MEASURING REAL-WORLD EMISSIONS FROM THE ON-ROAD HEAVY-DUTY TRUCK FLEET

Final Report

CARB Contract No. 12-315

Prepared by:

Chelsea V. Preble

Robert A. Harley

Thomas W. Kirchstetter

Department of Civil and Environmental Engineering

University of California, Berkeley

Berkeley, CA 94720-1710

Prepared for the California Air Resources Board and the
California Environmental Protection Agency

March 15, 2019

Acknowledgment:

This Report was submitted in fulfillment of CARB contract 12-315: “Measuring real-world emissions from the on-road heavy-duty truck fleet” by the University of California, Berkeley under the sponsorship of the California Air Resources Board. Work was completed as of March 15, 2019.

Abstract

This study measured pollutant emissions from thousands of on-road trucks in California to quantify the in-use performance of diesel particle filters (DPFs) and selective catalytic reduction (SCR) emission control technologies. These systems are ubiquitous on heavy-duty diesel trucks manufactured in the United States, beginning with engine model years 2007 for DPFs and 2010 for SCR. These after-treatment emission control technologies are needed to comply with exhaust emission standards for particulate matter (PM) and oxides of nitrogen (NO_x). California has advanced the adoption of these emission controls in the on-road fleet by implementing the Statewide Truck and Bus Regulation, which mandates modernization of the on-road truck fleet operating statewide on an accelerated schedule.

Heavy-duty truck emissions were measured at the Caldecott Tunnel in the San Francisco Bay Area, in 2014, 2015, and 2018. Emission factors expressed per unit mass of fuel burned were determined using plume capture and carbon balance methods for individual trucks operating at freeway speeds and climbing a 4% roadway grade. Compared to baseline measurements made in 2010 at the same location, the median truck model year observed in 2018 increased by 9 years, and DPF and SCR penetration increased from 15 to 91% and 2 to 59%, respectively. Over this period, fleet-average emission rates of BC and NO_x decreased by 79 and 57%, respectively. Fleet-average NO_2 emission rates remained about the same, despite the intentional oxidation of engine-out NO to NO_2 in DPF systems, due to the effectiveness of SCR systems in reducing NO_x emissions and mitigating the DPF-related increase in primary NO_2 emissions. Fleet-average emissions of NH_3 and N_2O increased from near-zero to levels that are comparable to NH_3 emissions from three-way catalyst-equipped light-duty cars, and to levels

about equal to the N_2O emission limit for heavy-duty trucks. The g kg^{-1} reduction in the emissions of NO_x is about 150 times the increase in NH_3, which is a precursor to atmospheric formation of ammonium sulfate and ammonium nitrate. The reduced BC emissions from DPF-equipped trucks and the ~4% fuel economy gained with the addition of SCR outweigh effect of the N_2O global warming potential increase.

Truck license plates were recorded, transcribed, and matched to entries in state-maintained databases to link the emission profiles of individual trucks to engine model year and emission control technology. BC emissions from trucks with 2010+ engines were 97% lower than from trucks with 1965–2003 engines. Furthermore, 2010+ engines equipped with both DPF and SCR emitted on average 82% less BC than 2007–2009 engines that have DPFs only, even though both categories of trucks are expected to meet the same exhaust PM emission standard. A 57% increase in BC emissions from 2007–2009 DPF-equipped engines between 2014 and 2015 raised concerns about the durability of DPF systems installed on some heavy-duty trucks. However, the BC emission factor for the 2007–2009 engines was no higher in 2018 than in 2014, and lower in 2018 than in 2015, possibly due to repair or replacement of some high-emitting trucks. In the spring of 2018, ~10% of the on-road truck fleet was either exempt from or noncompliant with the Truck and Bus Regulation; nearly 60% of the remaining on-road BC emissions comes from these trucks.

Introduction

Diesel engines are a major source of black carbon (BC)—a major constituent of particulate matter (PM) emitted in diesel exhaust—and nitrogen oxides (NO_x).[1–4] To reduce these emissions and their associated adverse effects on human health and the environment,[5–10] new heavy-duty diesel trucks sold in the U.S. are required to meet increasingly stringent emission limits.[11] Starting with 2007 and 2010 model year engines, heavy-duty diesel trucks are typically equipped with diesel particle filter (DPF) and selective catalytic reduction (SCR) systems, respectively. Similar approaches are being used in other parts of the world to reduce diesel engine emissions.[12]

As the in-use truck fleet turns over, fleet-average emissions decrease gradually as new trucks replace older, higher-emitting trucks. By implementing the Drayage Truck Regulation and the Statewide Truck and Bus Regulation, California has mandated a more rapid transition to cleaner engines. As part of ongoing efforts to reduce PM and NO_x emissions associated with goods movement, the Drayage Truck Regulation first required retrofit or replacement of older diesel drayage trucks that serve ports and rail yards beginning in 2010.[13] Two years later, the Statewide Truck and Bus Regulation began requiring diesel trucks and buses that operate on roadways throughout California to be upgraded to reduce emissions.[14] By 2023, all heavy-duty diesel engines operating on California roadways are expected to meet the federal 2010 heavy-duty engine NO_x emission standard.

The anticipated statewide PM and NO_x emissions reductions associated with the Truck and Bus Regulation are far greater than those associated with normal fleet turnover.[15,16] At the same time, there may be unintended consequences like increases in co-emitted pollutants that result from the deployment of these new emission control technologies. Concomitant increases in emissions of ultrafine particles have been associated with reductions in PM emissions.[17,18] Intentional conversion of engine-out NO to NO_2 to enable passive regeneration of DPFs can increase tailpipe NO_2 emissions and the NO_2/NO_x emission ratio.[19–21] Use of diesel exhaust fluid—a solution of urea and water that yields ammonia (NH_3) that reacts in SCR systems to reduce NO_x emissions—can lead to increased NH_3 emissions from diesel trucks.[22]

The in-use effectiveness and durability of emission control systems are key issues that will affect current and future emissions from the heavy-duty diesel truck fleet. Laboratory testing and field measurements of in-use trucks have shown that DPFs and SCR can reduce diesel PM and NO_x emission rates by more than 90 and 75%, respectively,[18,19,30,31,21,23–29] However, Haugen and Bishop[30] and Preble et al.[31] reported unexpectedly high and increasing PM and BC emissions from first-generation filter-equipped trucks (i.e., 2007–2009 model year engines) at the Ports of Los Angeles and Oakland in 2015. Failures of even a relatively small fraction of filter systems could impair efforts to reduce diesel PM emissions. As it pertains to in-use performance of SCR, the exhaust temperature must be at least ~200 °C to ensure SCR function and NO_x reduction.[32] In cases where this temperature requirement is not met, urea injection is deliberately disabled and the SCR system is not functional, resulting in elevated NO_x emissions. Elevated NO_x emissions have also been measured for in-use SCR-equipped trucks even under conditions where exhaust temperatures were sufficiently high.[33] In July 2018, an engine manufacturer announced a recall of 500,000 heavy-duty trucks with defective SCR catalysts that led to excess NO_x emissions.[34] Thus, it important to verify emission control system performance and durability, not just in laboratory certification tests of new engines, but also in the real world and over time.

The objective of this study is to quantify the in-use performance of DPF and SCR emission control technologies deployed on heavy-duty diesel trucks. Emissions were measured from thousands of trucks driving on a highway approaching the Caldecott Tunnel in the San Francisco Bay Area. Measurements were made in 2014, 2015, and 2018 when the truck fleet was evolving following introduction of the Truck and Bus Regulation. Results are compared to baseline emissions data measured at the same site in 2010.

Methods

Figure 1 shows the Caldecott Tunnel field sampling site, which has been used for on-road emission studies for decades.[6,35,36] In the current study, truck emissions were measured in (i) July–August 2014, by which time the Truck and Bus Regulation required all 1996–2006 model year engines be equipped with DPFs either by retrofit or replacement; (ii) September–October 2015, when pre-1994 engines had been replaced with 2010+ engines; and (iii) March–April 2018, when all heavy-duty diesel trucks were required to be DPF-equipped.

At the study site, trucks were driving on Highway 24 on an uphill grade of 4% at speeds ranging from 50 to 120 km h^{-1}. A diverse mix of trucks was observed, including cement mixers, dump trucks, tractor-trailer combinations, flatbeds, and construction equipment, in addition to a significant number of drayage trucks (drayage accounted for 15–29% of the fleet at the Caldecott Tunnel) hauling containers from the nearby Port of Oakland. All truck types were included in our analysis for this location.

Figure 1. Instrumented van positioned on an overpass at the Caltrans facility at the Caldecott Tunnel, sampling the exhaust from a truck as it travels eastbound on Highway 24 and enters Bore 1 of the tunnel. The van is circled in the wide-view image and shown in more detail in the inset picture. The roadside camera positioned at the entrance to the tunnel is also circled.

The plume capture method was used to measure emission factors from individual trucks as they drove by. Exhaust/ambient air mixtures sampled above the roadway were delivered to an instrumented van via a flexible aluminum duct, as shown in Figure 1. Concentrations of several gas- and particle-phase pollutants were measured at 1 Hz or faster using the instruments listed in Table A1 in the Appendix. A sample pollutant concentration time series showing peaks associated with three trucks that drove by in succession is also presented in the Appendix (Figure A1). 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:[37]

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

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_2. When [P] and [CO_2] have mass concentration units (e.g., μg m^{-3}), the ratio compares the relative abundances of pollutant P and CO_2 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,[37] and the factor of 44/12 converts CO_2 to carbon mass. This analysis assumes that all fuel carbon is converted to CO_2 during combustion, with negligible emissions of carbon monoxide and volatile organic compounds relative to emitted CO_2.[36] NO_2 emission factors for each truck were computed as the difference of NO_x and NO emission factors. NO_x emission factors were calculated using the molecular weight of NO_2.

Emission factors were computed for trucks when the peak CO_2 concentration rose more than 7% above baseline roadway concentrations, following Dallmann et al.[24] 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_2 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_2 plume capture was successful but without clearly detectable peaks for other pollutants, emission factors were still computed and the resulting near-zero emission factors could be slightly positive or negative.

The performance of pollutant analyzers was verified twice daily by confirming zero responses and verifying the span of gaseous pollutant concentrations at the start and end of sampling. The sample flow rates of all analyzers were also verified every few days. Measured BC concentrations from the model AE16 aethalometer were post-processed to include site-specific adjustments for the filter loading artifact, as described in Preble et al.[21] and Dallmann et al.[36] The length of the sampling line from the sampling manifold inside the research van—to which the flexible aluminum duct delivered the exhaust/ambient air mixture from the roadway—to the ammonia analyzer was minimized and the line was heated to minimize losses of NH_3. An in-line dilution system was used to avoid exceeding the concentration limits of the ultrafine, butanol-based condensation particle counter used to measure particle number (PN) concentrations. The dilution rate was actively monitored during the study. Normalized particle size distributions were measured using a fast mobility particle sizer (FMPS) to estimate size-resolved PN emission factors, as described in Preble et al.:[21]

$$\Delta E_{PN} = \frac{\Delta \mathrm{N}}{\mathrm{N}} \mathrm{E}_{PN} \tag{2}$$

Particle number concentrations measured in each size bin at the leading side of the particle number concentration peak, ΔN, 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.

A video camera at roadway level recorded truck license plates, which were later transcribed and matched with entries in relevant databases maintained by the state of California: the Drayage Truck Registry (DTR), the Truck Regulation Upload, Compliance, and Reporting System (TRUCRS), and the Department of Motor Vehicles (DMV) vehicle registration database. Measured emission factors were linked on a truck-by-truck basis with specific vehicle attributes including chassis model year, engine model year, and any verified installed emission control systems. Self-reporting for the vehicle fleet subjected to the Truck and Bus Regulation is voluntary. For this reason, it was not possible to categorize each truck with a transcribed license plate; if the truck owner did not self-report, there was more limited information available from the state vehicle registration database to classify the vehicle by model year and inferred emission control category.

Trucks and emission factors are discussed below in term of fleet-average values as measured in each calendar year of the study. Results are also presented by grouping trucks into one of five categories based on engine model years and verified emission controls: (a) older, pre-2004 engine model years without DPFs; (b) modern, 2004–2006 engines without DPFs; (c) trucks with 1994–2006 engines that were retrofitted with DPFs; (d) 2007–2009 model year engines that were equipped with a DPF at the time of manufacture; and (e) trucks with 2010 and newer engines that were equipped with both DPF and SCR systems at the time of manufacture.

Results and Discussion

Caldecott Tunnel Fleet Composition

The truck fleet composition in 2010, 2014, 2015, and 2018 is reported in Table 2. Figure 2 shows the age distribution of heavy-duty diesel trucks in 2010 and 2018. Data for calendar year 2010, which serves in the present study as a baseline prior to the start of the California's Statewide Truck and Bus Regulation, are based on EMFAC model estimates of heavy-duty diesel truck travel by model year for Alameda County for summer 2010.[38]

Table 1. Distribution of heavy-duty diesel trucks observed at the Caldecott Tunnel by emission control category, as measured in 2014, 2015, and 2018, and as reported for 2010 in the EMFAC model.[38] For the 2010 fleet, all trucks with pre-2007 model year engines were assumed to be part of the No DPF category.

Calendar Year	**Engine Model Year Range**	**Median Engine Model Year**	**No DPF (pre-2007)**	**Retrofit DPF (1994–2006)**	**DPF (2007–2009)**	**DPF + SCR (2010+)**
2010 (15% DPF, 2% SCR)	1965–2010	2002	85%	0%	13%	2%
2014 (72% DPF, 33% SCR)	1965–2015 (N = 1139)	2008	28% (n = 320)	8% (n = 88)	31% (n = 357)	33% (n = 374)
2015 (80% DPF, 46% SCR)	1979–2016 (N = 1198)	2009	20% (n = 242)	13% (n = 157)	20% (n = 245)	46% (n = 554)
2018 (91% DPF, 59% SCR)	1979–2018 (N = 1192)	2011	9% (n = 87)	12% (n = 116)	20% (n = 182)	59% (n = 549)

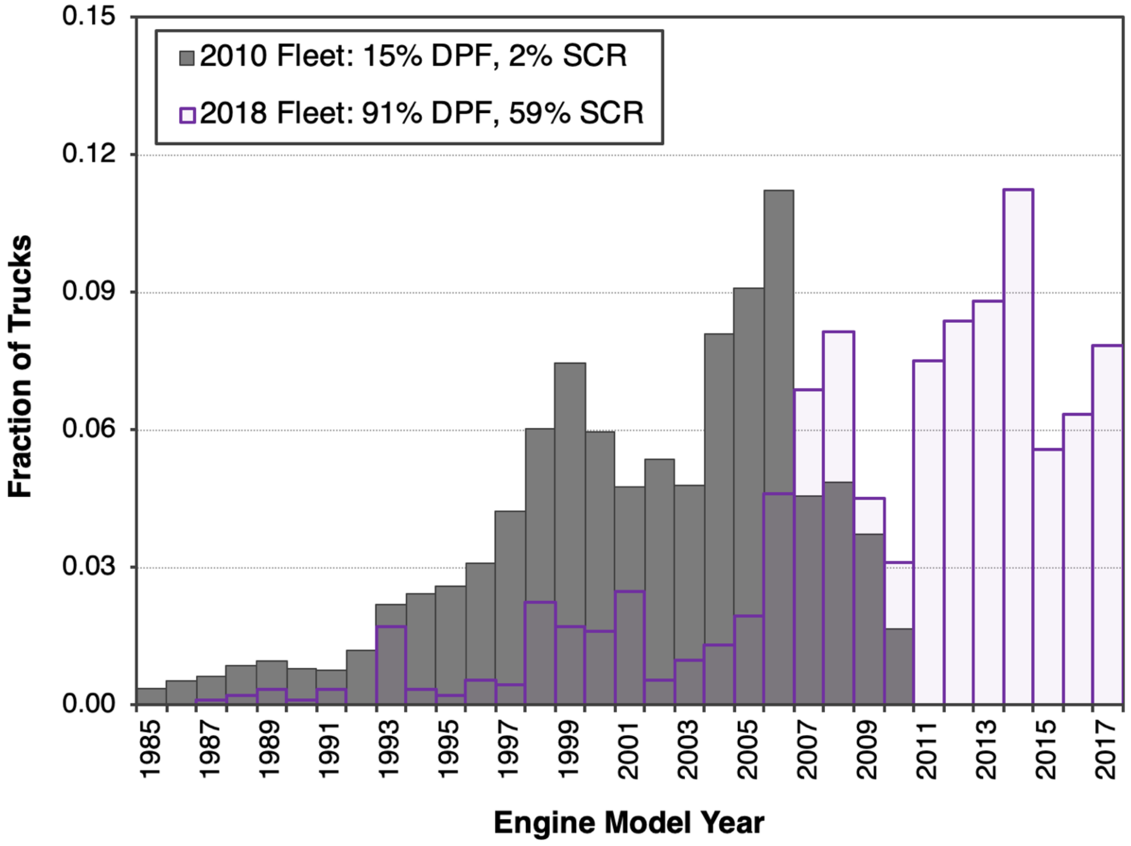


Figure 1. Engine age distribution of heavy-duty diesel trucks operating at the Caldecott Tunnel in 2010 and 2018.

The on-road fleet operating at the Caldecott Tunnel has increasingly adopted DPF and SCR systems as a result of the Regulation. The truck fleet modernized significantly between 2010 and 2014: the median engine model increased by 6 years, DPF penetration increased from 15 to 72%, and SCR penetration increased from 2 to 33%. In 2018, the final year of this study, 91% of the Caldecott Tunnel fleet was equipped with DPFs and 59% of the fleet also was equipped with SCR. The Truck and Bus Regulation allows for some exemptions, meaning that some older engines are allowed to remain in service and will not follow the retrofit or replacement requirements. Trucks without DPFs in the 2018 fleet (9% of the total) were either exempt from (e.g., low-mileage) or noncompliant with regulatory requirements.

BC Emission Factor Distributions and Trends

Probability distributions of measured BC emission factors are shown by calendar year and different technology categories in Figures 3a and 3b. Data from 2014, 2015, and 2018 have been combined for the categories presented in Figure 3b. These probability plots represent the likelihood that a given truck would have a BC emission rate that is less than the value indicated on the vertical axis. Median values correspond to 50% probability and average values are shown as white-colored circles on each data series. Data from perfectly lognormal distributions would plot as straight diagonal lines on the axes used in Figure 3. The average (± 95% confidence interval) BC emission factors corresponding to each distribution shown in Figure 3 are reported in Table A2 in the Appendix. Emission factors from the Caldecott Tunnel in 2010 are taken from Dallmann et al.[36] and were adjusted to account for differences in post-processing of the BC data and to account for an artifact in the CO_2 measurements, as described in Preble et al.[21]

The Tunnel fleet-average BC emission factor (reported in Table A2 and shown in Figure 3a) decreased by 79 ± 17% between 2010 and 2018 as DPF penetration in the truck fleet increased from 15 to 91%. The increasing steepness of the emission factor distributions shown in Figure 3a indicates that the skewness of the distributions increased over time. As new DPF-equipped engines entered into service and accounted for a larger portion of the truck fleet, the lower half of the distributions became cleaner and the median BC emission rate decreased (Table 2, Figure 3a). The highest-emitting fraction of these distributions remained approximately the same with respect to BC emission rate, but the slope of the distributions increased around the 95th percentile in 2015 and around the 99th percentile in 2018. The increasing contribution to overall emissions from a high-emitting sub-group of trucks is apparent as an increasing disparity over time between median and mean values for BC emission factors. Relative to fleet averages observed in 2010, the median value of the BC emission rate decreased by more than an order of magnitude (by 93%) by 2018, whereas the mean value decreased by 71%. The mean exceeded the median by nearly an order of magnitude as of 2018. Average BC emission rates for DPF-equipped trucks with 2007–2009 engines were 70% lower than those for 2004–2006 engines without filters, while 2010+ engines equipped with both DPF and SCR showed reductions of 94% in BC emission rates relative to the same baseline.

In the U.S., the exhaust emission standard for PM from heavy-duty diesel trucks with 1994–2006 model year engines is 0.1 g hp-hr^{-1} versus 0.01 g hp-hr^{-1} for trucks with 2007 and newer engines.[11] These standards limit PM emissions relative to engine work output, which can be related to fuel input through an engine efficiency parameter known as brake-specific fuel consumption (bsfc). A lower value of bsfc indicates less fuel is needed to produce a given amount of useful work output. Assuming bsfc = 175 g hp-hr^{-1},[39] corresponding allowable PM emission factors are approximately 0.6 and 0.06 g kg^{-1} for 1994–2006 and 2007+ engines, respectively. Many of the category median and mean values for BC by engine class approach or exceed the corresponding PM emission limits (Figure 3b, Table A2). As illustrated in Figure 3b, approximately 45% of the DPF-equipped engines and 25% of 2010+ engines have BC emissions above the PM certification level. Further, BC is a major but not the only component of diesel PM. Lubricating oil emissions that contribute to organic aerosol and total PM mass are not included as part of BC; the addition of organic aerosol emissions would increase the likelihood that some relatively new trucks are emitting above the applicable PM emission standard.[40,41]

BC emission rates for 2010+ engines equipped with both DPF and SCR were on average ~80% lower than 2007–2009 engines that have DPFs only (Figure 3b, Table A2). This is interesting because the PM emission standard remained unchanged, and SCR is used to control

NO_x rather than PM emissions. Differences in engine age and associated wear and tear, engine management strategy trade-offs to limit engine-out PM and NO_x emissions, or possible improvements in DPF system durability may explain the lower BC emissions from 2010+ engines.[42,43]

The range of measured emission factors shown in Figure 3 spans more than three orders of magnitude, from 0.01 to >10 g kg^{-1}. The distribution for DPF-equipped trucks was shifted towards lower emission rates and was more skewed than the distributions for trucks without filters, as indicated by the steeper slope shown in Figure 3b. However, DPF-equipped trucks exhibited a similar range of BC emission rates as observed for trucks without filters. This overlap can also be seen in the histograms shown in Figure 4—some trucks without DPFs had BC emission rates that were comparable to the lowest-emitting DPF-equipped trucks. Conversely, a small fraction of DPF-equipped trucks (4%) had BC emission rates that were higher than the average values for modern (2004–2006 engine) trucks without filters.

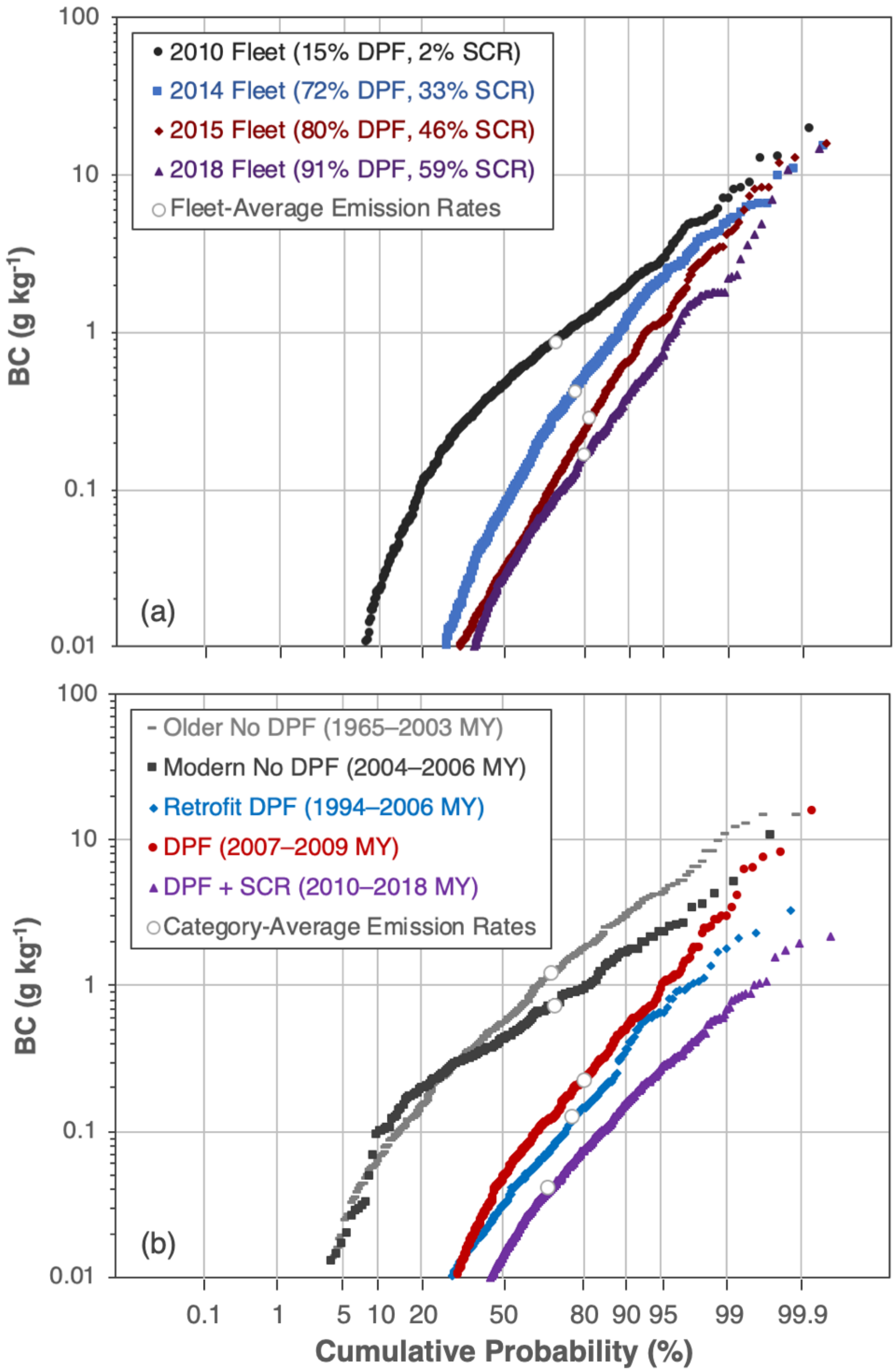
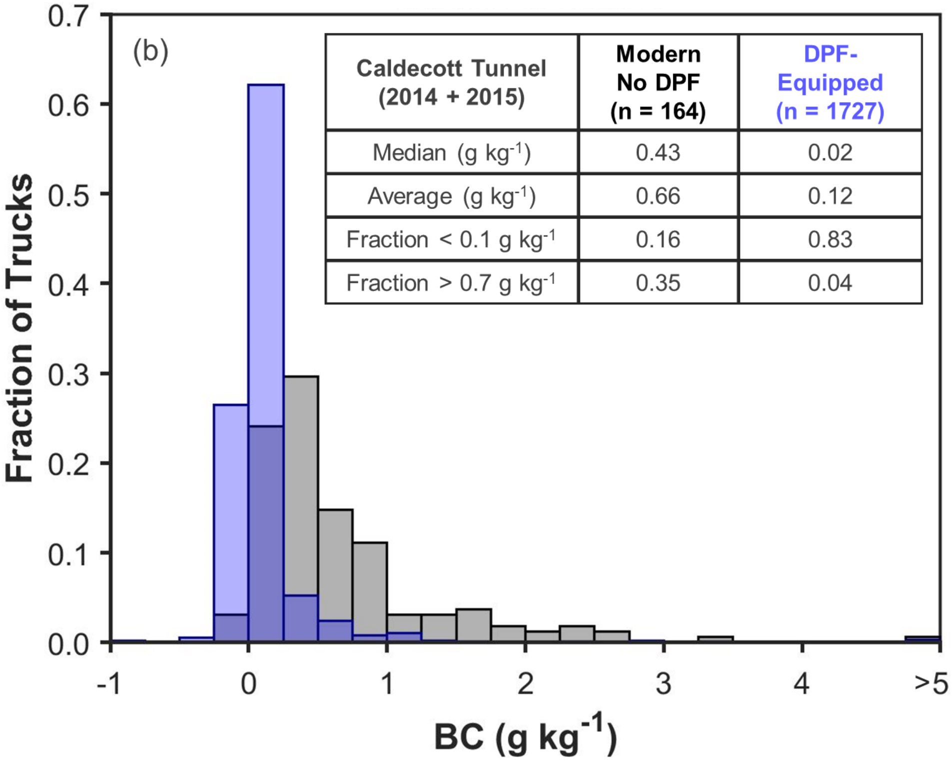


Figure 3. Cumulative probability distributions of black carbon (BC) emission factors for the Caldecott Tunnel truck fleets over time as diesel particle filters (DPFs) became more prevalent (a) and by types of installed emission control technology for the combined 2014, 2015, and 2018 data (b). The truck fleet composition and control technology mix for 2010 at the Caldecott Tunnel was based on EMFAC model estimates for Alameda County (see text).



Caldecott Tunnel (2014 + 2015)	Modern No DPF (n = 164)	DPF-Equipped (n = 1727)
Median (g kg^{-1})	0.43	0.02
Average (g kg^{-1})	0.66	0.12
Fraction < 0.1 g kg^{-1}	0.16	0.83
Fraction > 0.7 g kg^{-1}	0.35	0.04

Figure 4. Distributions of black carbon (BC) emission factors for trucks with and without diesel particle filters (DPFs) measured at the Caldecott Tunnel (in 2014 and 2015). The Modern No DPF category is limited to 2004–2006 engines.

Evidence of DPF Deterioration

In Figure 5, the changes over time in the distributions of BC emission factors for three categories of DPF-equipped trucks are shown: older engines equipped with retrofit DPFs, 2007–2009 engines equipped with DPFs alone, and 2010+ engines equipped with DPFs and SCR. The DPF-equipped 2007–2009 model year engine category stands out from the other two categories. Between 2014 and 2015 at the Caldecott Tunnel, the median BC emission factor for DPF-equipped trucks with 2007–2009 engines remained approximately constant at 0.038 and 0.043 g kg^{-1}, respectively, but the average value increased by 67% from 0.18 to 0.30 g kg^{-1}. These results are consistent with findings of Haugen and Bishop,[29] who reported increases in drayage truck BC emissions at the Port of Los Angeles for a fleet that consisted mostly of trucks with 2007–2009 engines. These observations suggest that deterioration of diesel particle filters installed on trucks with 2007–2009 model year engines can turn relatively new trucks into "high-emitters."

Factors that may contribute to DPF deterioration over time include the tuning of 2007–2009 engines without SCR towards higher engine-out PM in favor of lower engine-out NO_x.[42–44] With this tuning, it is possible for engines to meet the 2007 NO_x emission limit, while the DPF mitigates the high engine-out particle mass emission rate. DPFs on 2007–2009 trucks may thereby become overburdened by heavy PM loading and more frequent/intense active regeneration events. Trucks with 2010+ engines and SCR systems, on the other hand, are operated with higher engine-out NO_x and lower engine-out PM.[42–44] SCR systems are used to address the high engine-out NO_x emission rate, while DPFs can generally employ less stressful, passive regeneration. Other factors that may contribute to DPF failure include the use of cordierite rather than silicon carbide filters, engine durability, and insufficient filter maintenance, the latter of which may allow incombustible ash to slowly accumulate and fouls the filter substrate until the point of failure.[45,46]

Perhaps as surprising as the increase in BC emissions between 2014 and 2015 for 2007–2009 engines is the return in 2018 to a similar rate as measured in 2014. Haugen and Bishop[30] noted that removal or repair of a few high-emitting DPF-equipped trucks from the Port of Los Angeles drayage fleet similarly returned the average PM and BC emission rates to the baseline established immediately after universal adoption of DPFs by that fleet. The return of the 2007–2009 engine BC emission factor to 2014 levels at the Caldecott Tunnel may also be due to removal/repair of trucks that previously had high BC emissions.

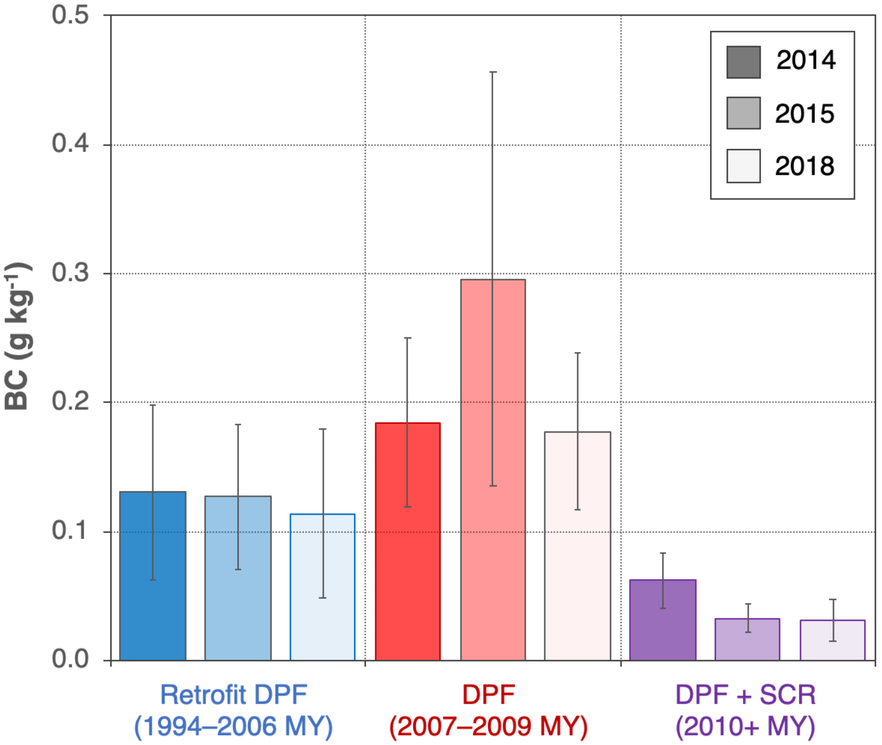


Figure 5. Distributions of black carbon (BC) emission factors for diesel particle filter (DPF) categories, as measured at the Caldecott Tunnel in 2014, 2015, and 2018.

Figure 6 shows the cumulative distribution for BC emitted by the 2018 fleet, with measured emission factors ranked from highest to lowest and identified by emission control category. As discussed earlier, the distribution of BC emissions is highly skewed. Most of the trucks in the on-road fleet have very low BC emissions: ~80% of the truck fleet constitutes slightly more than 10% of total BC emissions. The highest-emitting 10% of trucks were responsible for 73% of total BC emissions in 2018. The skewed nature of pollutant emissions from vehicles is a common feature of on-road fleets, such that pollutants are disproportionately emitted from a minority of high-emitting vehicles.[26,30,36,37] The 9% of trucks that were not equipped with DPFs in 2018—those that were either exempt from or noncompliant with the Truck and Bus Regulation—emit nearly 60% of total remaining BC emissions.

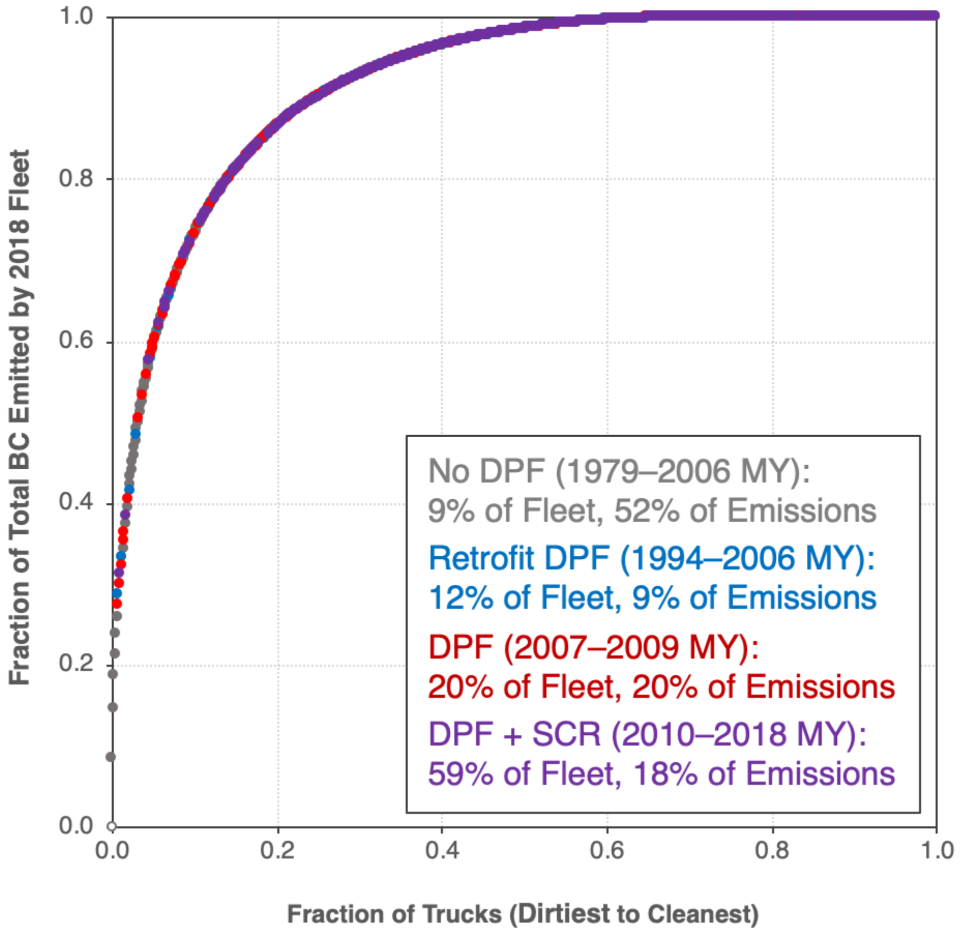


Figure 6. Cumulative distribution of black carbon (BC) emission factors for the truck fleet measured at the Caldecott Tunnel in 2018.

Particle Number and Size Distribution Emissions

Particle number (PN) emission rates are shown for engine/emission control categories and separately for each year of this study in Figure 7. Trucks without filters emitted a comparable number of particles on a per kg of fuel basis as trucks with 2007+ engines equipped with DPFs at the time of manufacture, with and without SCR. The average PN emission rate by trucks retrofitted with DPFs, on the other hand, was approximately twice that of trucks without filters.

These relationships are different than those observed for a nearby fleet of drayage trucks that were measured while operating at lower speeds on a flat arterial street en route to the Port of Oakland.[21] DPF-equipped trucks at the Port of Oakland had lower average PN emission rates by a factor of 2–4 relative to trucks without filters. Also, the PN emission rates were approximately an order of magnitude higher for the trucks measured at the Tunnel than at the Port. Previous studies have similarly found increased emissions of nucleation mode particles in trucks with catalyzed DPFs—like those commonly used in retrofit systems that rely on passive regeneration—under operating conditions that include cruise driving cycles, higher engine temperatures, and high engine loads.[17,18,47] The higher PN emissions under such operating conditions may be related to evaporation of engine oil and subsequent nucleation to form ultrafine particles or sulfur oxidation.[17,18,47]

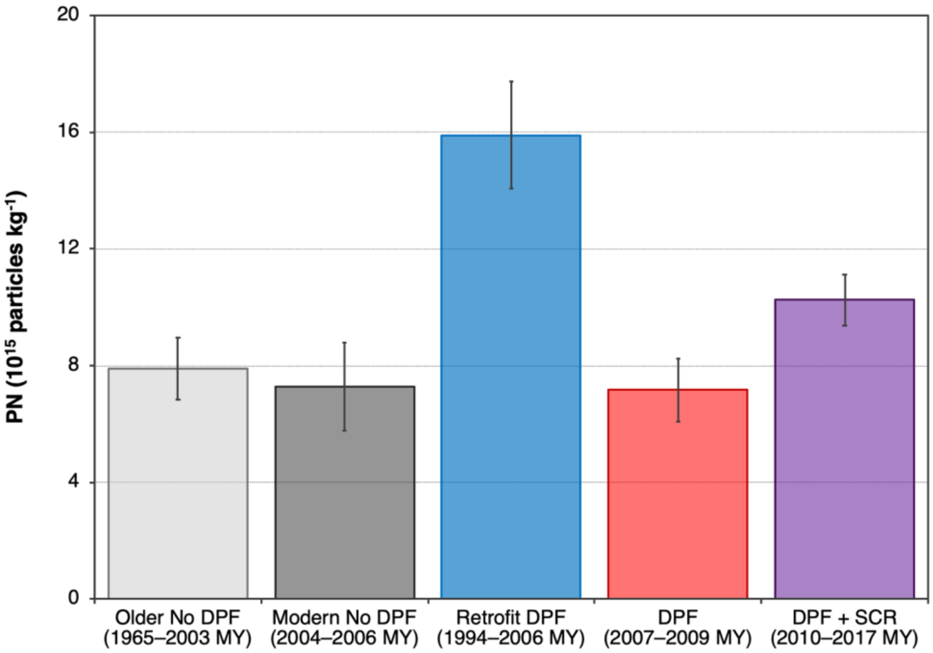


Figure 7. Average particle number (PN) emission factors by emission control category, based on combined 2014, 2015, and 2018 data. The range of engine model years for each category is indicated. Error bars reflect 95% confidence intervals about the mean.

The size-resolved particle number emission rate distributions determined for each emission control category at the Caldecott Tunnel shown in Figure 8. The number of particles emitted per kg of fuel burned were similar across the particle sizes shown for the trucks without filters and with original equipment DPFs. The emission rate of particles less than 50 nm in diameter by trucks with retrofit filters, on the other hand, was on average 3.2 times the average emission rate for the other three categories of trucks. This significant increase in nucleation mode particles is consistent with the observed increase in total PN emission rate by retrofit DPF trucks shown in Figure 7.

All four truck categories at the Caldecott Tunnel exhibited a similar near-unimodal distribution of particles emitted in the size range between 5.6 and ~200 nm with a peak value around 10 nm (Figure 6). This trend differs from the previously presented trimodal distribution observed for trucks without DPFs at the Port of Oakland, and the related observation that DPFs were most effective at removing particles larger than ~15 nm under those driving conditions.[21] These emission differences as a function of sampling site emphasize how driving mode can impact the effects diesel particle filters have on emitted particle number.

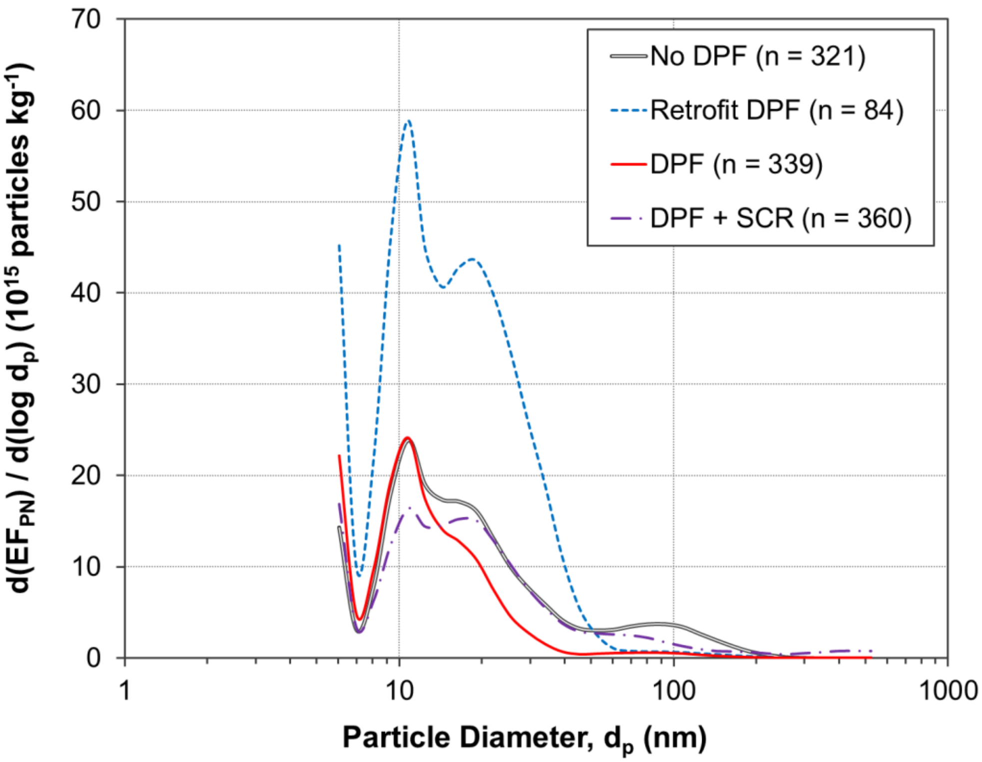


Figure 8. Characteristic particle number emission rate distributions for each emission control technology, based on 2014 field measurements at the Caldecott Tunnel.

Nitrogenous Species Emissions

As illustrated above for BC emission factors, probability distributions of measured NO_x emission factors are shown by calendar year and different technology categories in Figures 9a and 9b. Average NO_x emission factors for trucks by emission control categories are also shown in Figure 10. NO_x emissions from 2010+ engines with SCR are 87% lower than from pre-2004 engines and 84% lower than from 1994–2006 model year engines. These emissions reductions are attributable to increasingly stringent emission standards for new heavy-duty highway diesel engines.[11] It is notable, however, that the average emission factor measured for 2010+ engines is ~4 times higher, on average, than emission certification level (0.2 g bhp-h^{-1} = 1.1 g kg^{-1} assuming bsfc = 175 g hp-hr^{-1}).[39] At the Caldecott Tunnel, where trucks climb a 4% roadway grade at freeway speeds, the high engine load may represent a high engine-out NO_x mode of operation, but these driving conditions also represent a case where high exhaust temperatures and SCR functionality are expected.

Consistent with prior work,[19–21] this study finds that intentional catalytic oxidation of engine-out NO to NO_2 to aid in DPF regeneration leads to increased tailpipe NO_2 emissions: DPFs increase NO_2 to 3–4 times baseline values for trucks without DPF, as shown in Figure 11. These emissions changes are relevant because NO_2 is toxic and increased primary NO_2 emissions promote ozone formation. However, the average NO_2 emission factor for 2010+ SCR-equipped engines is slightly lower than baseline values. Thus, at the Caldecott Tunnel, SCR systems completely mitigate the undesirable NO_2 increase seen for older DPF-equipped engines.

Figures 12–14 show average NO_x and NO_2 emission factors and NO_2/NO_x emission ratios for the truck fleets measured at the Tunnel in calendar years 2010, 2014, 2015, and 2018. Consistent with the modernization of the California on-road truck fleet (Table 1 and Figure 2) and the truck age and emission control performance discussed above, fleet-average NO_x emissions decreased 57 ± 7% between 2010 and 2018 (Figure 9a and Figure 11). Owing to simultaneously increasing penetration of DPF and SCR systems in the on-road fleet, average NO_2 emission factors remained approximately constant and the NO_2/NO_x emission ratio doubled from 7 to 15% over this period (Figures 13 and 14, respectively).

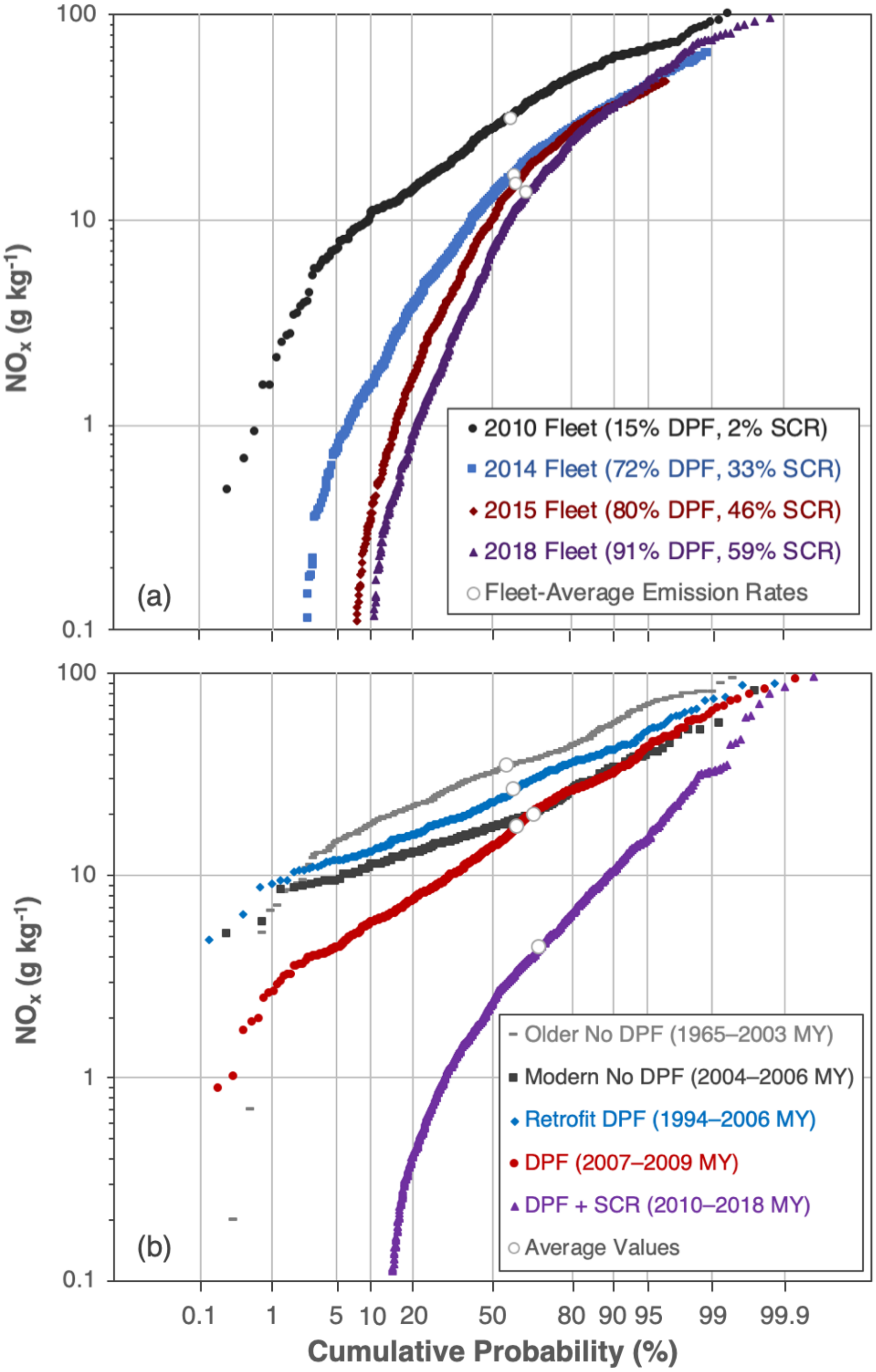


Figure 9. Cumulative probability distributions of oxides of nitrogen (NO_x) emission factors for the Caldecott Tunnel truck fleets over time as selective catalytic reduction (SCR) became more prevalent (a) and by types of installed emission control technology for the combined 2014, 2015, and 2018 data (b). The truck fleet composition and control technology mix for 2010 at the Caldecott Tunnel was based on EMFAC model estimates for Alameda County (see text).

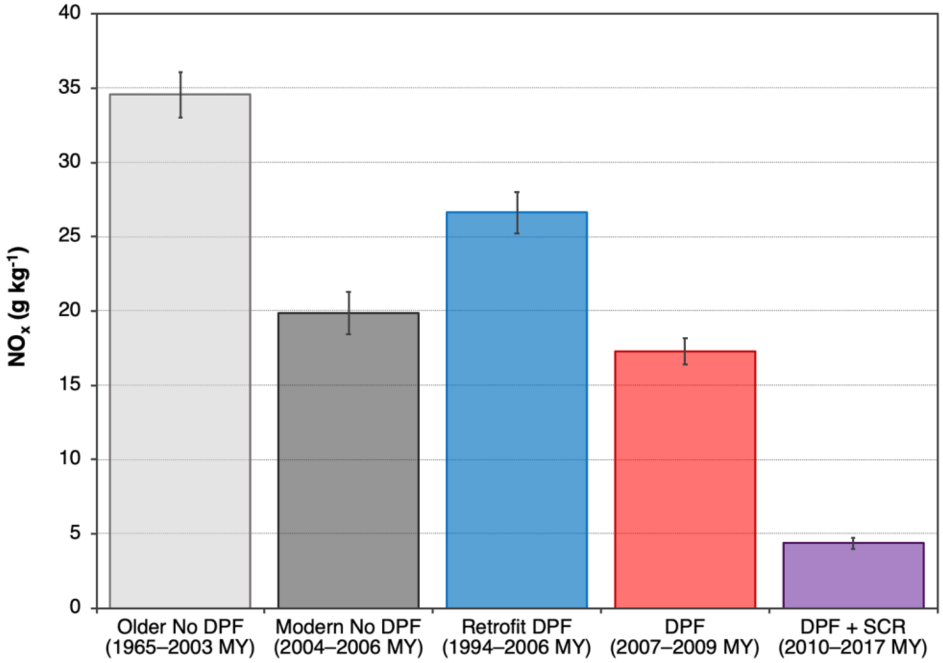


Figure 10. Average nitrogen oxides (NO_x) emission factors by emission control category, based on combined 2014, 2015, and 2018 data. The range of engine model years for each category is indicated. Error bars reflect 95% confidence intervals about the mean.

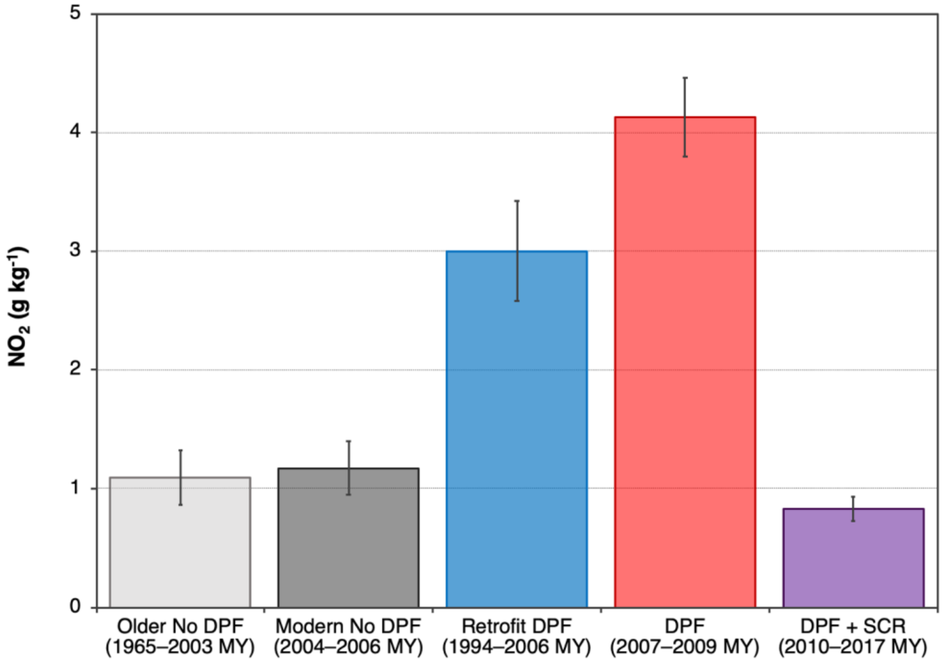


Figure 11. Average nitrogen oxides (NO_2) emission factors by emission control category, based on combined 2014, 2015, and 2018 data. The range of engine model years for each category is indicated. Error bars reflect 95% confidence intervals about the mean.

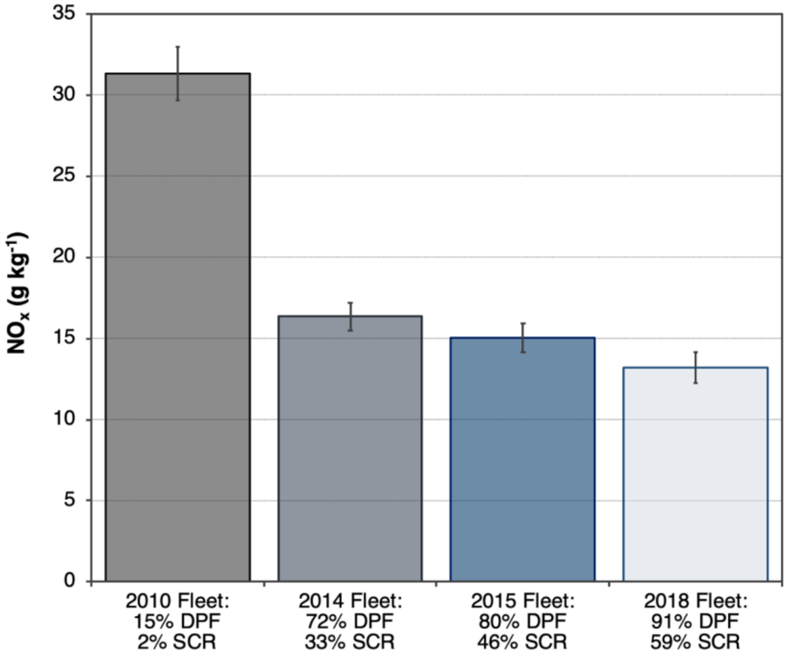


Figure 12. Average nitrogen oxide (NO_x) emission factors for the truck fleet measured at the Caldecott Tunnel in 2010, 2014, 2015, and 2018. Error bars reflect 95% confidence intervals about the mean.

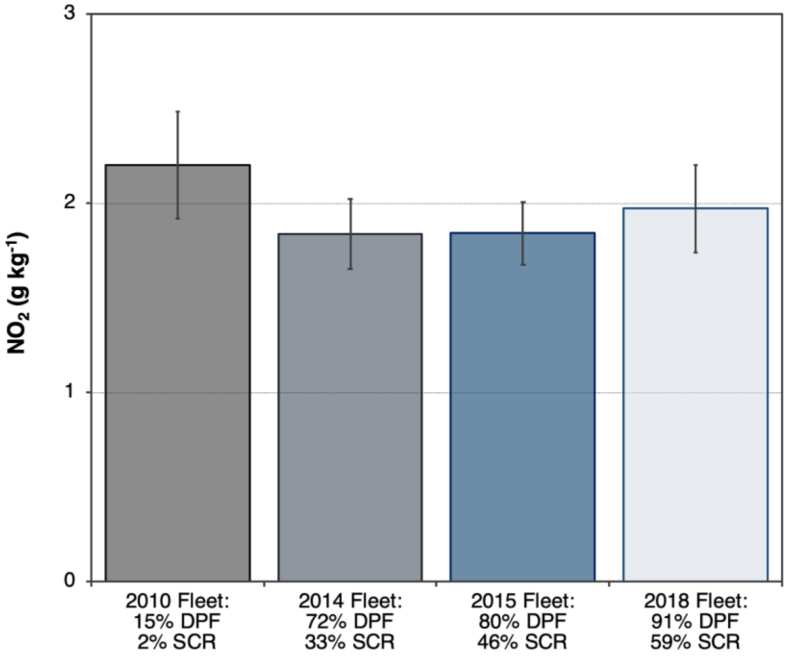


Figure 13. Average nitrogen dioxide (NO_2) emission factors for the truck fleet measured at the Caldecott Tunnel in 2010, 2014, 2015, and 2018. Error bars reflect 95% confidence intervals about the mean.

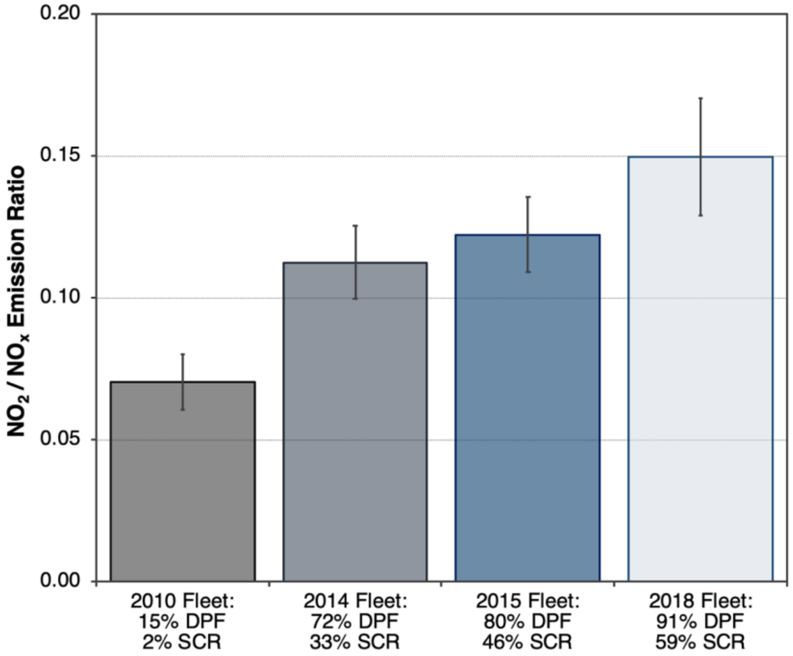


Figure 14. Average nitrogen NO_2/NO_x emission ratios for the truck fleet measured at the Caldecott Tunnel in 2010, 2014, 2015, and 2018. Error bars reflect 95% confidence intervals about the mean.

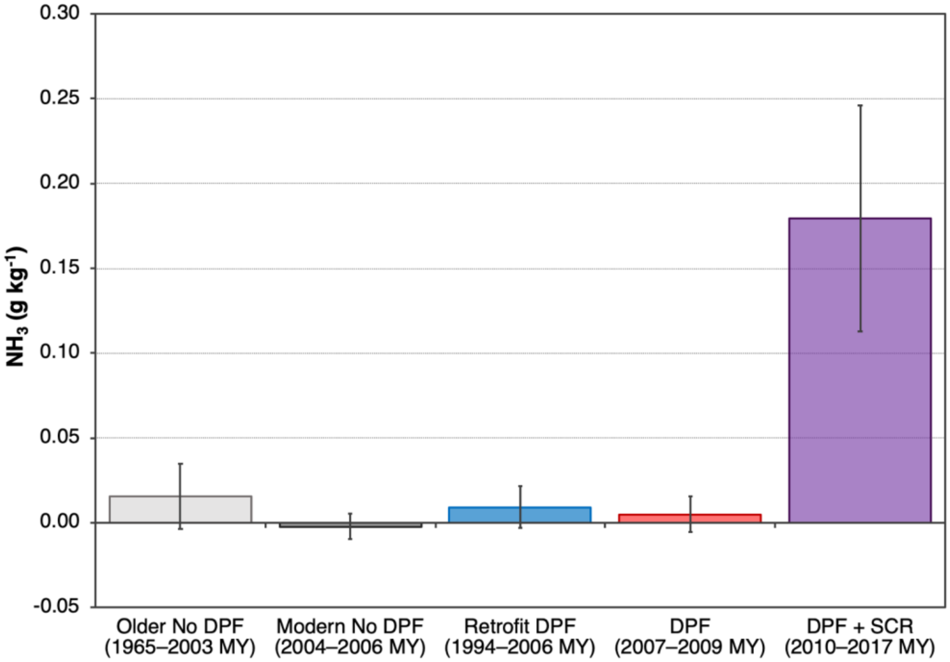


Figure 15. Average ammonia (NH_3) emission factors for the truck fleet measured at the Caldecott Tunnel in 2018. Error bars reflect 95% confidence intervals about the mean.

As shown in Figure 15, use of SCR increased fleet-average NH_3 emission factors from heavy-duty diesel trucks at the Caldecott Tunnel from a near-zero value to a level that is comparable to emissions from three-way catalyst-equipped light-duty vehicles.[48] NH_3 emissions among trucks in this study, however, are very highly skewed, as indicated by the wide confidence intervals shown in Figure 15 and the cumulative emissions distributions shown in Figure 16. Emissions of NH_3 are much more skewed than emissions of other nitrogenous species. Figure 17 shows that the highest NH_3 emissions are generally from trucks with low NO_x emissions. These observations suggest that high NH_3 emissions may be due to overdosing of diesel exhaust fluid in some trucks equipped with SCR. This results in an excessive NH_3/NO_x ratio.[49] Another contributing factor may be an absent or ineffective ammonia slip catalyst on some SCR-equipped trucks.

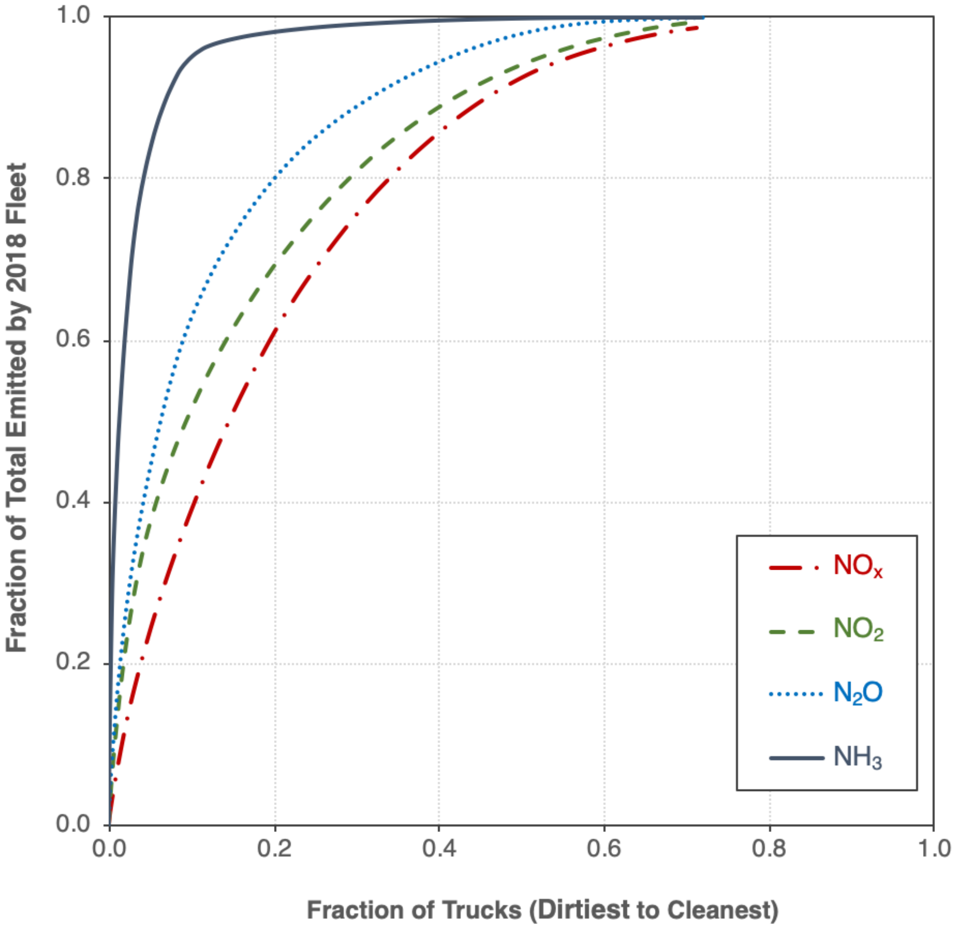


Figure 16. Cumulative distribution of NO_x, NO_2, N_2O, and NH_3 emission factors for the truck fleet measured at the Caldecott Tunnel in 2018.

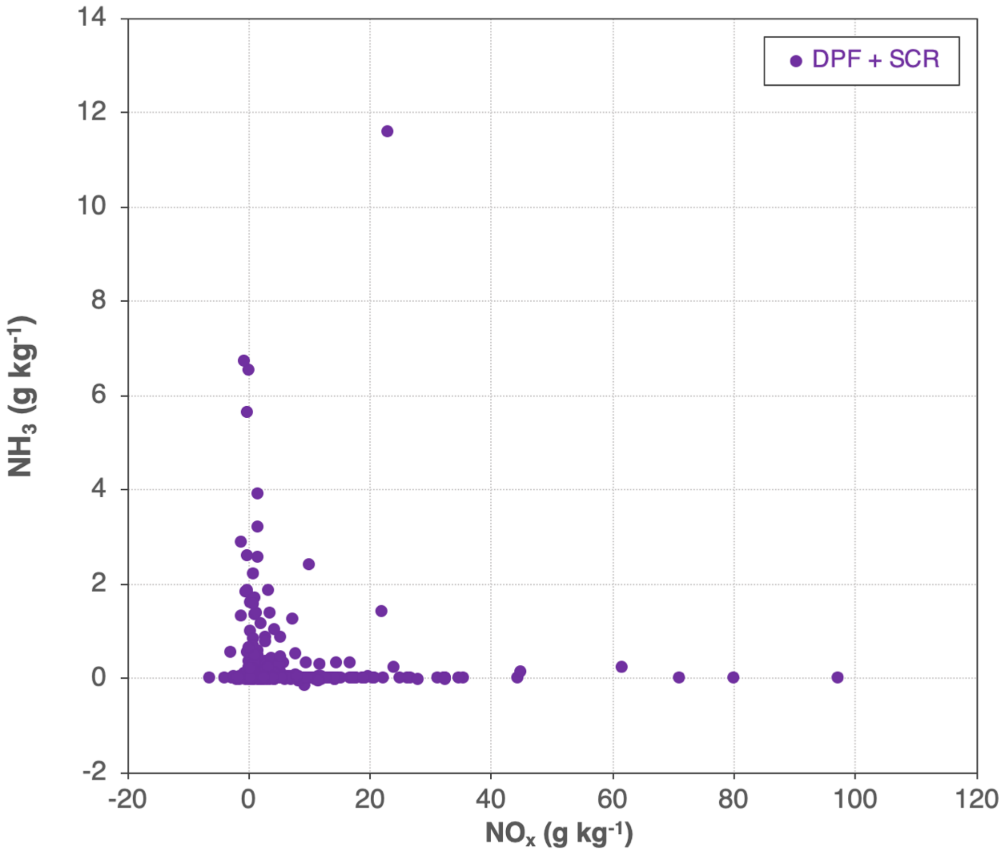


Figure 17. Relationship between NO_x and NH_3 emission factors for the truck fleet measured at the Caldecott Tunnel in 2018 (only emissions from SCR-equipped trucks are shown in this plot; ammonia emissions from non-SCR trucks are negligible, as shown in Figure 12).

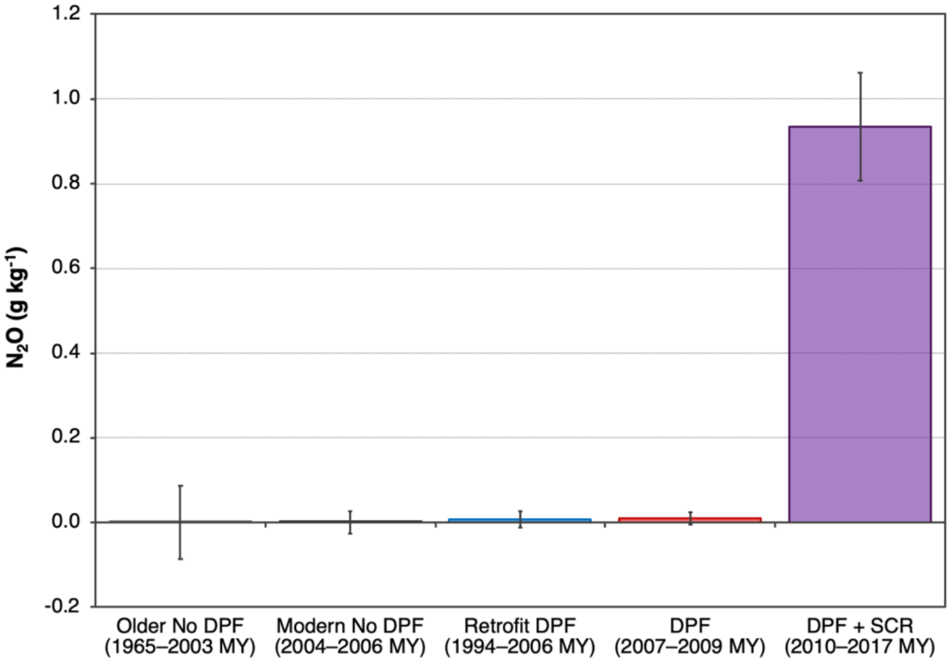


Figure 18. Average nitrous oxide (N_2O) emission factors for the truck fleet measured at the Caldecott Tunnel in 2014, 2015, and 2018. Error bars reflect 95% confidence intervals about the mean.

Use of SCR also increased N_2O emissions from heavy-duty diesel trucks at the Caldecott Tunnel from a rate of near-zero to a level in excess of the California limit (0.6 g kg^{-1} assuming bsfc = 175 g $hp\text{-}hr^{-1}$).[39,50] In trucks with SCR systems, N_2O is the product of either direct oxidation of NH_3 by O_2 or the thermal decomposition of ammonium nitrate that can form when NH_3 and NO_2 react.[51–53] While emissions of N_2O are not considered a public health concern, N_2O is a potent greenhouse gas with a long atmospheric lifetime and is an increasingly important stratospheric ozone-depleting substance in the atmosphere.[54,55] According to CARB's 2016 emission inventory, on-road vehicles emitted 24% of statewide anthropogenic N_2O and heavy-duty diesel trucks emitted 5 Gg of N_2O.[56] That year, 12 billion L of highway diesel was sold in California (equal to 10 billion kg, assuming density of diesel is 0.85 kg L^{-1}).[57,58] Multiplying this mass of diesel fuel sold by the combined average N_2O emission rate for the truck fleets measured at the Caldecott Tunnel (0.55 ± 0.08 g kg^{-1}, positive roadway grade, highway driving) and Port of Oakland (0.16 ± 0.03 g kg^{-1}, level roadway grade, arterial street driving) yields an estimate of ~3.4 Gg of N_2O emissions in 2016 from heavy-duty diesel trucks in California. This value is in reasonable agreement with the current inventory value. However, it suggests that the inventory value of 5.1 Gg for the year 2000 is too high because less diesel fuel was consumed and SCR systems were not used on trucks at that time, so N_2O emission factors would have been lower for older trucks (Figure 18).

Conclusions

This study measured on-road/in-use emissions from thousands of heavy-duty diesel trucks at the Caldecott Tunnel in 2014, 2015, and 2018. This time period overlapped with the phase-in of the Statewide Truck and Bus Regulation, which accelerated the turnover of the truck fleet. Significant increases in the penetration of new emission control technologies—specifically DPFs and SCR—occurred during the study. In 2010, when truck emissions were measured at this site prior to the regulation, 15% of the fleet was equipped with DPF and 2% was equipped with SCR. Compared to this baseline, DPF and SCR penetration increased to 91 and 59%, respectively, and the median engine model year was newer by 9 years in 2018. Over this period, fleet-average emissions of BC and NO_x decreased by 79 and 57%, respectively. NO_2 emissions remained relatively constant despite the intentional conversion of engine-out NO to NO_2 in DPF systems, due to the mitigating effect of SCR on NO_x emissions from 2010 and newer engines. Fleet-average emissions of NH_3 and N_2O increased from near-zero to levels that are comparable to NH_3 emissions from three-way catalyst-equipped light-duty cars and to the California N_2O emission limit for heavy-duty trucks.

BC emission rates for 2010+ engines equipped with both DPF and SCR were on average ~80% lower than 2007–2009 engines that have DPFs only, even though both truck categories are governed by the same exhaust PM emission standard. This study found that 2010+ engines had BC emissions that were 97% lower than trucks with 1965–2003 engines. Whereas BC emissions from 2007–2009 DPF-equipped engines increased by 67% between 2014 and 2015, the average BC emission factor from these engines was no higher in 2018 than in 2014. This return of the average BC emission rate for 2007–2009 engines to 2014 levels at the Caldecott Tunnel may be due to removal or repair of trucks that had high BC emissions. In the spring of 2018, ~10% of the on-road truck fleet was either exempt from or noncompliant with the Truck and Bus Regulation; more than half (~60%) of the remaining BC emissions from the heavy-duty diesel sector are coming from these trucks.

Diesel trucks are a major source of NO_x emissions nationally and in California. This study found that SCR reduces NO_x emissions by ~30 g kg^{-1} or ~90% compared to pre-2004 engines. This reduction can be compared to concomitant increases in NH_3 and N_2O emissions to ~0.2 g NH_3 kg^{-1} and ~0.9 g N_2O kg^{-1} for trucks with SCR. As such, the reduction in the mass emissions of NO_x is about 150 times the increase in NH_3 on a fuel normalized basis; both of these species are precursors to atmospheric formation of secondary particulate matter (e.g., ammonium nitrate, NH_4NO_3). Diesel trucks are a minor source of NH_3 emissions compared to emissions from soils and agricultural activities, but the increment in NH_3 emissions could offset a small fraction of the environmental benefits of a much larger decrease in NO_x emissions, especially in urban areas. Though N_2O is a potent greenhouse gas, the associated global warming potential increase of diesel truck emissions due to SCR-related N_2O emissions is outweighed by the BC reductions from DPFs and the ~4% fuel economy gained with the addition of SCR, as illustrated in Figure 19.[59] The changes in N_2O emissions are of greater potential concern with respect to possible depletion of the stratospheric ozone layer.[55]

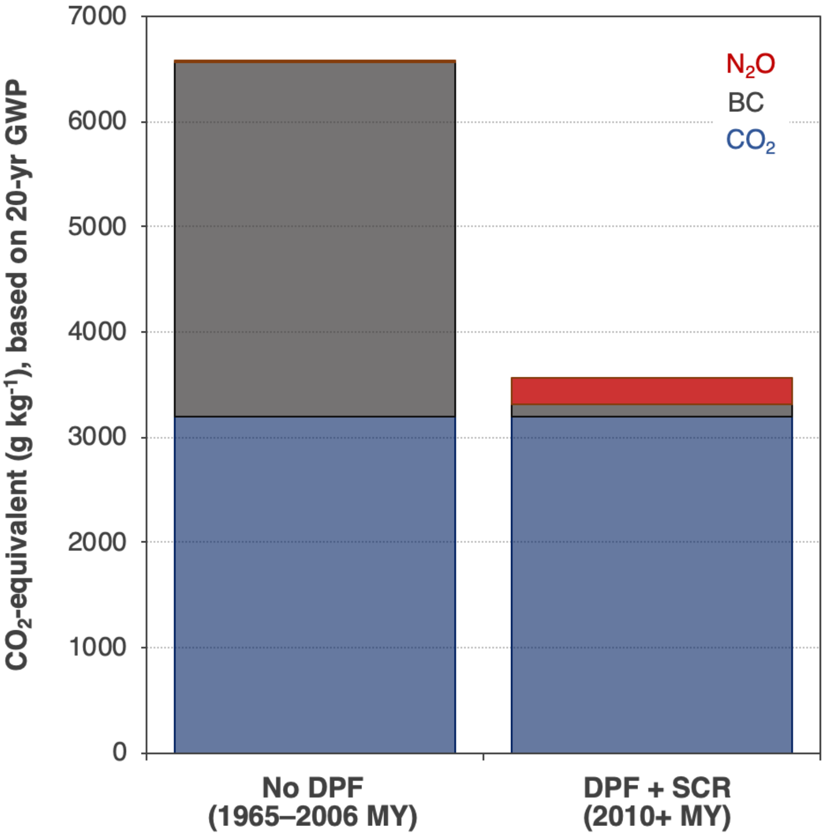


Figure 19. Global warming potential of truck emissions measured at the Caldecott Tunnel, expressed as CO_2-equivalent g kg^{-1}. The ~4% reduction in CO_2 emissions that accompany the fuel economy gain when SCR decreased reliance on exhaust gas recirculation does not appear in this figure because the CO_2-equivalent emissions are expressed on a fuel-normalized basis.

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Appendix

Table A1. Instrumentation used to measure truck exhaust emissions in this work at the Caldecott Tunnel.

Parameter	Sampling Year	Measurement Method/Analyzer	Time Resolution
CO_2 concentration	2014, 2015, 2018	Nondispersive infrared absorption (LI-COR LI-820 and LI-7000)	2 Hz
NO, NO_x concentrations	2014, 2015, 2018	Chemiluminescence (Two ECO Physics CLD-64 analyzers)	2 Hz
NO_2 concentration	2015, 2018	Absorption spectroscopy (Aerodyne CAPS)	1 Hz
N_2O concentration	2014, 2015, 2018	Cavity enhanced absorption (LGR Model 913-0015)	1 Hz
NH_3 concentration	2018	Cavity ring-down spectroscopy (Picarro Model G2123)	1 Hz
BC concentration	2014, 2015, 2018	Aethalometer (Magee Scientific AE16)	1 Hz
PN concentration	2014, 2015, 2018	Ultrafine, butanol-based condensation particle counter (TSI 3776)	10 Hz
PN concentration, size distribution	2014	Fast mobility particle sizer (TSI 3091)	1 Hz

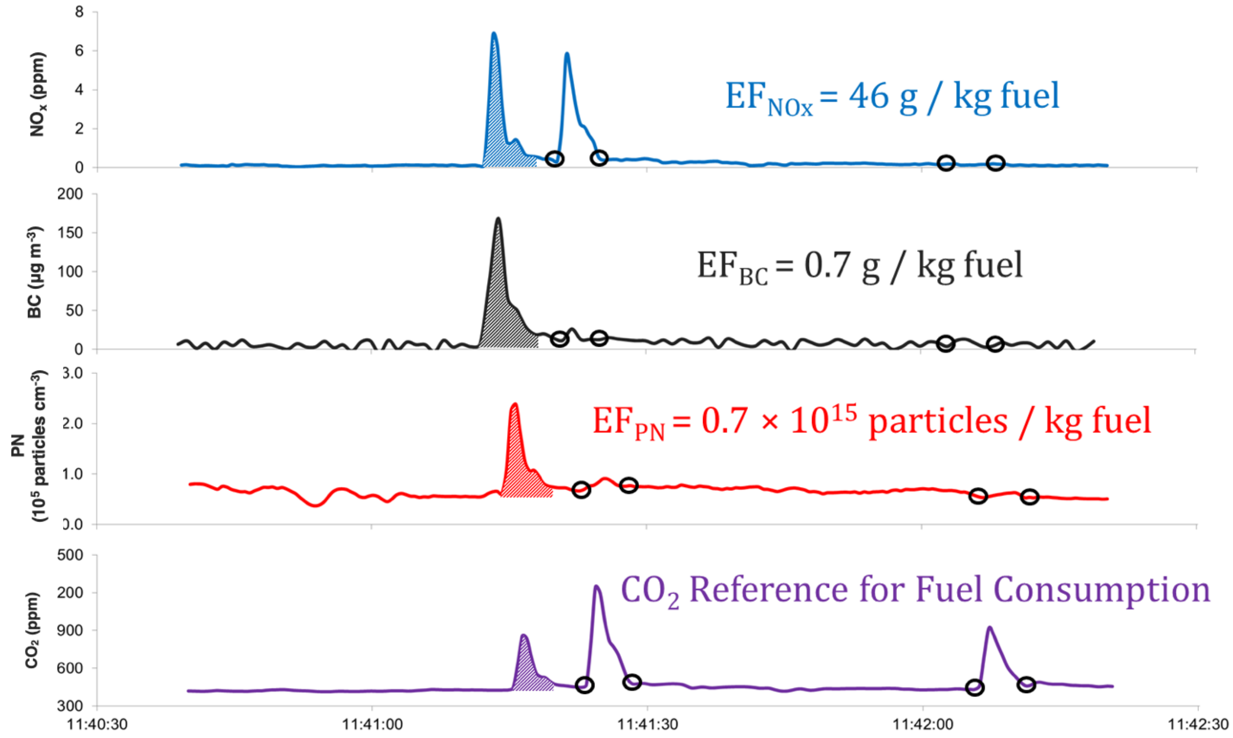

Figure A1. Pollutant concentration time series showing peaks that correspond to the exhaust plumes of three trucks. The first truck emitted appreciable amounts of NO_x, BC, and PN. The shaded peaks correspond to the integrated areas used to compute the emission factors shown in the figure. The second and third trucks emitted much smaller BC and PN concentrations and the third truck emitted essentially no NO_x. The integration boundaries are indicated with open circles for the second and third trucks.

Table A2. Average emission factors (± 95% confidence intervals) for the on-highway truck fleet characterized by emission control technology and engine model year, as measured at the Caldecott Tunnel.

Fleet or Truck Category	**Engine Model Years**	**NO_x (g kg^{-1})**	**NO_2 (g kg^{-1})**	**NO_2/ NOx Emission Ratio**	**NH_3 (g kg^{-1})**	**N_2O (g kg^{-1})**	**BC (g kg^{-1})**	**PN (10^{15} particles kg^{-1})**
2010 Fleet[a] (15% DPF, 2% SCR)	1965–2010[b]	31.3 ± 1.6 (n = 557)	2.2 ± 0.3 (n = 567)	0.07 ± 0.01 (n = 567)	N/A	N/A	0.86 ± 0.11 (n = 667)	N/A
2014 Fleet (72% DPF, 33% SCR)	1965–2015	16.3 ± 0.9 (n = 1139)	1.8 ± 0.2 (n = 1135)	0.11 ± 0.01 (n = 1135)	N/A	0.25 ± 0.06 (n = 1070)	0.41 ± 0.06 (n = 1127)	7.5 ± 0.7 (n = 1088)
2015 Fleet (80% DPF, 46% SCR)	1979–2016	15 ± 0.9 (n = 1194)	1.8 ± 0.2 (n = 1188)	0.12 ± 0.01 (n = 1188)	N/A	0.55 ± 0.14 (n = 1167)	0.28 ± 0.06 (n = 1154)	6.9 ± 0.5 (n = 1163)
2018 Fleet (91% DPF, 59% SCR)	1979–2018	13.2 ± 1.0 (n = 1192)	2.0 ± 0.2 (n = 1189)	0.15 ± 0.02 (n = 1189)	0.1 ± 0.03 (n = 1186)	0.55 ± 0.08 (n = 1168)	0.18 ± 0.04 (n = 1189)	16.3 ± 1.4 (n = 1098)
Older No DPF	1965–2003	34.6 ± 1.5 (n = 458)	1.1 ± 0.2 (n = 454)	0.03 ± 0.01 (n = 454)	0.02 ± 0.02 (n = 62)	0.00 ± 0.09 (n = 433)	1.20 ± 0.17 (n = 453)	7.9 ± 1.1 (n = 446)
Modern No DPF	2004–2006	19.9 ± 1.4 (n = 190)	1.2 ± 0.2 (n = 190)	0.06 ± 0.01 (n = 190)	0.00 ± 0.01 (n = 24)	0.00 ± 0.03 (n = 183)	0.72 ± 0.15 (n = 188)	7.3 ± 1.5 (n = 186)

Fleet or Truck Category	**Engine Model Years**	**NO_x (g kg^{-1})**	**NO_2 (g kg^{-1})**	**NO_2/ NOx Emission Ratio**	**NH_3 (g kg^{-1})**	**N_2O (g kg^{-1})**	**BC (g kg^{-1})**	**PN (10^{15} particles kg^{-1})**
Retrofit DPF	1994–2006	26.6 ± 1.4 (n = 361)	3.0 ± 0.4 (n = 359)	0.11 ± 0.02 (n = 359)	0.01 ± 0.01 (n = 114)	0.01 ± 0.02 (n = 346)	0.12 ± 0.04 (n = 351)	15.9 ± 1.8 (n = 334)
DPF	2007–2009	17.3 ± 0.9 (n = 783)	4.1 ± 0.3 (n = 780)	0.24 ± 0.02 (n = 780)	0.00 ± 0.01 (n = 181)	0.01 ± 0.01 (n = 744)	0.22 ± 0.06 (n = 776)	7.2 ± 1.1 (n = 737)
DPF + SCR	2010–2018	4.4 ± 0.4 (n = 1475)	0.8 ± 0.1 (n = 1471)	0.19 ± 0.03 (n = 1471)	0.18 ± 0.07 (n = 547)	0.93 ± 0.13 (n = 1447)	0.04 ± 0.01 (n = 1445)	10.2 ± 0.9 (n = 1406)

[a] Data from Dallmann et al.[18] and adjusted to account for differences in BC and CO_2 data, as described in Preble et al.[21]

[b] Fleet composition estimated from vehicle miles traveled in summer 2010 in Alameda County.[38]