	863	172 (20)	384 (44)	307 (36)
6/15/2010	12:00−14:45	17	60	5.2	614	131 (21)	115 (19)	368 (60)
6/16/2010	11:00−15:30	21	44	5.0	953	157 (16)	151 (16)	645 (68)
6/17/2010	10:00−14:30	20	50	4.2	1120	132 (12)	360 (32)	628 (56)

[a] Average values for each sampling period measured at Oakland International Airport, located ~13 km SE of our field sampling site. [b] CO_2 concentration rise <7% above baseline levels.

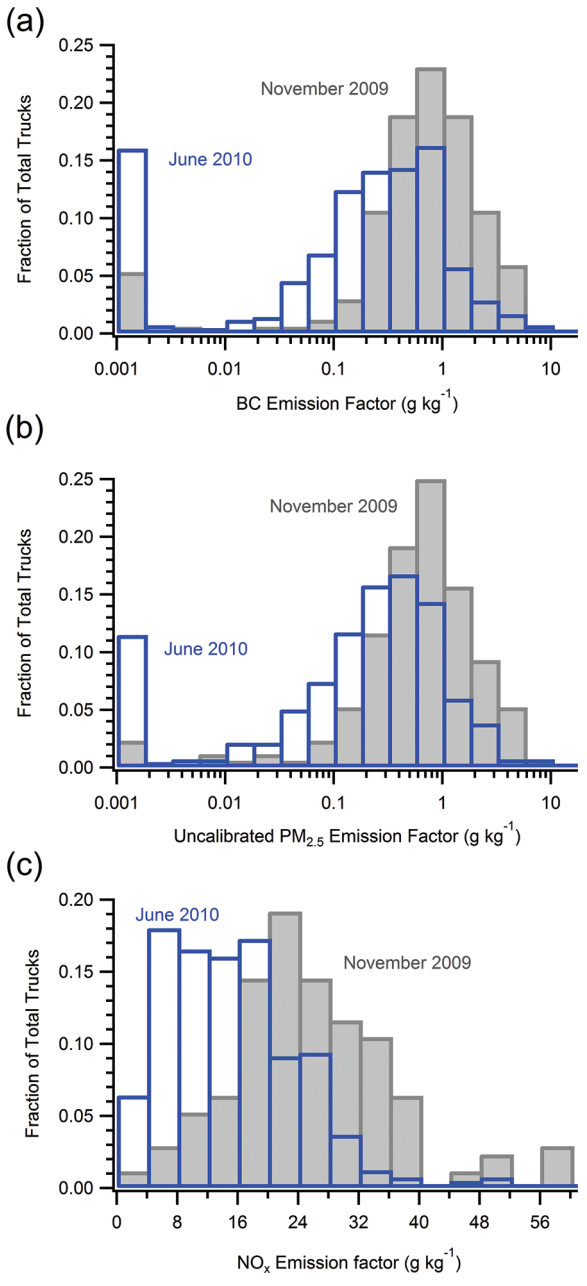

Figure 4. Emission factor distributions for (a) BC, (b) $PM_{2.5}$, and (c) NO_x.

diesel engines and its measurement using chemiluminescent techniques were found to be minor (<3%) and similar for each day of sampling.[31−33]

BC and $PM_{2.5}$ Emission Factors. Histograms showing BC emission factor distributions for successful individual truck plume captures are presented in Figure 4a. Low-emitting trucks with zero or negative emission factors calculated using eq 2 are included in the leftmost (lowest) bin of the BC emission factor distributions. BC emission factors span a wide range of values; note the use of logarithmic axes for emission factors in Figure 4a. In November 2009, the distribution of BC emission factors was log-normal, leaving aside the small fraction of trucks with emission factors <0.01 g kg^{-1}. These trucks were likely equipped with particle filters.

Table 2. Fleet-Average Emission Factors for Trucks Operating at the Port of Oakland[a]

	November 2009	June 2010	% change[d]
	individual plumes		
BC	1.07 ± 0.18 (169)	0.49 ± 0.08 (418)	−54 ± 11
NO_x[b]	25.9 ± 1.8 (172)	15.4 ± 0.9 (405)	−41 ± 5
	combined plumes[c]		
BC	1.16 ± 0.27 (100)	0.59 ± 0.10 (180)	−49 ± 15
NO_x[b]	25.7 ± 1.8 (100)	16.4 ± 1.0 (178)	−36 ± 6

[a] Emission factors reported in units of g pollutant emitted per kg of fuel burned. Table entries show mean ±95% confidence interval with total number of trucks (individual plumes) or truck cluster events (combined plumes) shown in parentheses. [b] NO_x mass emission factors reported as NO_2 equivalents. [c] For combined plumes, emission factors were calculated for each truck cluster. Unweighted average emission factors for all truck cluster events are reported here. The average number of trucks in each cluster was 3.8 and 3.5 for November 2009 and June 2010, respectively. [d] Statistical significance of the differences in emission factors was evaluated using two-tail t tests with significance set at $p < 0.05$ for NO_x emission factor data and log-transformed BC emission factor data. For all reported changes in fleet-average emission factors, $p < 0.0001$.

The BC emission factor distribution for individual trucks measured in June 2010 is shifted toward lower values relative to November 2009 (see Figure 4a). The shift in the BC emission factor distribution is characterized by a substantial decrease (from 36 to 11%) in the fraction of trucks with emission factors greater than 1 g kg^{-1} and a corresponding 3-fold increase in the fraction of very low-emitting trucks included in the first bin of the distribution. The changes in the distribution of BC emissions from November to June correspond to a decrease of ∼50% in average BC emission factors for trucks at the Port of Oakland (see Table 2). As shown in Table 2, the decrease in average BC emission factor computed from analysis of exhaust plumes of individual trucks is consistent with the decrease in the average emission factor calculated based on combined plume events.

Histograms showing $PM_{2.5}$ emission factor distributions for successful plume captures are shown in Figure 4b. Note these histograms show emission factors calculated using uncalibrated $PM_{2.5}$ mass concentration data and should not be interpreted as absolute measurements of $PM_{2.5}$ mass emission rates. Similar to BC, the $PM_{2.5}$ emission factor distribution is shifted toward lower-emitting trucks in June 2010 relative to the November 2009 distribution. Additionally there is a 5-fold increase in the number of trucks with no measurable $PM_{2.5}$ emissions (leftmost bin of distribution) between November 2009 and June 2010. This evidence, combined with measured decreases in the BC emission factor for Port trucks, suggests there was a substantial decrease in $PM_{2.5}$ mass emissions from Port trucks between November 2009 and June 2010. However, due to uncertainties about instrument response to diesel exhaust emissions, the $PM_{2.5}$ mass emission decrease will not be quantified here.

Results from this study show significant reductions in BC emissions from Port of Oakland trucks over a period of only seven months. By comparison, vehicle emissions measured at a nearby traffic tunnel (Caldecott tunnel on Highway 24) showed a similar reduction in the fleet-average BC emission factor for diesel trucks of 39 ± 26% over a period of nine years between 1997 and 2006.[34] Emission reductions observed in the highway

tunnel study were driven by natural fleet turnover. In contrast, emission changes reported here for trucks at the Port of Oakland are attributable to the large-scale retrofit of trucks with DPFs, as well as to accelerated replacement of older trucks with newer and cleaner models. Insight into the factors contributing to emission reductions observed in this study is gained by comparing truck age distributions prior to and following the implementation of the drayage truck rule, as shown in Figure 1.[7,35] BC emission factor reductions resulted from (1) removal of trucks with pre-1994 model year engines from the port fleet (17% of total trucks in 2008, 0% in 2010), (2) retrofit of trucks with model year 1994−2003 engines with DPFs (53% of truck fleet in 2010), and (3) introduction of trucks with 2007 and newer model year engines already equipped with a particle filter (2% of total trucks in 2008, 14% in 2010). A large increase in the fraction of 2004−06 model year engines was also observed at the Port, from 4 to 33% of the fleet. The $PM_{2.5}$ emission standard for these engines was the same as for 1994−2003 engines. However, some emissions benefits could still accrue even without retrofit of these engines in cases when they replaced pre-1994 models.

The results of this study may understate the BC emission reductions due to the drayage truck rule because (1) further emission reductions were expected after June 2010; in particular the 2004−06 engines must be retrofitted or replaced by 2013 and (2) some DPF retrofits may have occurred prior to baseline emission measurements in November 2009. On the other hand, DPF systems were only recently installed in the 1994−2003 truck engines when emissions were measured in June 2010. The durability and maintenance of these emission control systems will be important to preserving BC emission reductions in subsequent years. In the absence of the drayage truck rule requiring replacement/retrofit of older engines, a small reduction in Port truck emissions would still have been expected due to "natural" or unforced fleet turnover. Based on measured long-term trends at the Caldecott tunnel, BC emission factors from heavy-duty diesel trucks decreased at a rate of about 4% per year.[34] Even assuming no economic slowdown in more recent years, unforced fleet turnover could not have contributed significantly to the large (∼50%) emission reductions observed at the Port between November 2009 and June 2010.

NO_x Emission Factors. In addition to changes in BC, the drayage truck rule also appears to have reduced NO_x emissions from trucks operating at the Port of Oakland. As shown in Figure 4c, the NO_x emission factor distribution measured in June 2010 shifted toward lower emission levels relative to November 2009. Average NO_x emission factors evaluated for both individual trucks and cluster events show a decrease of approximately 40% between November and June (see Table 2). These results may appear surprising given the emphasis at the Port of Oakland on retrofitting existing trucks with DPFs.

Whereas the retrofit of DPFs and the replacement of older trucks both contributed to BC emissions reductions observed at the Port of Oakland, the change in NO_x emissions was likely driven almost entirely by the introduction of trucks with 2004 and newer engines to replace older trucks allowed at the Port. Prior work shows that DPF systems have little to no impact on total NO_x emissions from diesel engines in the absence of additional NO_x-specific exhaust after-treatment systems.[14,15] Thus, no major changes in NO_x emissions are expected from the extensive retrofit of model year 1994−2003 engines that occurred at the Port of Oakland. As shown in Figure 1, the fraction of trucks with 2004 and newer engines operating at the Port of Oakland increased from 6 to 47% between 2008 and 2010. Because allowed NO_x emissions for 2004 and newer engines are set at lower levels, NO_x emission reductions are expected from the accelerated replacement of older trucks. In comparison, a study of NO_x emissions from trucks operating at the Port of Los Angeles reported a 33% reduction in mean NO_x emission factor between 2008 and 2009.[11] This change was attributed to the introduction of many brand new trucks at the Port of Los Angeles due to the drayage truck rule.

Air Quality Implications. This study found substantial reductions in exhaust emissions of BC and NO_x from trucks operating in the vicinity of the Port of Oakland as a result of the implementation of a retrofit and accelerated truck replacement program. The average BC emission factor for this drayage truck fleet decreased by ∼50% while the average NO_x emission factor was reduced by ∼40%. Emission reductions for BC were driven by the retrofit of trucks with DPF systems and the replacement of older model year trucks with newer vehicles; reductions in NO_x emissions were mainly the result of truck replacement. Reductions in the average BC emission factor, a major portion of diesel $PM_{2.5}$, and a measured shift in the $PM_{2.5}$ emission factor distribution together suggest that exhaust $PM_{2.5}$ emissions from the Port truck fleet were also reduced. Although these emissions reductions are likely to improve air quality in communities surrounding the Port of Oakland where drayage truck activity is high, a more complete understanding of the air quality impacts of the drayage truck regulation requires measurement of emissions of species not considered here. Specifically, the possibility of increased emissions of NO_2 and ultrafine particles from trucks equipped with DPF systems should be investigated as part of future work on this issue.

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