PLUME CAPTURE MEASUREMENT OF VEHICLE EMISSIONS AT THE CALDECOTT TUNNEL FOR HEAVY-DUTY EMISSION PROGRAM DEVELOPMENT & VERIFICATION

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Prepared by:
Chelsea V. Preble
Robert A. Harley
Thomas W. Kirchstetter

Department of Civil and Environmental Engineering
University of California, Berkeley
Berkeley, CA 94720

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Abstract

Diesel engines are a major source of air pollution in California. The California Air Resources Board (CARB)'s Truck and Bus Regulation has accelerated the introduction of exhaust after-treatment devices to reduce emissions of particulate matter (PM) and oxides of nitrogen (NO_x) from on-road diesel engines. This regulation that first required diesel particle filters (DPFs) on 1996–1999 model year engines by January 2012 ultimately required that nearly all trucks and buses in the state have 2010 or newer model year engines as of January 2023. Most on-road heavy-duty vehicles in California incorporate selective catalytic reduction (SCR) aftertreatment to meet the 2010 engine standards.

This study quantified the emission rates of gas- and particle-phase pollutants from thousands of heavy-duty diesel trucks using a plume capture, carbon balance method at the Caldecott Tunnel in calendar years 2021, 2022, and 2023. This continues a measurement record that began in 2010 through the final stages of the Truck and Bus Regulation. Emission rates of NO_x, nitrogen monoxide (NO), nitrogen dioxide (NO_2), ammonia (NH_3), nitrous oxide (N_2O), and black carbon (BC) were quantified from approximately 1000 individual trucks in each year of this study. Emissions were linked to vehicle attributes, such as engine model year and emission control technologies, by matching vehicle license plates to state-maintained vehicle databases. The study assessed the emissions benefits of the Truck and Bus Regulation, interactive effects among pollutants present in diesel exhaust, and any age-related changes in the performance of exhaust after-treatment control systems.

DPF and SCR controls are now ubiquitous in the California heavy-duty truck fleet. DPF use increased from 15% in 2010 (pre-regulation) to >99% in 2023 (post-regulation), while SCR use increased from 2% to 98%. Over that same period, fleet-average BC and NO_x emission factors respectively decreased by 92% and 75%. There is evidence of increasing NO_x emissions from aging 2007 and newer model year engines, and most NO_x emission factors for pre-2016 engines were higher than the applicable emission standard. Additionally, fleet-average N_2O recently increased by 58% between 2021 and 2023, most notably for aging 2010–2012 engines. Most BC emission factors for 2010 and newer model year engines were below the corresponding PM emission standard. Average BC emissions from aging DPFs on 2010+ emissions have increased by a factor of 1.7 over 2021–2023 compared to 2014–2018. This upward trend is less pronounced and of lower absolute magnitude than has been observed for 2007–2009 DPF-equipped trucks, however. NH_3 emission factors are elevated when NO_x is low, indicative of NH_3 slip or overdosing by SCR systems. NH_3 emissions are also very skewed—most trucks emitted near-zero while the highest emitting 10% of the 2023 fleet was responsible for 100% of emitted NH_3. Differences in NO_x, N_2O, and BC emission factors for 2010 and newer engines by manufacturer suggest that SCR catalyst or system design may impact real-world performance and emissions. Together, this decade of on-road measurements in California may reflect changes occurring nationwide that are important for emission inventory and policy development. These results also highlight the importance of identifying and controlling the highest emitting trucks that contribute the most to the on-road fleet's total emissions.

Introduction

Heavy-duty diesel vehicles are important emitters of many pollutants that contribute to air quality and human health problems.[1,2] Diesel particulate matter (PM), which includes black carbon (BC), is considered a toxic air contaminant by the California Air Resources Board (CARB) and a carcinogen by the World Health Organization.[3] While there have been substantial reductions in diesel PM emissions associated with the increased use of diesel particle filters (DPFs) by the on-road fleet, a majority of the remaining PM is emitted from a minority of high-emitting vehicles in the fleet.[4,5] More information on these so-called “high emitters” is needed to achieve further reductions in exposure to diesel PM.

On-road heavy-duty vehicles are also large emitters of nitrogen oxides (NO_x), a precursor to both ozone (O_3) and fine particulate matter ($PM_{2.5}$).[6] Large portions of California are not in attainment of National Ambient Air Quality Standards for $PM_{2.5}$ and O_3, and air pollution mitigation plans for many of these regions call for sharp reductions in NO_x from heavy-duty vehicles. Traditionally, these types of reductions have been obtained by tightening certification and in-use compliance standards; the certification standard for NO_x was lowered to 0.2 grams per brake horsepower-hour (g $bhp\text{-}hr^{-1}$) for 2010 and newer (2010+) model year (MY) engines. However, many studies have found that in-use NO_x emissions from heavy-duty vehicles are higher than would be expected based on applicable emission standards.[7,8] Measurements of these real-world NO_x emissions are critical to gauge the effectiveness of new emission standards and control technologies.

California’s Truck and Bus Regulation requires that nearly all trucks and buses in the state have 2010+ MY engines by January 2023.[9] Most heavy-duty vehicles in California incorporate selective catalytic reduction (SCR) aftertreatment to meet the 2010 engine standards. In addition, starting in 2020, California registration of heavy-duty vehicles is contingent on Truck and Bus Regulation compliance. This study monitors the final phases of the implementation of this regulation to quantify its final real-world emissions benefit and determine how the emissions of various pollutants are changing as engines and emission controls age. Previous work, including measurements made at the Caldecott Tunnel, has indicated that SCR can effectively reduce NO_x emissions and is also associated with lower BC emissions compared to vehicles equipped with DPF alone.[4,7] The same study also measured concomitant increases in ammonia (NH_3), an important precursor to secondary $PM_{2.5}$ formation, and nitrous oxide (N_2O), a potent greenhouse gas.[7]

New legislation in California also directs state agencies to develop a heavy-duty vehicle inspection and maintenance program.[10] That development effort will be aided by characterization of the real-world fleet, including both fleet-average emissions, as well as specific characteristics of the high-emitting vehicles which dominate the fleet averages. Specific questions, such as the number and types of vehicles to target with an inspection and maintenance program, can be addressed using the data collected by this study.

Finally, while instantaneous plume capture measurements, like those made during this study, do not capture the duty-cycle dependence of emissions, they will capture the in-use emission rates for thousands of vehicles. Therefore, they can aid in developing California's emission inventories by providing information on trends in emissions with vehicle age and newly adopted emission control technologies.

Methods

Figure 1 shows the Caldecott Tunnel field sampling site, which has been used for on-road emission studies for decades.[4,7,11–14] Most recently, this site has been used to track the progress of the Truck and Bus Regulation. Table 1 summarizes the compliance schedule for the Truck and Bus Regulation and the corresponding calendar years during which measurements were made.[9] Over the previous study between 2014–2018, pre-2007 MY engines were equipped with DPFs. In the current study, truck emissions were measured over the final phases of the Truck and Bus Regulation that required replacement of 1996–2009 MY engines with 2010+ MY engines: (i) August–September 2021, by which time all 1996–2004 model year engines were replaced; (ii) August 2022, when 2005–2006 engines were replaced; and (iii) August–September 2023, when 2007–2009 engines were replaced and all heavy-duty diesel trucks were required to be equipped with 2010+ MY engines.

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 (a), and the roadside camera positioned at the entrance to the tunnel is also circled and shown in (b). Reproduced from Preble et al.[7]

Table 1. Summary of UC Berkeley field sampling campaigns of on-highway truck emissions at the Caldecott Tunnel during the phased implementation of the Truck and Bus Regulation.

Sampling Year	Compliance Schedule Change
2010	Pre-regulation fleet
2014	1996–2006 MY engines DPF-equipped
2015	Pre-1994 MY engines replaced with 2010+ engine
2018	1994–1995 MY engines replaced with 2010+ engine; mid-regulation fleet is DPF-equipped
2021	1996–2004 MY DPF-equipped engines replaced with 2010+ engine
2022	2005–2006 MY DPF-equipped engines replaced with 2010+ engine
2023	2007–2009 MY DPF-equipped engines replaced with 2010+ engine; post-regulation fleet is fully DPF + SCR 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 hauling containers from the nearby Port of Oakland. All truck types were included in our analysis for this location.

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 two 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 mass of pollutant emitted per mass of fuel burned (g kg^{-1}), using a carbon balance method:[13]

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

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 = 870 g C per kg diesel) is used to convert emission factors from per mass of carbon to mass of fuel burned,[13] 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.[14] 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.[15] 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 each pollutant analyzer 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. 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.

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.[16] and Dallmann et al.[14] For sampling years 2018, 2021, 2022, and 2023, a model AE33 aethalometer was concurrently deployed to also measure BC. The linear agreement between these two aethalometer models is very strong, with a slope of 0.87, near-zero intercept, and R^2 of 0.98 (Figure 2). All BC results presented below are from the AE16 model aethalometer, consistent with prior work.[4,14,16] AE33 emission factors are reported in Tables A2–A3 of the Appendix.

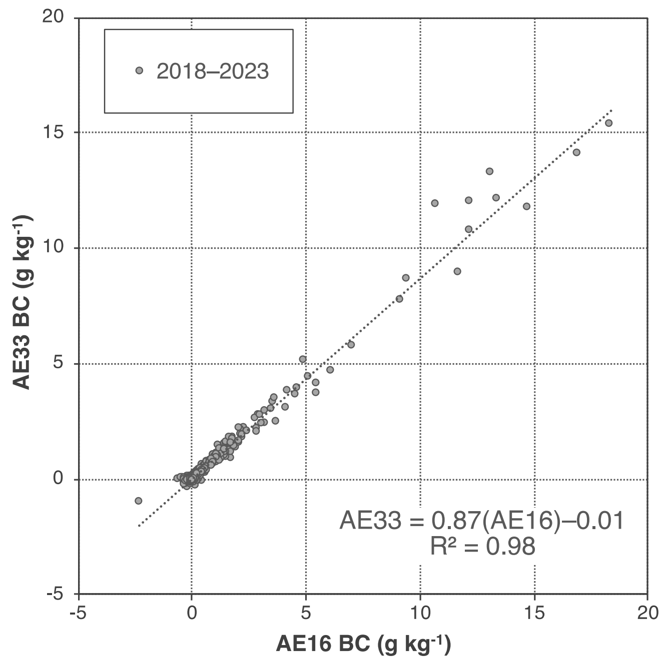

Figure 2. Comparison of 3,881 BC emission factors determined with two collocated aethalometers, models AE16 and AE33, during measurements in 2018, 2021, 2022, and 2023 at the Caldecott Tunnel. The linear best fit line is shown as the dashed line, with regression statistics noted.

A license plate recognition (LPR) 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: (1) Truck Regulation Upload, Compliance, and Reporting System (TRUCRS); (2) Drayage Truck Registry (DTR); and (3) Department of Motor Vehicles (DMV) vehicle registration database. A second camera was positioned on the hillside above the roadside, facing towards the Tunnel entrance and capturing the backside of the truck cabs. With this view, it was possible to determine whether trucks had an updraft versus downdraft exhaust. Truck refrigeration units (TRUs) were also noted from the recorded video.

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. Not every truck was matched in TRUCRS or DTR, and some plates only had a DMV match. 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 less information available from the state vehicle registration database to classify the vehicle by model year and emission control category.

Results and Discussion

Trucks and emission factors are discussed below in term of fleet-average values as measured in each calendar year of the study (Table A1). Results are also presented by grouping trucks into one of five categories based on engine model years and verified emission controls (Table

A2): (a) pre–2007 engines without DPFs; (b) trucks with 1994–2006 engines that were retrofitted with DPFs; (c) 2007–2009 model year engines that were equipped with a DPF at the time of manufacture; and (d) trucks with 2010 and newer engines that were equipped with both DPF and assumed SCR systems at the time of manufacture. Additionally, the 2010+ engines are further categorized by engine MY into three technology groups that describe levels of SCR and on-board diagnostics (OBD) compliance: (a) 2010–2012 MY engines that were transitioning to SCR, (b) 2013–2015 MY engines that were transitioning to OBD, and (c) 2016+ MY engines that were fully OBD compliant. These two sets of categorized results are presented using combined data from the 2021, 2022, and 2023 field sampling campaigns, unless otherwise noted. All model years refer to the engine rather than the truck chassis. Reported uncertainty ranges provide 95% confidence intervals for the corresponding mean values.

Results below are also compared to relevant exhaust emission standards, converted from power-based units (g $bhp\text{-}h^{-1}$) to fuel-based values (g kg^{-1}) by assuming an average brake-specific fuel consumption of 0.175 kg of fuel per bhp-h.[17] Table 2 summarizes these exhaust emission standards by engine MY for NO_x, N_2O, and PM.[18,19] NO_x emissions are limited to 0.2 g $bhp\text{-}hr^{-1}$ for 2007+ engines based on a phased-in percent-of-sales schedule.[18] In practice, most manufacturers certified 2007−2009 engines to 1.2 g $bhp\text{-}hr^{-1}$, and the 0.2 g $bhp\text{-}hr^{-1}$ emission limit was only met by 2010+ engines. This practice is reflected in Table 2 and the discussion that follows below. The federal NO_x and PM emission standards will be tightened for 2027+ MY engines, and California has set more stringent NO_x limits for 2024–2026 and 2027+ MY engines.[20,21]

Table 2. Exhaust emission standards for heavy-duty compression-ignition engines, in original power-based units (g $bhp\text{-}h^{-1}$) and converted to equivalent fuel-based values (g kg^{-1}). All standards are set at the federal level by the EPA, except for those California-specific limits that are denoted by an asterisk.

<table>
<tr><th rowspan="2">Engine MY</th><th colspan="3">Power-Based Emission Standard (g $bhp\text{-}h^{-1}$)</th><th colspan="3">Equivalent Fuel-Based Emission Standard (g kg^{-1})</th></tr>
<tr><th>NO_x</th><th>N_2O</th><th>PM</th><th>NO_x</th><th>N_2O</th><th>PM</th></tr>
<tr><td>2007</td><td>1.2</td><td rowspan="2">N/A</td><td rowspan="3">0.01</td><td>6.9</td><td rowspan="2">N/A</td><td rowspan="3">0.06</td></tr>
<tr><td>2010</td><td rowspan="2">0.2</td><td rowspan="2">1.1</td></tr>
<tr><td>2014</td><td rowspan="4">0.1</td><td rowspan="4">0.6</td></tr>
<tr><td>2024*</td><td>0.05</td><td rowspan="3">0.005</td><td>0.3</td><td rowspan="3">0.03</td></tr>
<tr><td>2027*</td><td>0.02</td><td>0.1</td></tr>
<tr><td>2027</td><td>0.035</td><td>0.2</td></tr>
</table>

Caldecott Tunnel Fleet Composition

The truck fleet composition in 2021, 2022, and 2023 are reported along with those from previous measurement years (2010, 2014, 2015, and 2018) in Table 3. Figure 2 shows the engine model year distributions of heavy-duty diesel trucks in the 2010 pre-regulation fleet and the 2023 post-regulation fleet. Data for calendar year 2010, which serves in the present study as a baseline prior to the start of the 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.[22]

Table 3. Distribution of heavy-duty diesel trucks observed at the Caldecott Tunnel by emission control category, as measured in 2014, 2015, 2018, 2021, 2022, and 2023, and as reported for 2010 in the EMFAC model.[22] 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 MY Range	Median Engine MY	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)
2021 (99% DPF, 87% SCR)	1960–2021 (N = 1047)	2014	1% (n = 9)	3% (n = 27)	10% (n = 104)	87% (n = 907)
2022 (>99% DPF, 91% SCR)	1991–2022 (N = 1000)	2015	<1% (n = 4)	1% (n = 7)	8% (n = 78)	91% (n = 911)
2023 (>99% DPF, 98% SCR)	1993–2023 (N = 1027)	2015	<1% (n = 1)	<1% (n = 3)	2% (n = 19)	98% (n = 1004)

Following the Regulation's compliance schedule, the on-road fleet operating at the Caldecott Tunnel has increasingly adopted DPF and SCR systems—between 2010 and 2023, DPF penetration increased from 15 to >99% and SCR use increased from 2 to 98%. The median engine model age was 8 years in both 2010 and 2023. Drayage accounted for ~10% of the fleet, as determined by matches in the DTR in 2021 and 2022. Of the trucks operating at this site, ~30% had downdraft exhausts. Because of the better likelihood of strong plume capture with updraft exhausts compared to more diluted downdraft exhaust plumes, the final emission factors in this study were slightly biased towards updraft exhausts; updrafts made up 80% of the final dataset but comprised ~70% of the observed truck fleet operating at the Caldecott Tunnel.

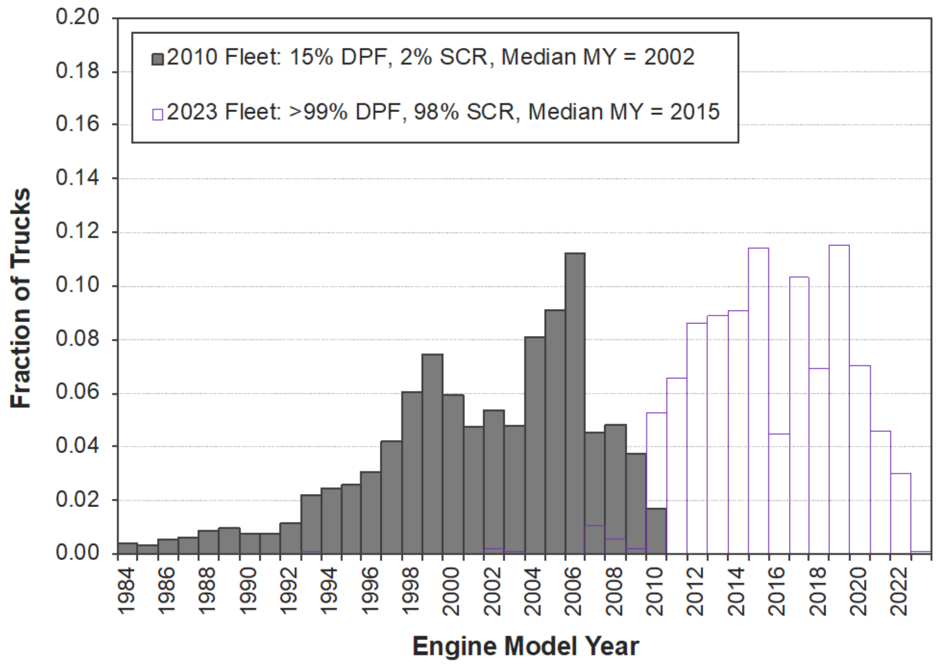

Figure 2. Engine model year distributions of heavy-duty diesel trucks operating at the Caldecott Tunnel in 2010, prior to the Truck and Bus Regulation, and after the regulation was fully implemented in 2023.

Emissions of Nitrogen Oxides

Emission Factor Distributions and Trends

Average NO_x and NO_2 emission factors and NO_2/NO_x emission ratios for the truck fleets measured at the Caldecott Tunnel in each sampling year since 2010 are shown in Figure 3. Between 2010 and 2023, as fleet adoption of 2010+ engines increased from 2% to 98%, the fleet-average NO_x emission factor decreased by 75 ± 8%. The 2023 post-regulation fleet has an average NO_x emission rate of 7.8 ± 1.2 g kg^{-1}, which is 6.9 times greater than the emission standard of 1.1 g kg^{-1} for 2010+ engines. Over the same period, NO_2 decreased by and 37 ± 19%, from 2.2 ± 0.3 g kg^{-1} to 1.4 ± 0.3 g kg^{-1}. More of emitted NO_x is in the form of NO_2 rather than NO, though, as indicated by the increasing NO_2/NO_x emission ratio—in 2010, the fleet-average emission ratio was 0.07 ± 0.01, and this ratio increased by 2.5× to 0.18 ± 0.05 in 2023.

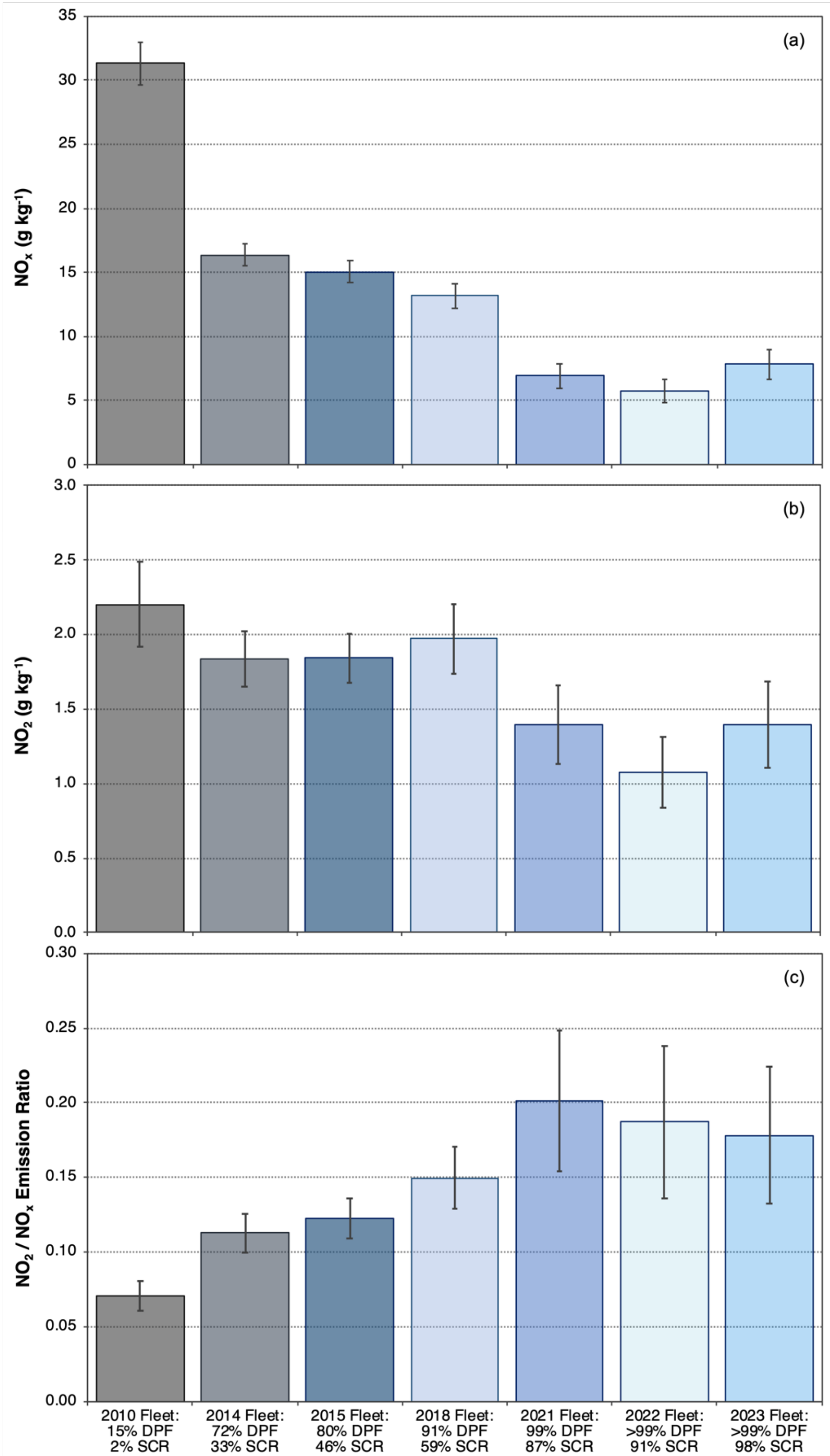

Figure 3. Fleet-average (a) NO_x, (b) NO_2, and (c) NO_2/NO_x emission ratio for each sampling campaign year over the course of the Truck and Bus Regulation. Error bars show 95% confidence intervals about the mean, as also reported in Table A1.

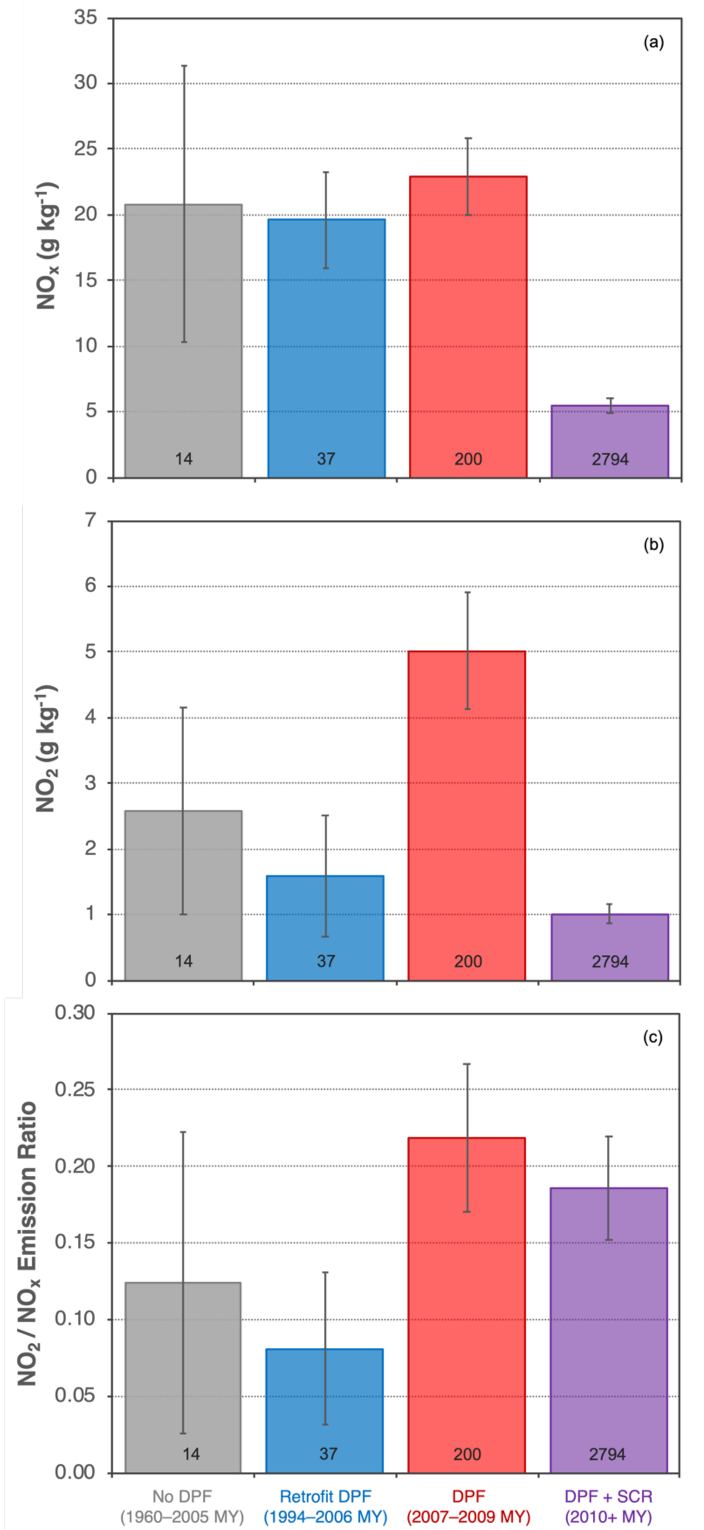

Figure 4. Average (a) NO_x emission factors, (b) NO_2 emission factors, and (c) NO_2/NO_x emission ratios by emission control category, as measured at the Caldecott Tunnel in 2021, 2022, and 2023. Sample sizes for each category are noted at the bottom of each bar and error bars show 95% confidence intervals about the mean, as also reported in Table A2.

Figure 4 shows the average NO_x and NO_2 emission factors and NO_2/NO_x emission ratios for the four emission control categories, based on combined data from 2021, 2022, and 2023 measurements at the Caldecott Tunnel. NO_x emissions from 2010+ engines are 75% lower than 2007–2009 MY engines without SCR. Consistent with results previously reported in Preble et al.,[7] we find that SCR systems mitigate the undesirable tailpipe NO_2 increase observed in 2007–2009 MY engines that results from the intentional catalytic oxidation of engine-out NO to NO_2 for DPF regeneration; the average NO_2 emission rate is 80% lower for 2010+ engines with SCR than trucks with 2007–2009 MY engines. It is notable, however, that the average emission factor measured for 2010+ engines is 4.8 times higher, on average, than exhaust emission standard. At the Caldecott Tunnel, where trucks climb a 4% roadway grade at highway speeds, the high engine load may represent a high engine-out NOx mode of operation, but these driving conditions also represent a case where high exhaust temperatures and SCR functionality are expected.

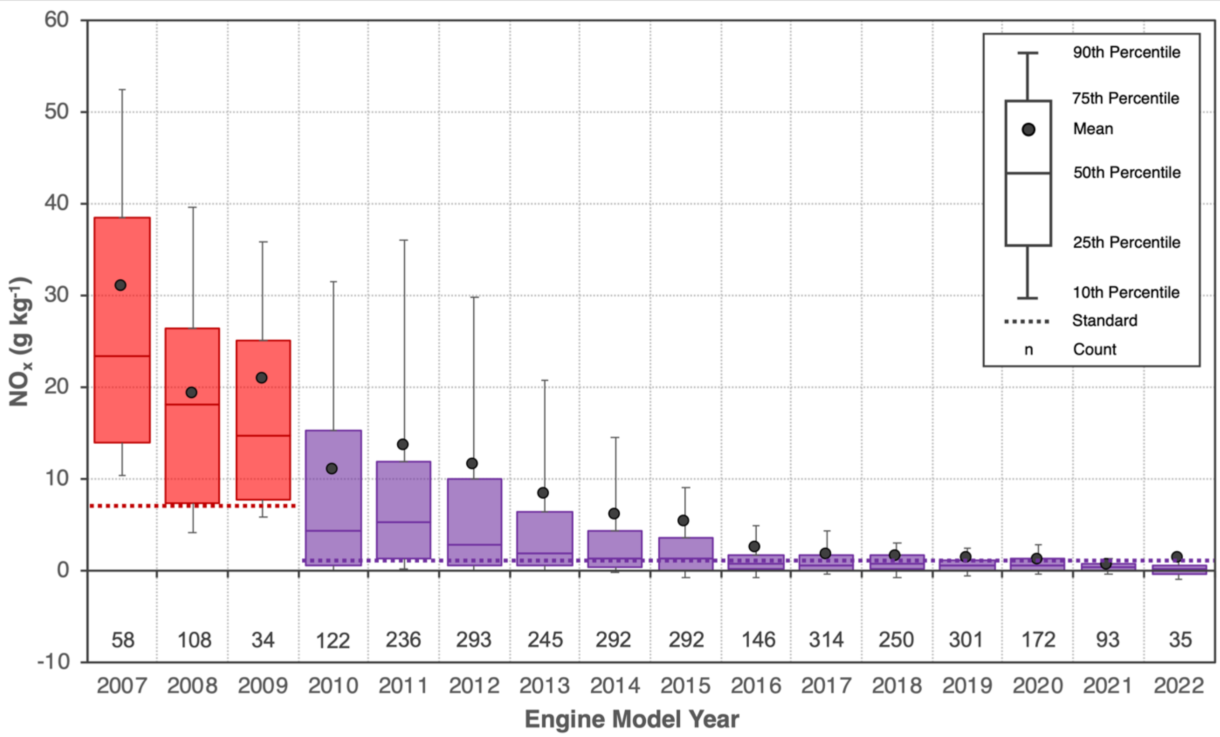

Figure 5. Distributions of measured NO_x emission factors by engine model year for trucks operating at the Caldecott Tunnel in 2021, 2022, and 2023. The corresponding exhaust standards are shown as dashed lines as comparison benchmarks.

The distributions of NO_x emissions for 2007+ engines are further broken down by engine MY in Figure 5 and compared to the corresponding exhaust emission standards from Table 2. A majority of in-use emission factors for pre-2016 MY engines exceed the standard. 100% of the distribution for the 2007 MY and 75% of the distributions for 2008 and 2009 exceed the standard of 6.9 g kg^{-1}, and the mean emission factors are 3.1–4.5 times greater. Similarly, >50% of each 2010–2015 MY distribution is higher than the 1.1 g kg^{-1} standard, and the mean values are 4.6–11.9 times greater. The distributions for 2011–2015 MY engines are especially skewed, with means that exceed the 75th percentile and widely extending 90th percentile whiskers. Even if the comparison thresholds were increased by 50% to the not-to-exceed (NTE) values (10.3 and 1.7 g kg^{-1}, respectively), a majority of the 2007–2013 MY distributions would still exceed the corresponding emission limits.

Evidence of Increasing NO_x Emissions by Aging Systems

As shown in Figure 6, there is evidence of increasing NO_x emission rates from aging 2007+ MY engines. Here, average NO_x emission factors by emission control category are shown separately for each sampling campaign between 2014–2023. For each category section, the darker shaded boxes on the lefthand side correspond to measurements made in calendar year 2014, and the most transparent boxes on the righthand side show measurements from 2023. Thus, moving from left to right in each category section moves forward in time as these technologies age from newer to older systems. The category-average for 2007–2009 MY engines has roughly plateaued, but the broader confidence intervals suggest that emissions are becoming more variable as these engines age. Prior to 2023, the trend for this category of engines suggested an increase in NO_x emissions with age. Note that the sample size for this category is especially small in 2023 compared to other years, so this last data point should be considered with caution. The reverse is true for the 2010+ MY engines, which have an increasing sample size with each subsequent year, adding confidence to the observed trend. Between 2014 and 2022, the average NO_x emission rate for these newer engines were comparable from year to year. In 2023, however, the average was 1.74 times greater, increasing from ~4.3 g kg^{-1} to 7.5 g kg^{-1}.

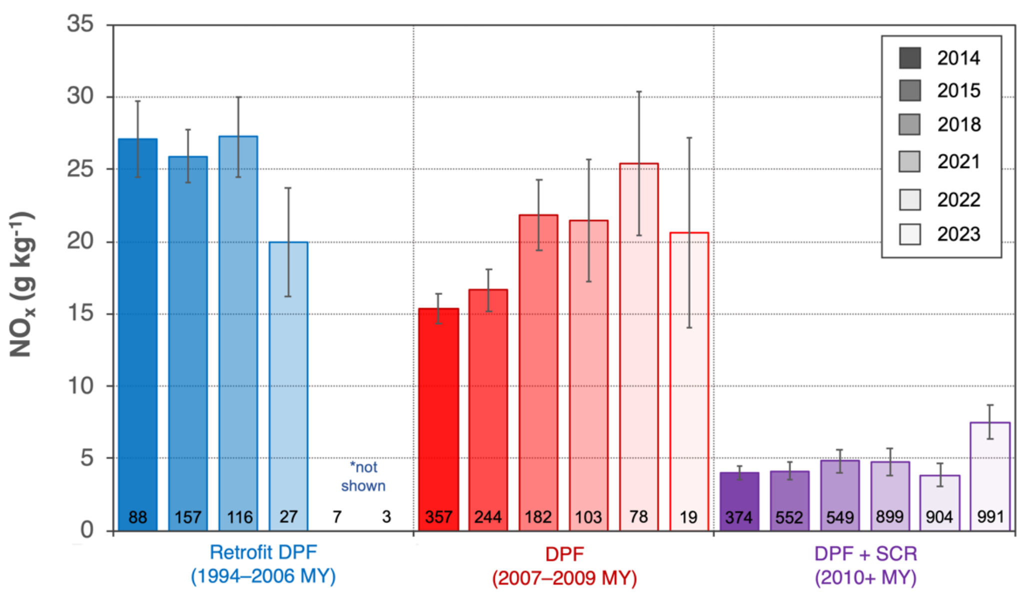

Figure 6. Average NO_x emission factors by emission control category, as measured at the Caldecott Tunnel in each sampling campaign between 2014–2023. Sample sizes for each category are noted at the bottom of each bar and error bars show 95% confidence intervals about the mean.

To examine the 2023 increase in NO_x emissions by 2010+ MY engines, Figure 7 shows the average emission rates by the three categories of SCR-equipped trucks: (1) SCR Transition, 2010–2012 MY; (2) OBD Transition, 2013–2015 MY; and (3) OBD Compliant, 2016+ MY. Figure 7a reports combined average values across the three sampling years, while Figure 7b shows the measured means separately for 2021, 2022, and 2023. On average, 2010–2012 MY engines that were transitioning to SCR have 5.6 times higher NO_x emission factors than 2016+ MY engines that are OBD compliant. The mean emission rate by OBD compliant trucks exceeds the 1.1 g kg^{-1} emission standard by 91%, however. Across all engine groupings, NO_x emissions have increased between 2021 and 2023, with the 2023 average 1.8–2.6 times higher than the 2021 mean.

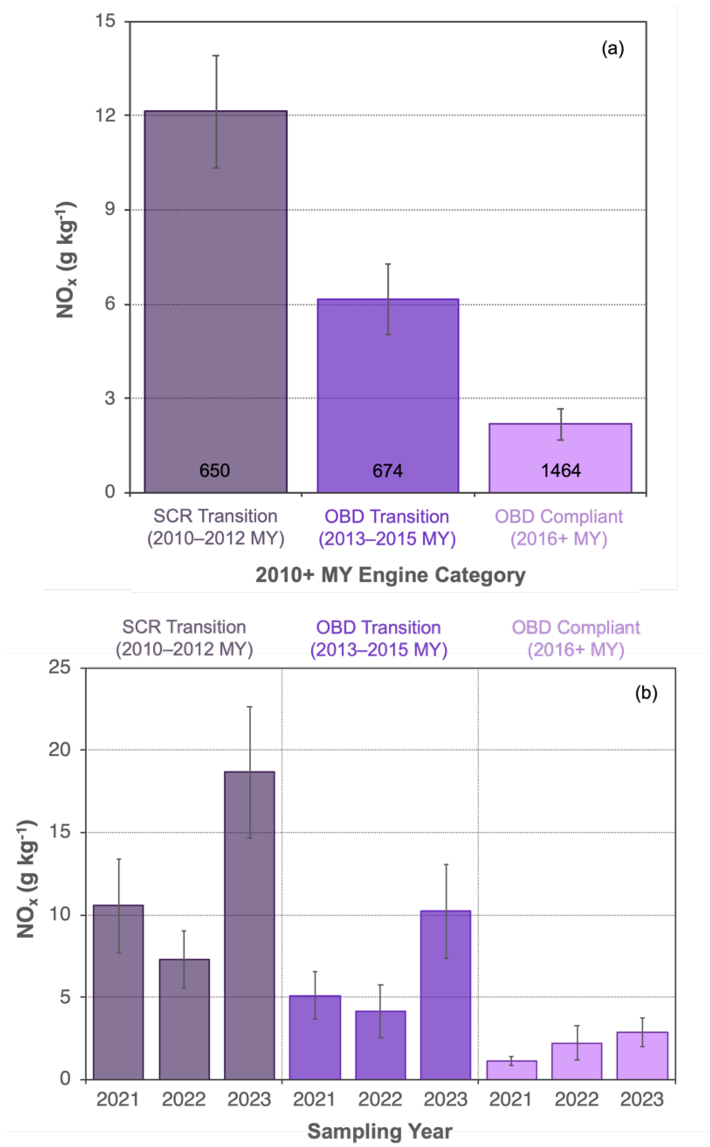

Figure 7. Average NO_x emission factors by engine model year grouping for 2010+ engines. Data is combined for 2021, 2022, and 2023 in (a), while (b) shows the average for each sampling year. Sample sizes for each category are noted at the bottom of each bar in (a), and error bars represent 95% confidence intervals about the mean.

Differences by Engine Manufacturer

For a subset of trucks measured in 2021, 2022, and 2023 where specific engine information was available, the average NO_x emission factors are plotted by 2010+ engine group and manufacturer in Figure 8. Note the small sample size for International and Navistar engines; their results should be interpreted with caution. Overall, Paccar engines tend to have low NO_x emissions across all engine MY groups, even for 2010–2012 engines that were transitioning to SCR; the SCR transition category-average for other manufacturers were 2.9–5.5 times higher than that of Paccar. The OBD compliant engines from Cummins and Paccar meet the current NO_x emission standard of 1.1 g kg^{-1} on average, while the other manufacturers emit ~2.2 times above the limit. The OBD transition engines from International and Navistar also meet the standard, but only 12 trucks were captured in three years of measurements and broader conclusions for these manufacturers cannot be made.

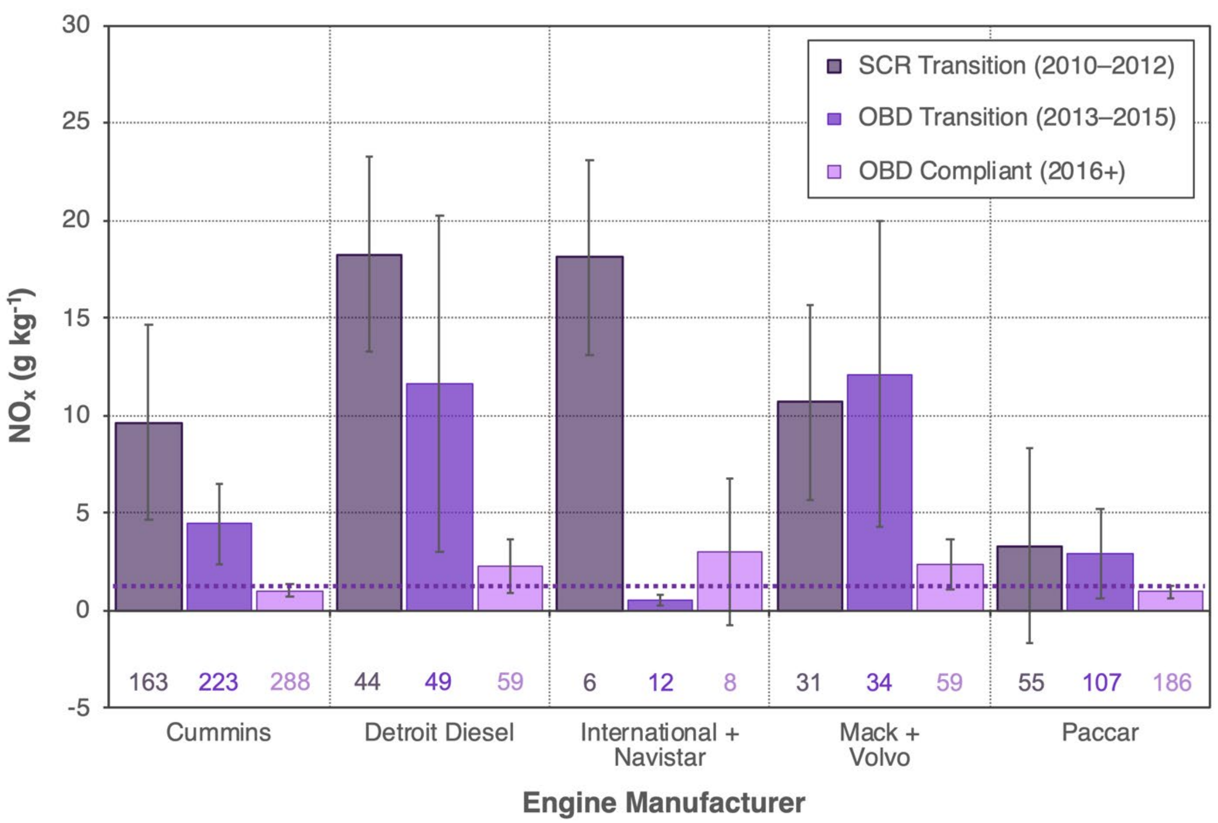

Figure 8. Average NO_x emission factors by engine manufacturer for 2010+ engines measured in 2021, 2022, and 2023 at the Caldecott Tunnel. The dashed horizontal line indicates the 2010+ MY emission standard of 1.1 g kg^{-1}. Sample sizes are noted at the bottom of each bar and error bars represent 95% confidence intervals about the mean.

Considering Future Low NO_x Emission Targets

Finally, looking forward to the new low NO_x standards set for 2024+ engines in California and 2027+ engines nationwide (Table 2), Figure 9 shows the emission factor distributions for 2019+ engines. These are duplicated from Figure 5, but with a narrower range on the y-axis that zooms in on these distributions and with a second emission standard line that shows the upcoming 2027 emission limit of 0.2 g kg^{-1}. For these most modern SCR-equipped engines, most emission factors meet the current standard, especially if the threshold is increased to the NTE limit of 1.7 g kg^{-1}. Conversely, most of these modern trucks could not meet the upcoming federal 2027 standard, nor the more stringent standards set in California for 2024–2026 and 2027+ MY engines (0.3 and 0.1 g kg^{-1}, respectively). Manufacturers will need to continue to improve technology and tuning for SCR and engines to achieve these fast-approaching low NO_x targets.

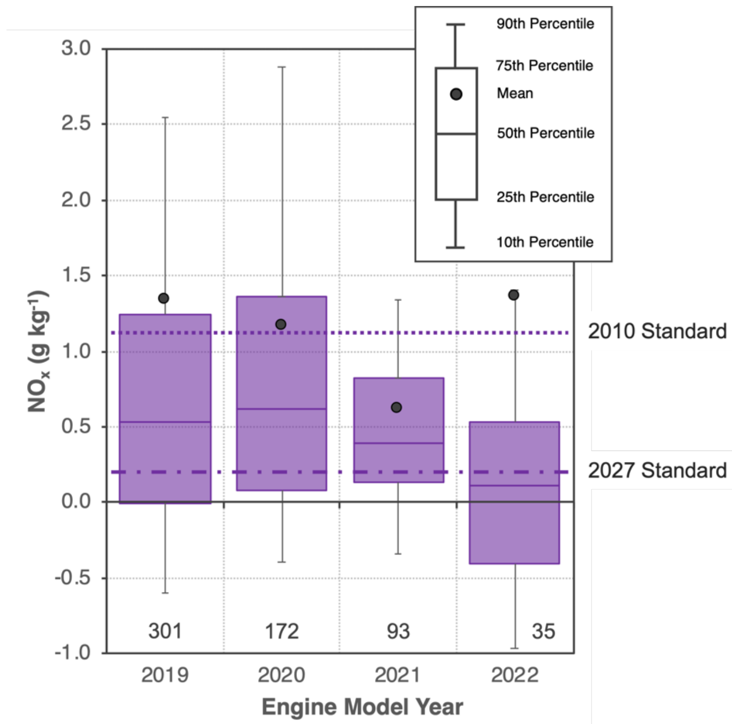

Figure 9. Distribution of NO_x emission factors for 2019–2022 model year engines measured in 2021, 2022, and 2023 at the Caldecott Tunnel. The top dashed horizontal line indicates the 2010+ MY emission standard, while the bottom dashed horizontal line shows the lowered standard that will go into effect in 2027. Sample sizes are noted at the bottom of each boxplot.

Emissions of Nitrous Oxide

Emission Factor Distributions and Trends

Like for NO_x above, fleet-average N_2O emission factors are shown in Figure 10, Figure 11 presents category averages, and engine MY distributions are reported in Figure 12. N_2O was not measured prior to the start of the Truck and Bus Regulation, but the 2010 fleet-average when SCR use was minimal is expected to be near-zero. After an initial increase between 2014 and 2015 that was previously reported, the fleet-average emission rate was relatively steady around 0.5 g kg^{-1} through 2021. Between 2021 and 2023, however, N_2O emissions increased by 58 ± 28%. Over this time, there was only a modest increase in SCR adoption, from 87% to 98% of the fleet, that does not explain the rapid, significant increase.

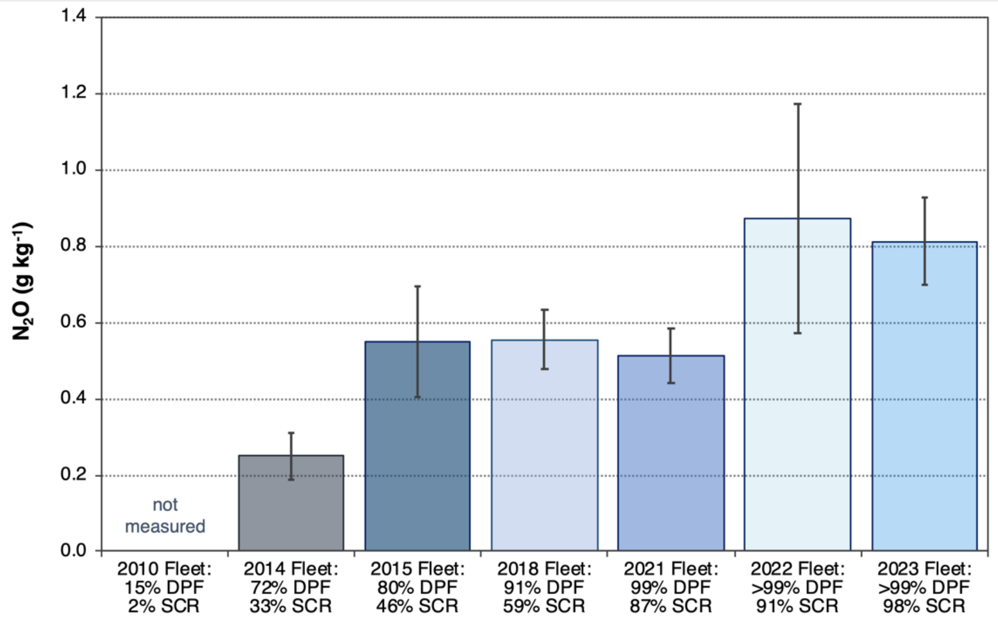

Figure 10. Fleet-average N_2O emission factors for each sampling campaign year over the course of the Truck and Bus Regulation. Error bars show 95% confidence intervals about the mean, as also reported in Table A1.

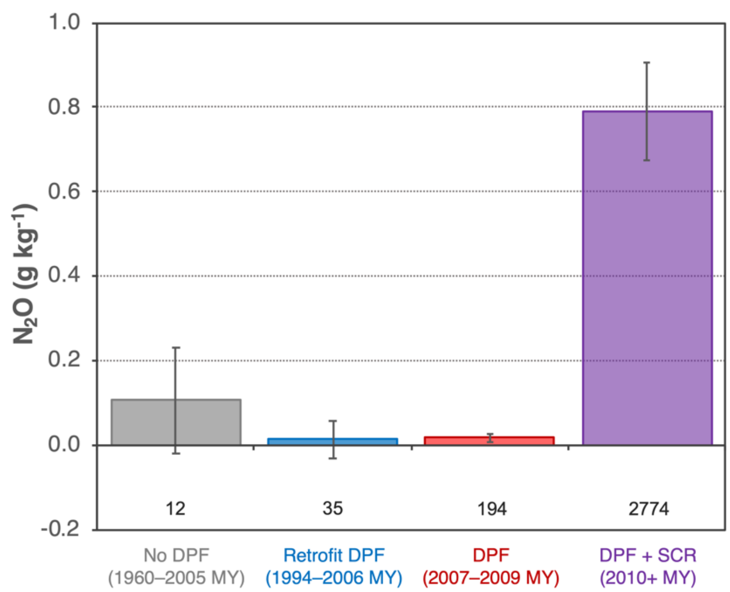

Figure 11. Average N_2O emission factors by emission control category, as measured at the Caldecott Tunnel in 2021, 2022, and 2023. Sample sizes for each category are noted at the bottom of each bar and error bars show 95% confidence intervals about the mean, as also reported in Table A2.

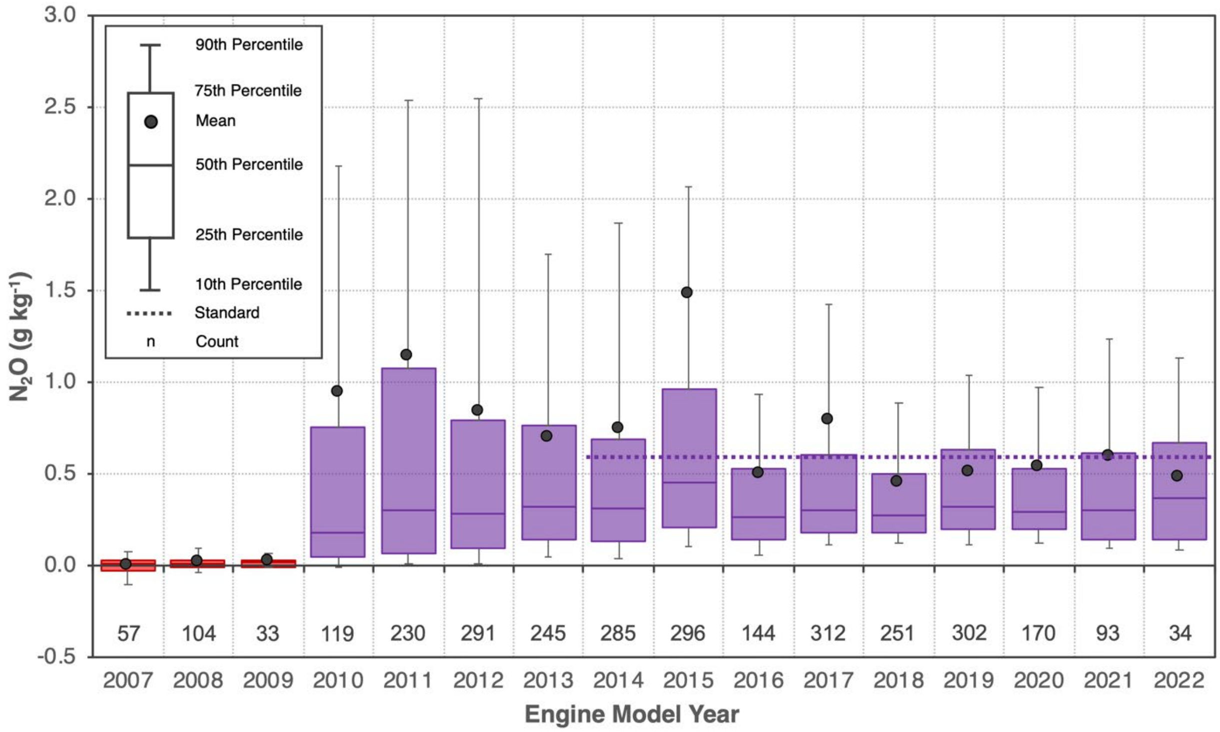

Figure 12. Distributions of measured N_2O emission factors by engine model year for trucks operating at the Caldecott Tunnel in 2021, 2022, and 2023. The corresponding exhaust standard for 2014+ MY engines is shown as a dashed line as a benchmark comparison.

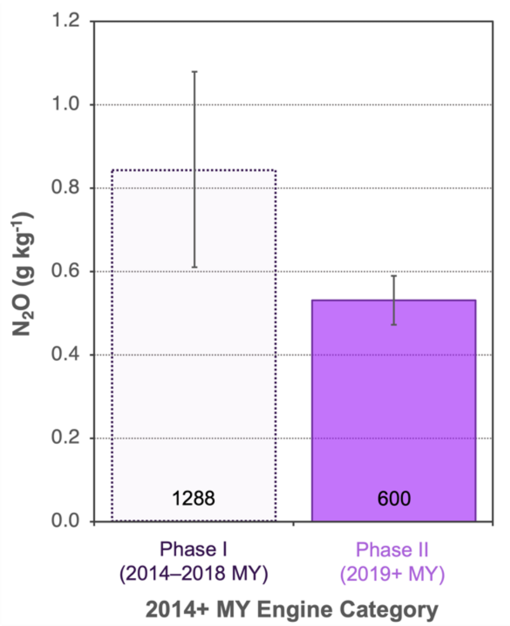

Figure 13. Average N_2O emission factors for trucks with 2010+ model year engines operating at the Caldecott Tunnel in 2021, 2022, and 2023, categorized by Phase I and Phase II of the greenhouse gas emissions regulation. Sample sizes are noted at the bottom of each bar and error bars show 95% confidence intervals.

Consistent with results previously reported in Preble et al.,[7] we find that SCR-equipped trucks have elevated emission rates of N_2O compared to trucks with pre-2010 MY engines that have near-zero emissions (Figures 11 and 12). Most 2014+ MY engines that are subject to the N_2O emission limit of 0.6 g kg^{-1} meet that standard, but emission distributions are skewed with mean values exceeding the 75^{th} percentile for many model years. This is also evident in Figure 13, which shows the average emission rates for 2014+ engines that are subject to Phase I (2014–2018 MY) versus Phase II (2019+ MY) of the greenhouse gas regulations for heavy-duty vehicles that set the N_2O emission limit.[19] Phase I engines had an average N_2O emission rate that was 1.6 times greater than the Phase II average and 1.5 times higher than emission standard. The Phase II engines, on the other hand, meet the standard with an average emission factor of 0.5 ± 0.1 g kg^{-1}.

Evidence of Increasing N_2O Emissions by Aging SCR Systems

Like for NO_x above, average emission rates by the three engine MY groups of SCR-equipped trucks are compared overall and by sampling year in Figure 14. 2010–2012 MY engines that were transitioning to SCR have an average N_2O emission factor that is 38% higher than that of 2016+ MY engines that are OBD compliant (Figure 14a). Note that emissions were highly variable and the confidence intervals for all three 2010+ MY groups overlap, as also shown in Figure 12. Relative to the emission standard for 2014+ engines, the mean emission rate for OBD compliant trucks is 24% higher. While the OBD transition category remained relatively steady between 2021 and 2023, there are notable increases over time for the other two groups; average 2023 N_2O emission rate was larger by 2.6× for the SCR transition group and 1.4× for OBD compliant engines. These increases likely explain the observed rise in fleet-average emissions between 2021 and 2023. While the fraction of SCR-equipped trucks with 2010–2012 MY engines decreased from 27% in 2021 to 20% in 2023, the corresponding fraction of total N_2O emissions from this group increased from 23 to 32% (Figure 15). Concurrently, OBD compliant engines comprised 45% of SCR trucks in 2021 and 37% of emissions, but these fractions increased to 61% and 50% by 2023.

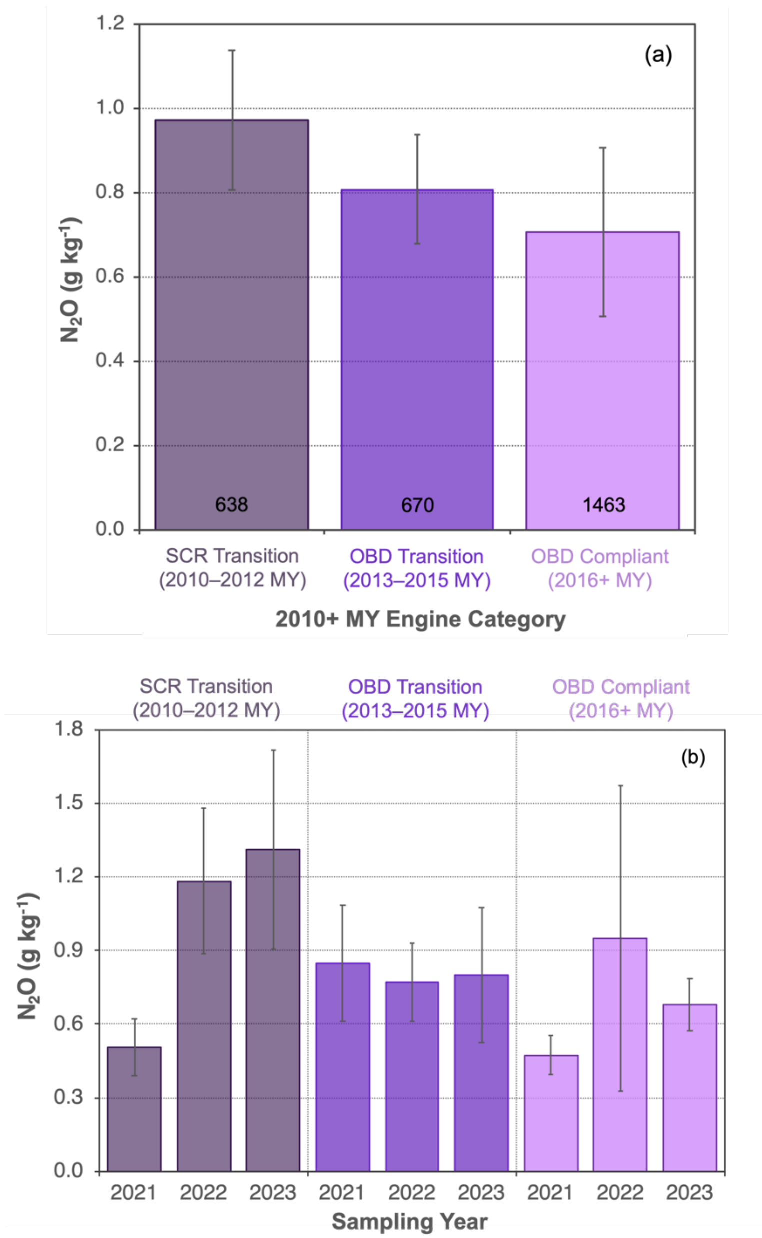

Figure 14. Average N_2O emission factors by engine model year grouping for 2010+ engines. Data is combined for 2021, 2022, and 2023 in (a), while (b) shows the average for each sampling year. Sample sizes for each category are noted at the bottom of each bar in (a), and error bars represent 95% confidence intervals about the mean.

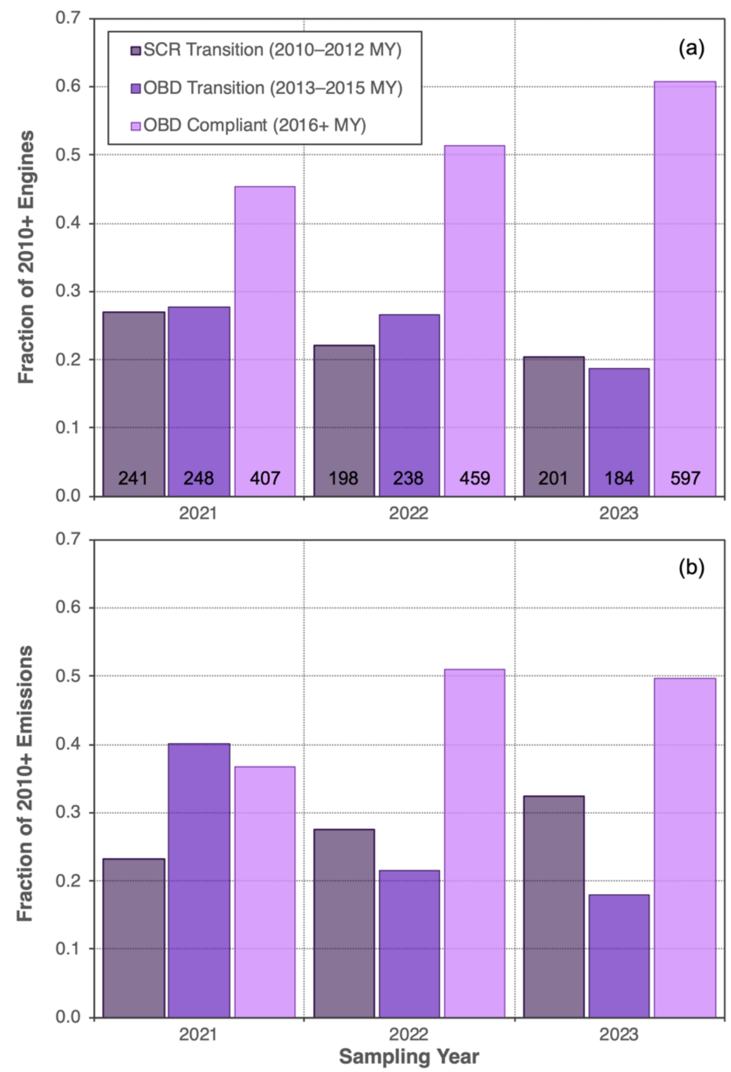

Figure 15. Fraction of each 2010+ engine model year grouping that (a) comprises SCR-equipped trucks in each sampling year, and (b) their corresponding fraction of emissions.

Differences by Engine Manufacturer

For a subset of trucks measured in 2021, 2022, and 2023 with available details, average N_2O emission factors are plotted by 2010+ engine group and manufacturer in Figure 16. Note the small sample size for International and Navistar engines; their results should be interpreted with caution. Overall, Paccar and Cummins engines tend to have low N_2O emissions that are comparable across all engine MY groups and meet the 0.6 g kg^{-1} emission standard, even for 2010–2012 engines that were transitioning to SCR. Mack and Volvo engines have the highest average N_2O emission rates, especially for pre-2016 engines. There is one major outlier included in the OBD transition category for Mack and Volvo engines; without this outlier, the average for 2010–2012 and 2013–2015 MY engines would be comparable for these manufacturers. International and Navistar also have lower average emissions, but the small sample sizes captured for this manufacturer make broad conclusions difficult.

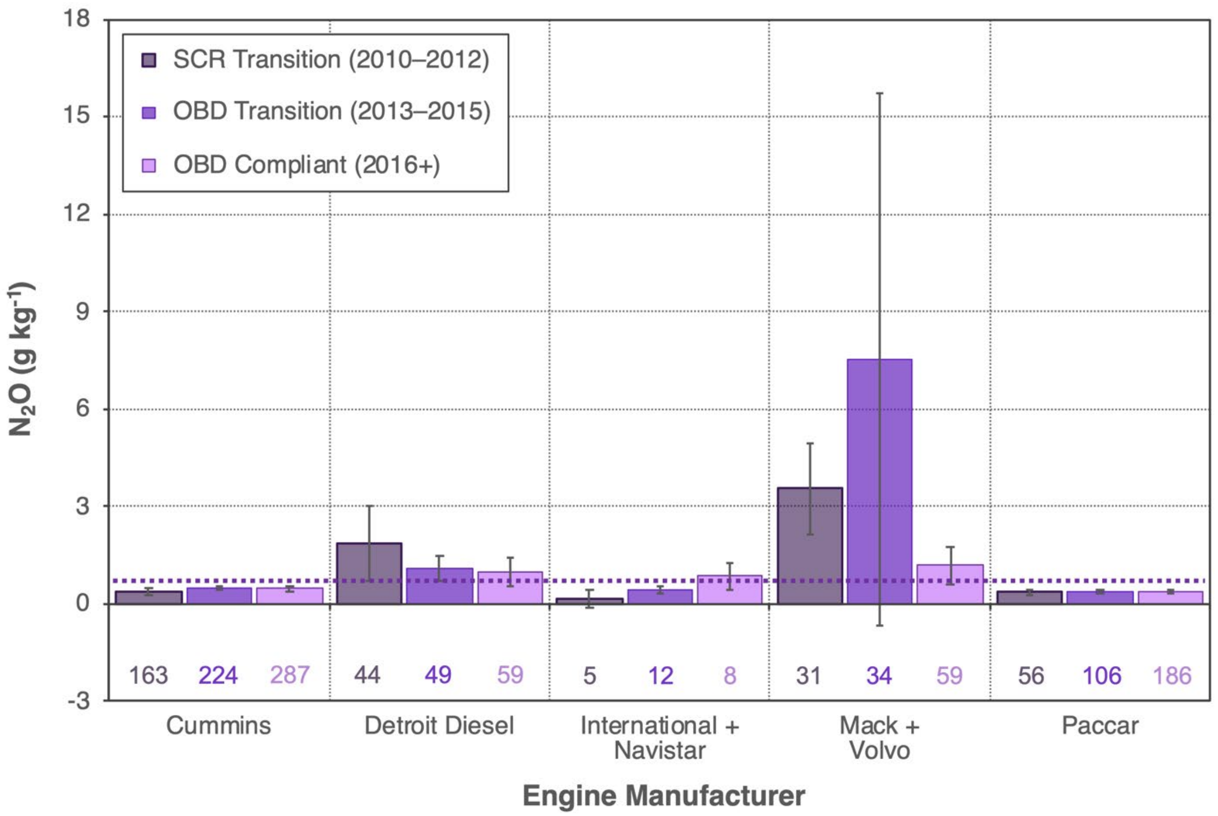

Figure 16. Average N_2O emission factors by engine manufacturer for 2010+ engines measured in 2021, 2022, and 2023 at the Caldecott Tunnel. The dashed horizontal line indicates the 2014+ MY emission standard of 0.6 g kg^{-1}. Note that not all trucks shown here are held to that exhaust limit. Sample sizes are noted at the bottom of each bar and error bars represent 95% confidence intervals about the mean.

Emissions of Ammonia

Emission Factor Distributions and Trends

Fleet-average NH_3 emission factors are shown in Figure 17 for sampling years 2018, 2022, and 2023, while Figure 18 presents category averages from the combined 2022 and 2023 campaigns. Between 2018 (mid-regulation) and 2023, fleet-average NH_3 increased by 134 ± 105%. As previously reported in Preble et al.,[7] trucks with SCR at the Caldecott Tunnel have elevated NH_3 emission factors, on average, relative to trucks without SCR (Figure 18). Because of this trend—though NH_3 was not measured prior to 2018—the pre-regulation 2010 fleet-average when SCR use was minimal is expected to be near-zero. The average NH_3 emission factor for SCR-equipped trucks (0.17 ± 0.05 g kg^{-1}) is slightly lower than but the same order of magnitude as what has been reported for light-duty vehicles in California.[23,24] Reported NH_3 emission factors for compressed natural gas (CNG) trucks also tend to be higher by a factor of 2–10 than the average value measured in the current study for SCR trucks.[25,26] Finally, NH_3 emissions by 2010+ engines are highly skewed, as shown in the engine MY distributions in Figure 19 that have narrow interquartile ranges and means that exceed the 90th percentile whiskers. This means that most SCR trucks have near-zero emission rates, while a few high emitters are responsible for most emissions.

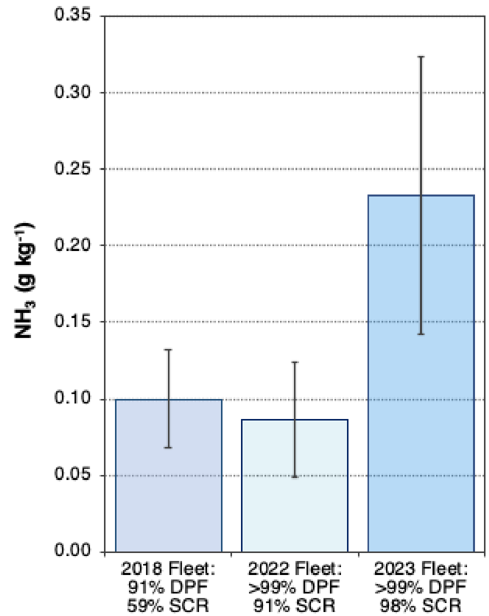

Figure 17. Fleet-average NH_3 emission factors for the 2018, 2022, and 2023 sampling campaigns at the Caldecott Tunnel. Error bars show 95% confidence intervals about the mean, as also reported in Table A1.

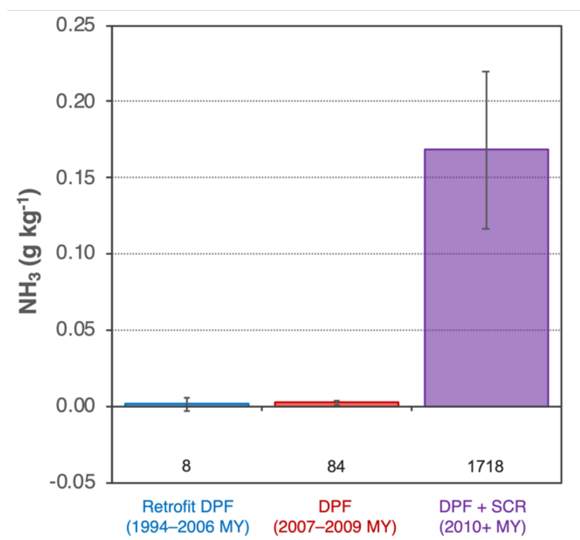

Figure 18. Average NH_3 emission factors by emission control category, as measured at the Caldecott Tunnel in 2022 and 2023. Sample sizes for each category are noted at the bottom of each bar and error bars show 95% confidence intervals about the mean, as also reported in Table A2. Results are not shown for the No DPF category because of insufficient sample size.

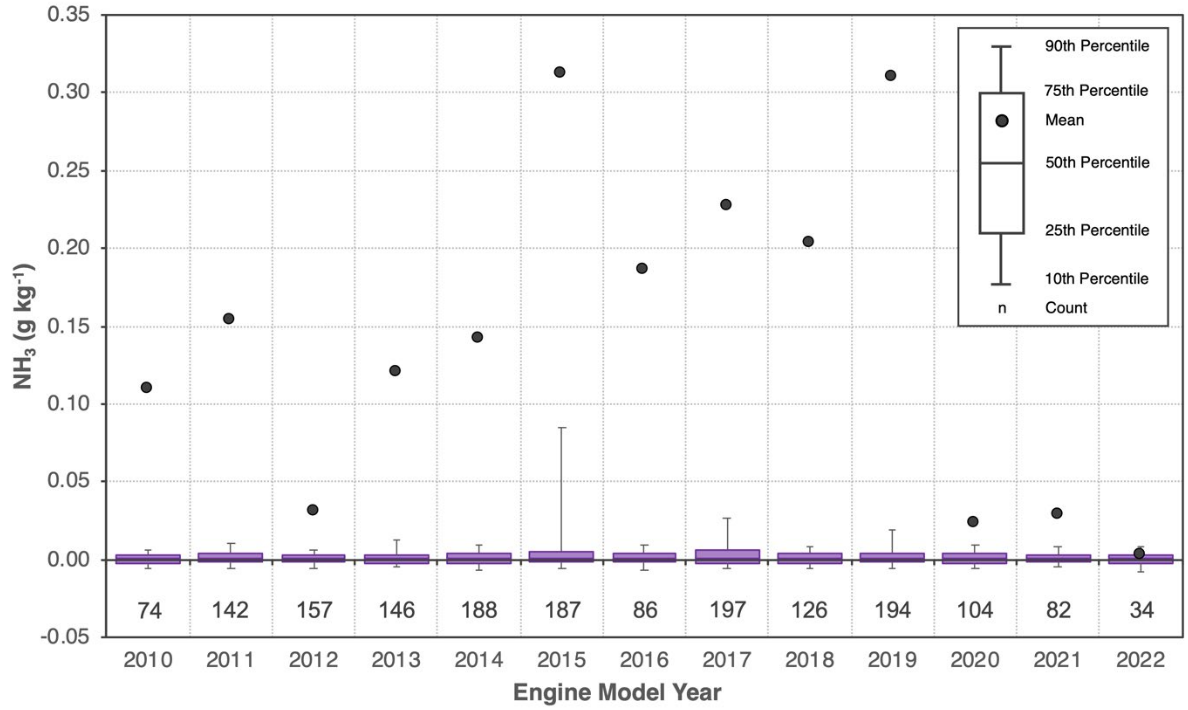

Figure 19. Distributions of measured NH_3 emission factors by engine model year for SCR-equipped trucks operating at the Caldecott Tunnel in 2022 and 2023.

Like in Figure 7 for NO_x above, the category averages by calendar year are reported in Figure 20 to examine the differences in NH_3 emissions as these 2007+ engines and technologies age. While 2007–2009 MY engines have consistently low emission factors that are near zero, there are differences in the average NH_3 emission rate by 2010+ engines with SCR over time. It is difficult to determine whether this trend is due to aging systems with increased ammonia slip or overdosing, or if the differences by calendar year are a function of the frequency that high emitters are captured. Considering differences in NH_3 emissions by 2010+ engine group, though, there does appear to be an upward trend in emission factors with newer engines and SCR systems (Figure 21). 2016+ MY engines that are OBD compliant have an average NH_3 emission rate that is 2.2 times greater than that of 2010–2012 MY engines that were transitioning to SCR. Note that the confidence intervals for all three 2010+ MY groups overlap, indicating that emissions were highly variable with overlapping distributions between these categories, as also shown in Figure 19. This difference by 2010+ engine MY group might explain the increase in fleet- and category-average NH_3 between 2018 and 2023: the fraction of lower emitting 2010–2012 MY engines decreased from 27% in 2021 to 20% in 2023, while higher emitting OBD compliant 2016+ engines increased to 45% to 61% of SCR-equipped trucks.

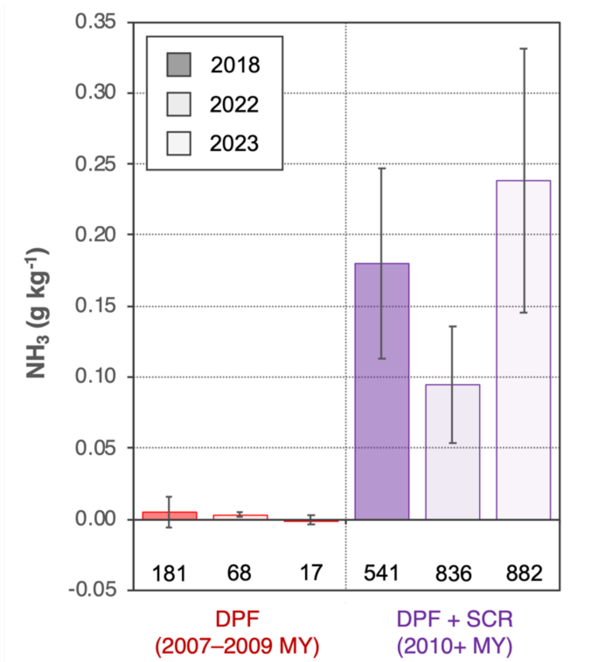

Figure 20. Average NH_3 emission factors by emission control category for 2007+ model year engines, as measured at the Caldecott Tunnel in the 2018, 2022, and 2023 sampling campaigns. Sample sizes for each category are noted at the bottom of each bar and error bars show 95% confidence intervals about the mean.

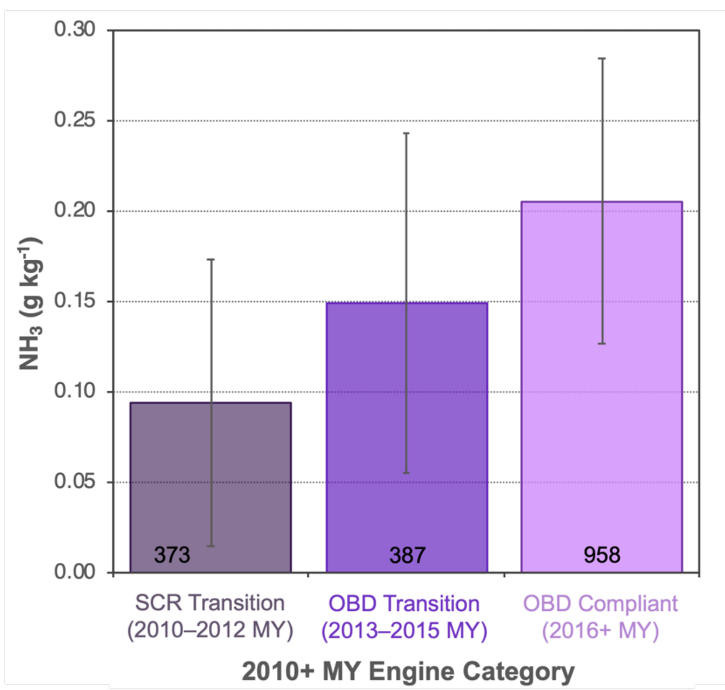

Figure 21. Average NH_3 emission factors by engine model year grouping for 2010+ engines. Data is combined for 2022 and 2023 measurements, sample sizes for each category are noted at the bottom of each bar, and error bars represent 95% confidence intervals about the mean.

Emissions of Black Carbon

Emission Factor Distributions and Trends

Fleet- and category-average BC emission factors are shown in Figures 22 and 23, and Figure 24 presents distributions in BC emissions by engine model year. Between 2010 and 2023, as fleet adoption of 2010+ engines became nearly universal, the fleet-average BC emission factor decreased by 92 ± 18% (Figure 22). The 2023 post-regulation fleet has an average BC emission rate of 0.07 ± 0.02 g kg^{-1}, which is ~10% greater than the relevant PM emission standard of 0.06 g kg^{-1} for 2007+ engines. BC emission rates by 2010+ engines equipped with both DPF and SCR were 88% lower than 2007–2009 engines that have DPFs only (Figure 23). This result is consistent with previously published work and is likely due to differences in engine management strategy trade-offs to limit PM and NO_x emissions, differences in filter regeneration methods, and possible improvements to DPF system durability. [4,27,28]

As shown in Figure 24, BC emission factors for 2007–2009 DPF-equipped trucks are more variable than those measured for 2010+ engines with both DPF and SCR systems, as previously reported in Preble et al.[4] Distributions are most skewed for 2007–2012 MY engines, with mean values that exceed the 75th percentile and are in excess of the relevant PM standard by a factor of 2–14. Most BC emissions by 2010+ engines are less than the PM emission standard, though, with a majority of the BC distributions falling below the dashed horizontal line. This difference is interesting, since both control categories are subject to the same PM standard. It is important to note that BC is a major but not sole constituent of diesel PM. Thus, PM emission rates are expected to be larger than the BC emission factors reported here.

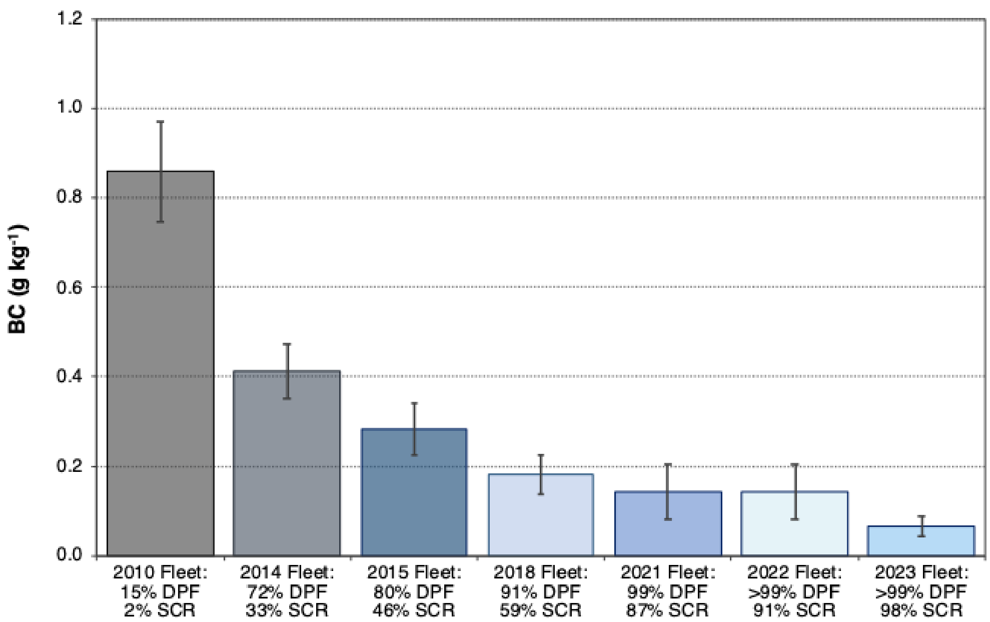

Figure 22. Fleet-average BC emission factors for each sampling campaign year over the course of the Truck and Bus Regulation. Error bars show 95% confidence intervals about the mean, as also reported in Table A1.

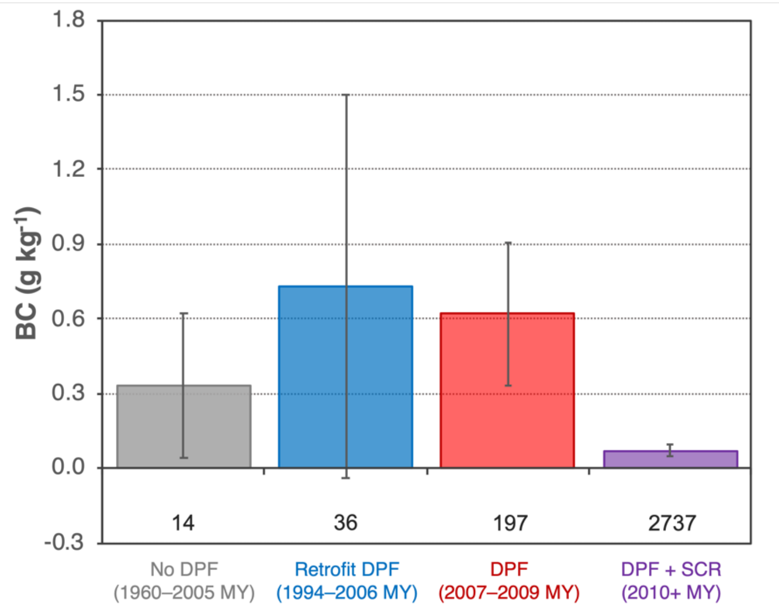

Figure 23. Average BC emission factors by emission control category, as measured at the Caldecott Tunnel in 2021, 2022, and 2023. Sample sizes for each category are noted at the bottom of each bar and error bars show 95% confidence intervals, as also reported in Table A2.

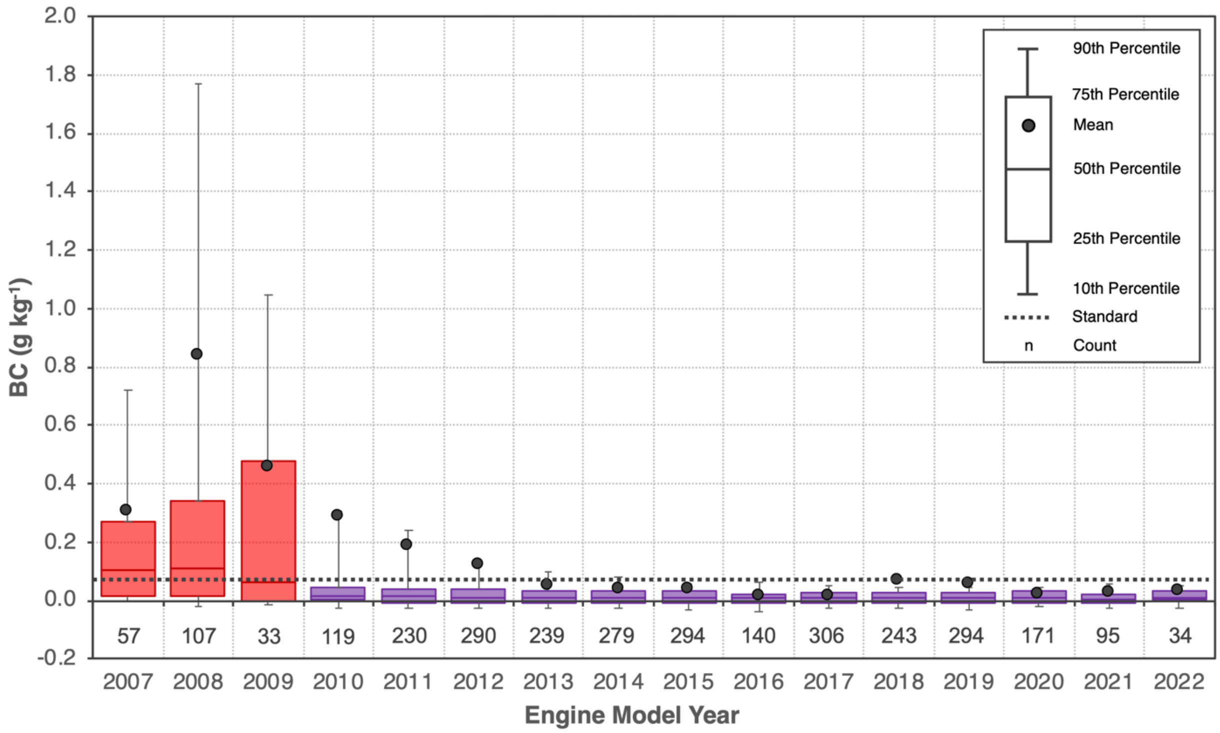

Figure 24. Distributions of measured BC emission factors by engine model year for trucks operating at the Caldecott Tunnel in 2021, 2022, and 2023. The corresponding exhaust standard for 2007+ MY engines is shown as a dashed line as a comparison benchmark.

Evaluation of Aging DPF Performance

Like for NO_x above, Figure 25 shows BC emission factors by control category for each sampling campaign between 2014–2023, such that moving from left to right in each subpanel moves forward in time as these technologies age from newer to older systems. Consistent with Preble et al.,[4] there is evidence of increasing BC emission rates from aging 2007–2009 MY trucks equipped with DPFs (Figure 25). Average emission rates for this emission control category vary from year to year with increasingly broad confidence intervals. The average over the last three years is 2.7 times greater than the average previously measured between 2014–2018 (0.59 versus 0.22 g kg^{-1}). Note that the sample size for this category is especially small in 2023 compared to other years, so this last data point should be considered with caution.

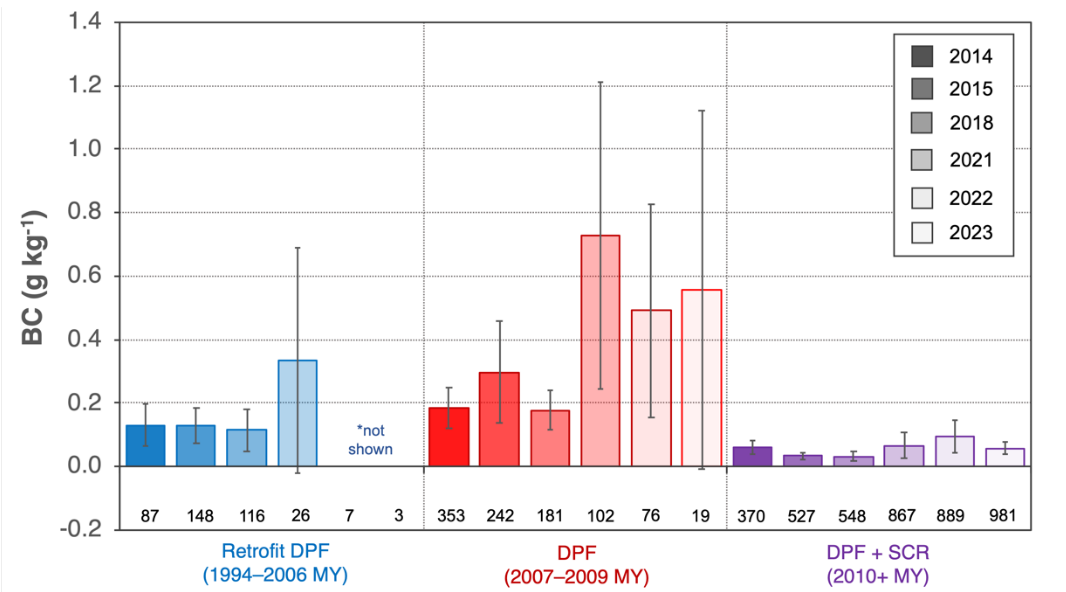

Figure 25. Average BC emission factors by emission control category, as measured at the Caldecott Tunnel in each sampling campaign between 2014–2023. Sample sizes for each category are noted at the bottom of each bar and error bars show 95% confidence intervals about the mean.

Conversely, DPFs on 2010+ MY trucks that also have SCR do not appear to show the same strong evidence of deteriorating performance with age as have been observed for the 2007–2009 DPFs. There are small differences over the years in the average BC emission factors measured for this category, with overlapping confidence intervals (Figure 25). The average over the last three years is 1.7 times higher than the average previously measured between 2014–2018 (0.07 versus 0.04 g kg^{-1}), a more modest upward trend than was measured for the 2007–2009 DPFs. To further examine how average emission rates vary for these SCR-equipped trucks, Figure 26 plots the average emission rates for the three engine MY groups of 2010+ engines. On average, 2010–2012 engines that were transitioning to SCR have BC emissions that are 4.3 times higher than that of 2013+ engines that are transitioning to or compliant with OBD requirements. There is also more year-to-year variability between 2021 to 2023 for the 2010–2012 MY engines, with an apparent increasing trend over time. The 2013–2015 and

2016+ MY trucks, on the other hand, have consistently lower BC emissions. Together, these results emphasize how the addition of SCR allows for engine tuning and DPF regeneration strategies that enable better DPF performance that is more durable over time compared to 2007–2009 trucks without SCR. Even so, these potential increases in BC emissions by aging 2010+ DPFs merit additional consideration in the future.

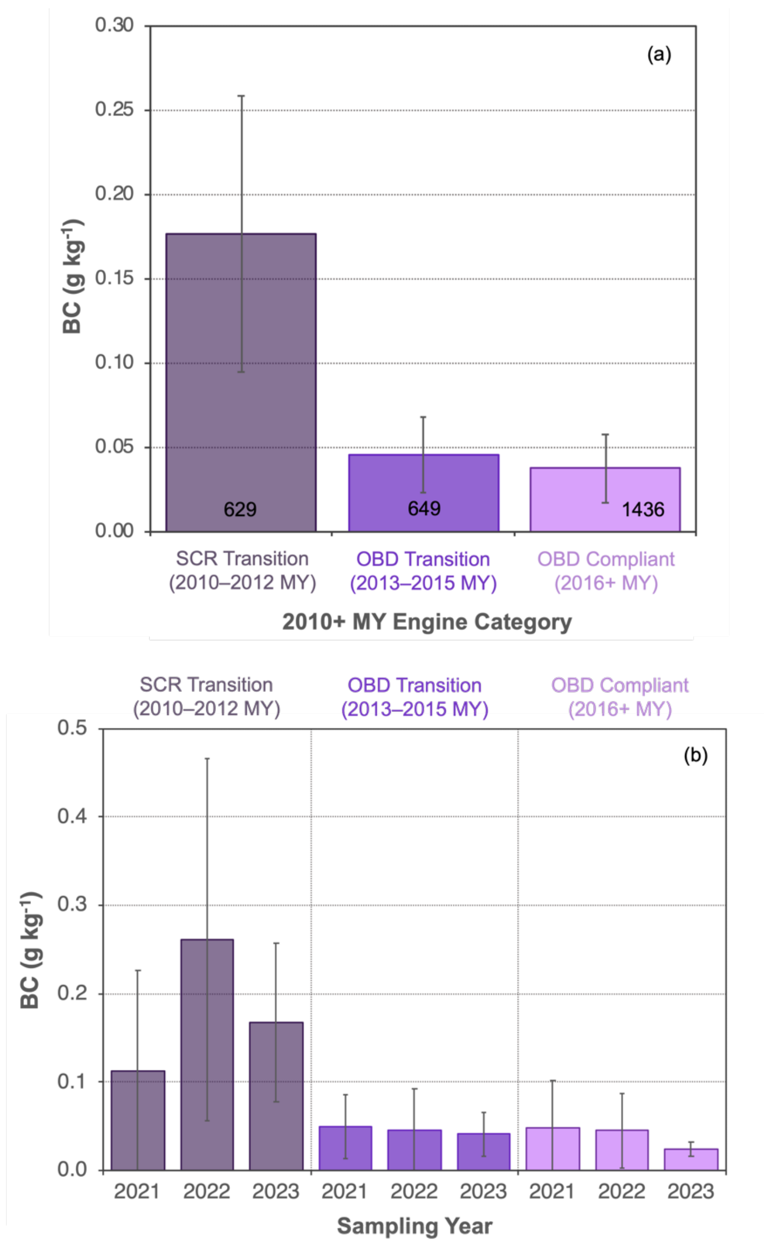

Figure 26. Average BC emission factors by engine model year grouping for 2010+ engines. Data is combined for 2021, 2022, and 2023 in (a), while (b) shows the average for each sampling year. Sample sizes for each category are noted at the bottom of each bar in (a), and error bars represent 95% confidence intervals about the mean.

Differences by Engine Manufacturer

Average BC emission factors are plotted by 2010+ engine group and manufacturer in Figure 8 for a subset of trucks measured in 2021, 2022, and 2023 with available information. Note the small sample size for International and Navistar engines; their results should be interpreted with caution. Most engine manufacturers meet the 0.06 g kg^{-1} PM emission standard for all engine MY groups, on average and within the 95% confidence interval. The biggest exceptions to this trend are 2010–2012 engines manufactured by Cummins and Detroit Diesel that were transitioning to SCR. Mean BC for these two groups 7.5 and 17.8 times higher than the average of all others, with broad confidence intervals that indicate variable emissions and the influence of high emission events.

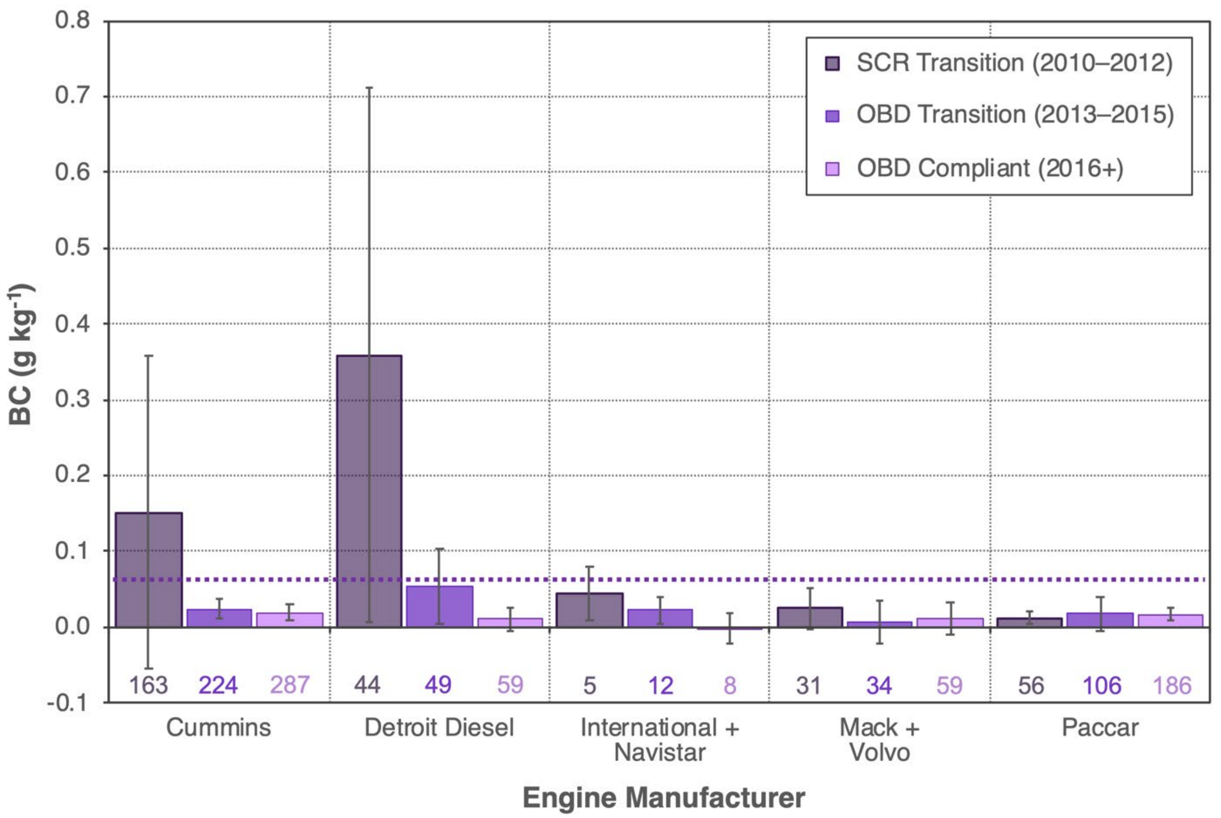

Figure 27. Average BC emission factors by engine manufacturer for 2010+ engines measured in 2021, 2022, and 2023 at the Caldecott Tunnel. The dashed horizontal line indicates the 2007+ PM emission standard of 0.06 g kg^{-1}. Note that BC is a major but not sole component of diesel PM. Sample sizes are noted at the bottom of each bar and error bars represent 95% confidence intervals about the mean.

Influence of TRUs on Measured BC

Figure 28 compares BC emission factors measured for trucks with and without TRUs. In 2023, 6% of measured trucks were equipped with a TRU. This small fraction of the fleet has a slightly higher average BC emission rate with a broader confidence interval compared to those trucks without TRUs (0.09 ± 0.07 vs 0.07 ± 0.02 g kg^{-1}). Even so, the distributions of measured emission factors for both truck categories overlap and both have similar rates of occurrences of high emission events that exceed 0.5 g kg^{-1}. Given the small number of trucks with TRUs at this sampling location and the small differences in emission factor distributions, we assume that any contributions of BC emitted from TRUs in addition to the tailpipe that are captured in our measurements have a minimal impact on the trends described above.

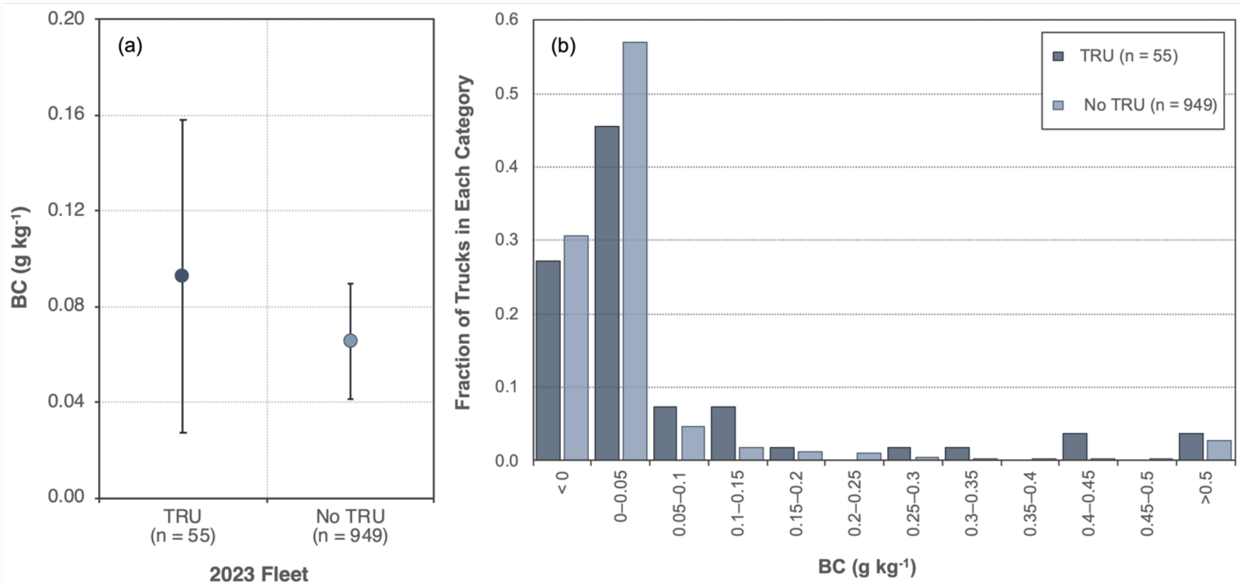

Figure 28. Comparison of BC emission factors for those trucks with a truck refrigeration unit (TRU) compared to those without a TRU present. The mean values and 95% confidence intervals for these two groups are shown in (a), while (b) presents the emission factor distributions for each category.

Interactive Effects of Co-Emitted Pollutants

Nitrogenous Species and SCR

Emission factors of NO_x, N_2O, and NH_3 from 2010+ MY trucks measured at the Caldecott Tunnel in 2021, 2022, and 2023 are compared in Figure 29, highlighting the tradeoffs of these co-emitted nitrogenous pollutants in SCR systems. The highest emissions of both NH_3 and N_2O are generally from SCR-equipped trucks with low NO_x emission rates, and high NH_3 emissions tend to occur when N_2O emissions are low. Together, these relationships suggest several interactive impacts of SCR systems on emitted nitrogenous species. First, the relationship between high NH_3 and low NO_x emissions indicate that elevated NH_3 emissions are due to overdosing of diesel exhaust fluid, such that the NH_3/NO_x ratio is imbalanced too high and excess NH_3 is emitted at the tailpipe, especially if an ammonia slip catalyst is absent or ineffective.[29] There is an emissions trade-off with ammonia slip catalysts, though, where N_2O can form via the oxidation of NH_3.[30] This effect is evident in Figure 29, where N_2O emissions tend to be high when NO_x and NH_3 are low. This tradeoff merits further consideration, as N_2O is regulated for 2014+ engines and NH_3 is not, but both are species of concern—N_2O because of its role as a potent greenhouse gas and in stratospheric ozone depletion, and NH_3 because it is an important precursor for secondary inorganic aerosol formation.

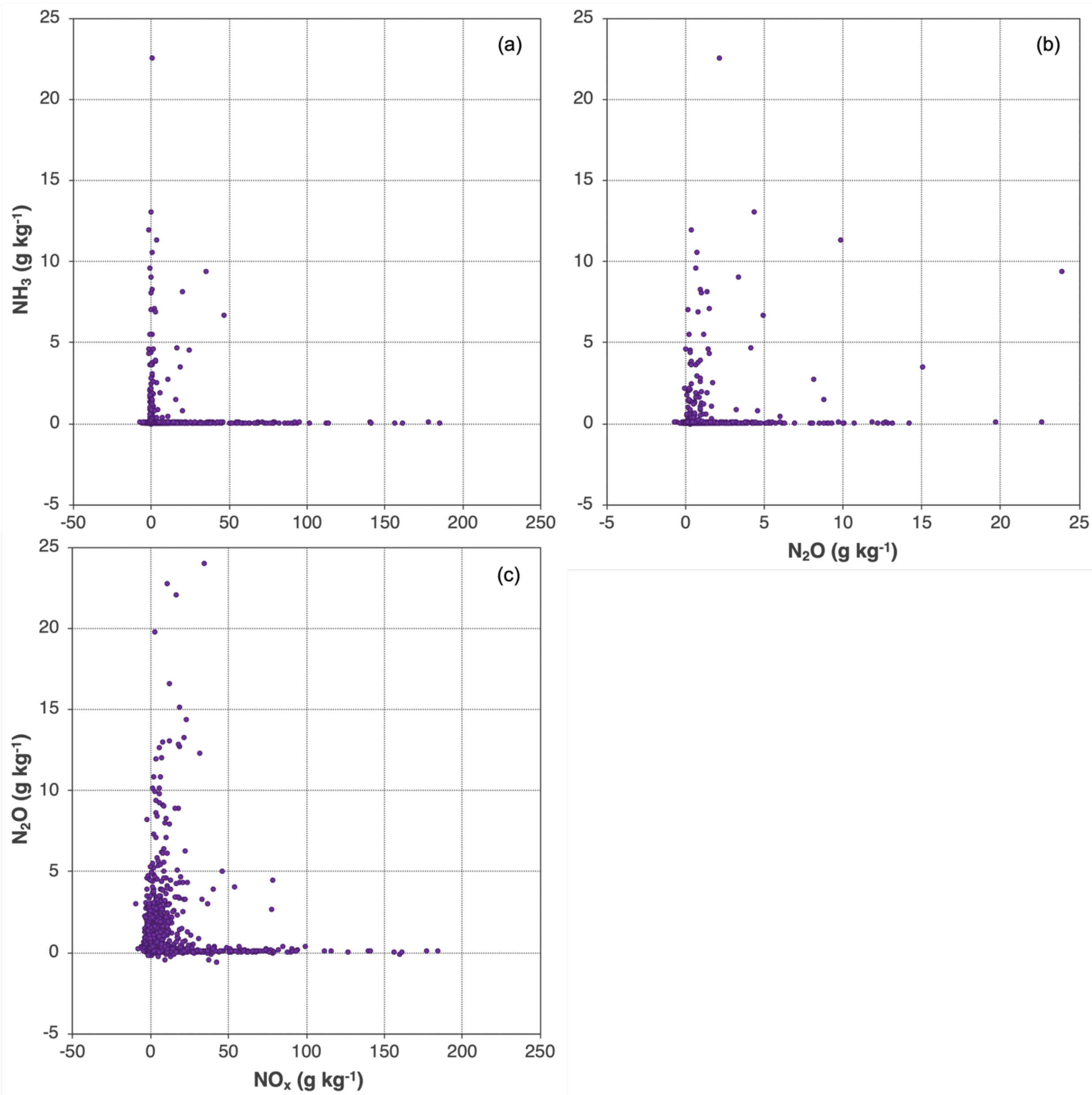

Figure 29. Relationship between emission factors of co-emitted nitrogenous species for SCR-equipped trucks with 2010+ model year engines measured at the Caldecott Tunnel in 2021, 2022, and 2023: (a) NO_x and NH_3, (b) N_2O and NH_3, and (c) NO_x and N_2O.

Contributions of Highest Emitting Trucks to Fleet Emissions

Emission factor distributions for NO_x, N_2O, NH_3, and BC are all skewed, such that a minority of trucks in the on-road fleet are responsible for a majority of the emissions of each pollutant. Figure 30 shows the cumulative distributions for each of these pollutants for the 2023 Caldecott

Tunnel fleet. Measured emission factors were sorted separately for each pollutant, ranked from highest to lowest and plotted in descending order on the horizontal axis. The corresponding cumulative contributions to total fleet emissions of each pollutant are plotted on the vertical axis. The NH_3 emission factor distribution is the most highly skewed, with the highest emitting 10% of trucks responsible for 100% of the emitted NH_3. In comparison, the top 10% of emitters for other pollutants were responsible for 83% of emitted BC, 69% of NO_x, and 57% of N_2O. It is important to note that the highest emitting trucks of one pollutant are typically not the highest emitting of other species. For example, there is little overlap between the highest emitters of NO_x, NH_3, and N_2O (Figure 29), and the highest emitters of BC tend to have low NO_x emissions (Figure 31).[7,16]

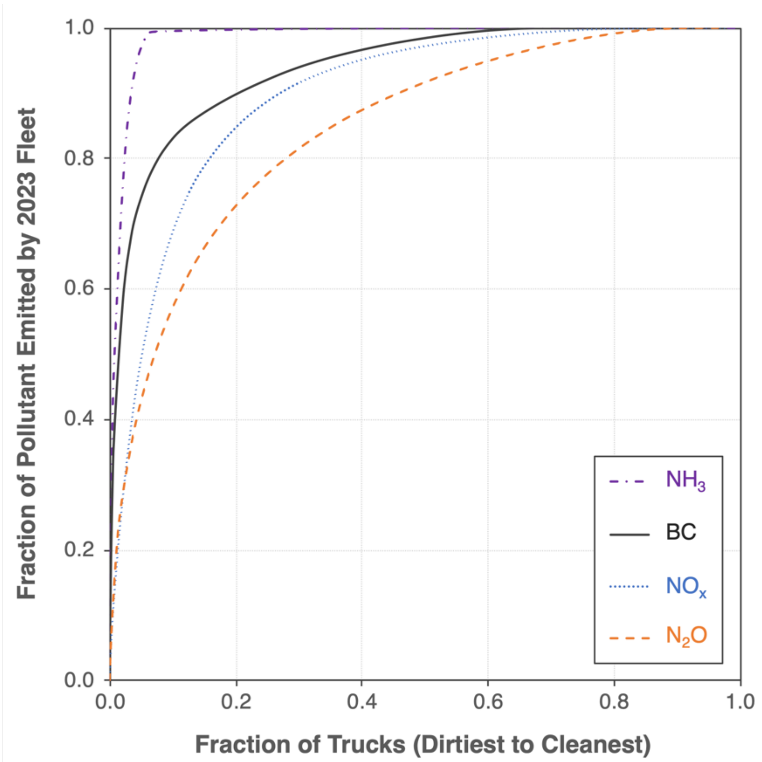

Figure 30. Cumulative distributions of NO_x, N_2O, NH_3, and BC emission factors for the port-regulation truck fleet measured at the Caldecott Tunnel in 2023.

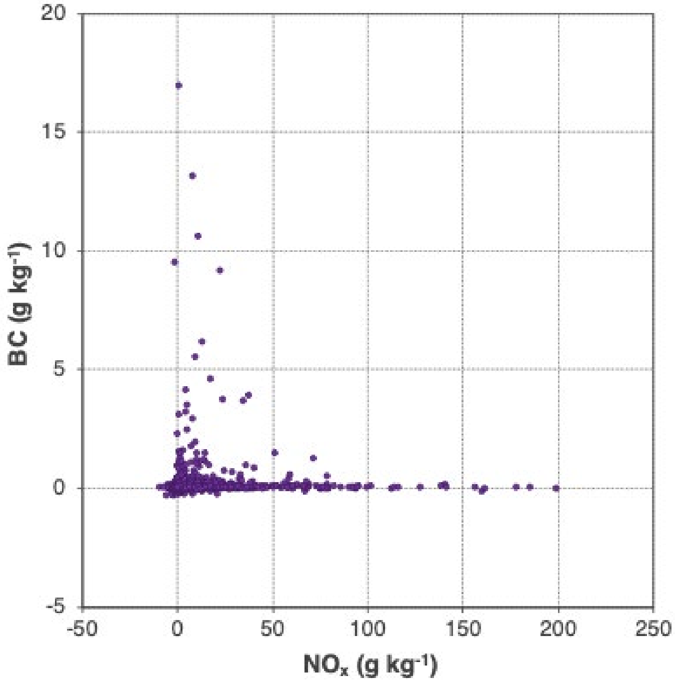

Figure 31. Relationship between NO_x and BC emission factors measured at the Caldecott Tunnel in 2021, 2022, and 2023 for SCR-equipped trucks with 2010+ model year engines.

Conclusions

This study measured in-use emissions from thousands of heavy-duty diesel trucks at the Caldecott Tunnel in 2021, 2022, and 2023. This period overlapped with the final stage of the phased implementation of California's Truck and Bus Regulation, which required the on-road truck fleet to adopt 2010+ MY engines. These new measurements continue a record of on-road fleet emissions sampling at this location, including prior to the start of the regulation in 2010 and over the course of the first phase of the regulation, in 2014, 2015, and 2018. Between 2010 and 2023, use of DPF and SCR emission control systems by the fleet has become nearly universal, increasing from 15% to >99% for DPFs and from 2% to 98% for SCR. Over this period, fleet-average emissions of NO_x and BC decreased by 75% and 92%, respectively. NO_2 emissions decreased by 37%, with SCR systems mitigating the conversion of engine-out NO to NO_2 in DPF systems. Fleet-average emissions of both N_2O and NH_3 increased from assumed near-zero to elevated values. N_2O emissions by the fleet were relatively constant ~0.5 g kg^{-1} between 2015 and 2021 but increased by 58% between 2021 and 2023, while NH_3 increased by 134% between 2018 (mid-regulation) and 2023.

Aging engines and emission control systems show evidence of increasing emission rates of some pollutants. For NO_x, average emissions increased by 65% between 2014 and 2022 for 2007–2009 MY engines. Emissions by 2010+ engines were similar from year to year until 2023, when the average increased by ~75%. Notable increases between 2021 and 2023 were also measured for N_2O emissions by 2010+ MY trucks, especially for 2010–2012 MY engines; the average emission factor for this group increased by a factor of 2.6 over the study period. On average, BC emissions by DPF-equipped trucks have also increased over the last three years compared to prior measurements: the average for 2021–2023 was 2.7 times higher than that from 2014–2018 for the 2007–2009 MY category and 1.7 times higher for 2010+ MY engines. BC emissions from 2010+ trucks were lower and less variable than the 2007–2009 category, with smaller absolute increases over time compared to the older DPF category. There is some evidence of increasing BC emissions by aging 2010–2012 MY engines with DPFs that were transitioning to SCR. These increases in emissions by aging DPF- and SCR-equipped trucks merit further investigation, especially with the tightening of the NO_x and PM exhaust emission standards in the near-future.

Emissions distributions were skewed, with a minority of trucks responsible for a majority of emissions by the fleet. Most NO_x emission factors for 2007–2015 MY engines exceeded the relevant exhaust emission standard, and the highest emitting decile of the fleet emitted 69% of NO_x in 2023. The average N_2O emission factor for 2014+ trucks equipped with SCR was 30% higher than the emission standard set for these engines. The top 10% of N_2O emitters were responsible for 57% of the 2023 fleet's emissions. NH_3 emissions by SCR-equipped trucks at the Caldecott Tunnel were highly skewed and on average lower than emission factors reported in other studies for light-duty vehicles equipped with three-way catalysts and CNG trucks. 100% of the 2023 fleet's NH_3 emissions resulted from the highest-emitting 10% of trucks. Finally, BC emissions by a majority of 2010+ engines were less than the relevant PM standard, and the top 10% of emitters were responsible for 83% of total emissions in 2023.

There is little overlap in trucks that are high emitters between pollutants. From a policy or inspection and maintenance program perspective, it is important to identify and fix or replace the high-emitting fraction of the fleet that contributes the most to total emissions. For example, if the ammonia slip from the 10% of high-emitting trucks could be prevented, the fleet's emissions of NH_3 would be entirely mitigated. Similarly, if the emissions from the top 10% of trucks for NO_x, N_2O, and BC were better controlled and reduced from their elevated values down to their respective current and most stringent emission standards (1.1, 0.6, and 0.06 g kg^{-1}, respectively), then the 2023 fleet-average emission factors would decrease substantially: by 68% from 7.8 to 2.5 g kg^{-1} for NO_x, by 50% from 0.8 to 0.4 g kg^{-1} for N_2O, and by 81% from 0.07 to 0.01 g kg^{-1} for BC. This targeted kind of find and fix/repair program would further reduce on-road emissions by this in-use fleet.

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Appendix

Table A1. Instrumentation used to measure truck exhaust emissions in this work at the Caldecott Tunnel, all with time resolution ≥ 1 Hz.

Parameter	Sampling Year	Measurement Method/Analyzer
CO_2 concentration	2014, 2015, 2018, 2021, 2022, 2023	Nondispersive infrared absorption (LI-COR LI-7000)
NO, NO_x concentrations	2014, 2015, 2018, 2021, 2022, 2023	Chemiluminescence (Two Eco Physics CLD64 analyzers)
N_2O, CO concentration	2014, 2015, 2018 2021, 2022, 2023	Cavity enhanced absorption (LGR Model 913-0015)
NH_3 concentration	2018, 2022, 2023	Cavity ring-down spectroscopy (Picarro Model G2123)
BC concentration	2014, 2015, 2018, 2021, 2022, 2023	Aethalometer (Magee Scientific AE16)
BC concentration	2018, 2021, 2022, 2023	Aethalometer (Magee Scientific AE33)

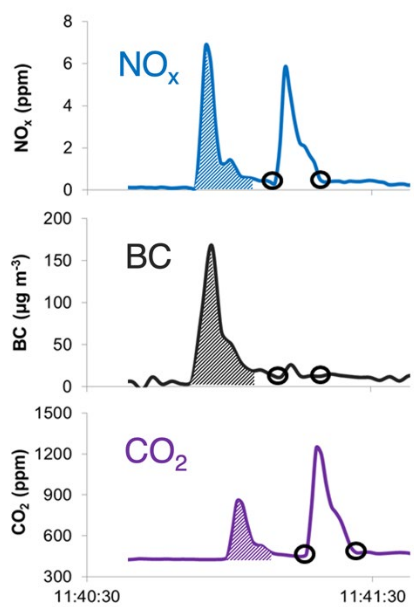

Figure A1. Pollutant concentration time series showing peaks that correspond to the exhaust plumes of two trucks (reproduced from Preble et al., 2015). The first truck emitted appreciable amounts of NO_x and BC, while the second truck emitted much less BC. The shaded peaks correspond to the integrated areas used to compute emission factors for the first truck, and the open circles indicate the integration boundaries for the second truck.

Table A2. Fleet-average emission factors (± 95% confidence intervals) for the on-highway truck fleet, as measured at the Caldecott Tunnel in each calendar year. 2010 data from Dallmann et al. (2012) and adjusted to account for differences in BC and CO_2 data, as described in Preble et al. (2015); fleet composition estimated from vehicle miles traveled in summer 2010 in Alameda County (EMFAC, 2017).

<table>
<tr><th>Sampled Fleet</th><th>Engine Model Years</th><th>NO_x (g kg^{-1})</th><th>NO_2 (g kg^{-1})</th><th>NO_2/ NOx Emission Ratio</th><th>N_2O (g kg^{-1})</th><th>NH_3 (g kg^{-1})</th><th>AE16 BC (g kg^{-1})</th><th>AE33 BC (g kg^{-1})</th></tr>
<tr><td>2010 Fleet (15% DPF, 2% SCR)</td><td>1965–2010</td><td>31.3 ± 1.6 (n = 557)</td><td>2.2 ± 0.3 (n = 567)</td><td>0.07 ± 0.01 (n = 567)</td><td>Not Measured</td><td rowspan="3">Not Measured</td><td>0.86 ± 0.11 (n = 667)</td><td rowspan="3">Not Measured</td></tr>
<tr><td>2014 Fleet (72% DPF, 33% SCR)</td><td>1965–2015</td><td>16.3 ± 0.9 (n = 1139)</td><td>1.8 ± 0.2 (n = 1135)</td><td>0.11 ± 0.01 (n = 1135)</td><td>0.25 ± 0.06 (n = 1070)</td><td>0.41 ± 0.06 (n = 1127)</td></tr>
<tr><td>2015 Fleet (80% DPF, 46% SCR)</td><td>1979–2016</td><td>15.0 ± 0.9 (n = 1194)</td><td>1.8 ± 0.2 (n = 1188)</td><td>0.12 ± 0.01 (n = 1188)</td><td>0.55 ± 0.14 (n = 1167)</td><td>0.28 ± 0.06 (n = 1154)</td></tr>
<tr><td>2018 Fleet (91% DPF, 59% SCR)</td><td>1979–2018</td><td>13.2 ± 1.0 (n = 1192)</td><td>2.0 ± 0.2 (n = 1189)</td><td>0.15 ± 0.02 (n = 1189)</td><td>0.55 ± 0.08 (n = 1168)</td><td>0.10 ± 0.03 (n = 1186)</td><td>0.18 ± 0.04 (n = 1189)</td><td>0.15 ± 0.04 (n = 1171)</td></tr>
<tr><td>2021 Fleet (99% DPF, 87% SCR)</td><td>1960–2021</td><td>6.9 ± 1.0 (n = 1038)</td><td>1.4 ± 0.3 (n = 1038)</td><td>0.20 ± 0.05 (n = 1038)</td><td>0.51 ± 0.07 (n = 1029)</td><td>Not Measured</td><td>0.14 ± 0.06 (n = 1004)</td><td>0.11 ± 0.05 (n = 992)</td></tr>
<tr><td>2022 Fleet (>99% DPF, 91% SCR)</td><td>1991–2022</td><td>5.7 ± 0.9 (n = 993)</td><td>1.1 ± 0.2 (n = 993)</td><td>0.19 ± 0.05 (n = 993)</td><td>0.87 ± 0.30 (n = 981)</td><td>0.09 ± 0.04 (n = 914)</td><td>0.14 ± 0.06 (n = 976)</td><td>0.12 ± 0.05 (n = 967)</td></tr>
<tr><td>2023 Fleet (>99% DPF, 98% SCR)</td><td>1993–2023</td><td>7.8 ± 1.2 (n = 1014)</td><td>1.4 ± 0.3 (n = 1014)</td><td>0.18 ± 0.05 (n = 1014)</td><td>0.81 ± 0.11 (n = 1005)</td><td>0.23 ± 0.09 (n = 901)</td><td>0.07 ± 0.02 (n = 1004)</td><td>0.05 ± 0.02 (n = 1002)</td></tr>
</table>

Table A3. 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 in 2021, 2022, and 2023.

Emission Control Category	Engine Model Years	NO_x (g kg^{-1})	NO_2 (g kg^{-1})	NO_2/ NOx Emission Ratio	N_2O (g kg^{-1})	NH_3 (g kg^{-1})	AE16 BC (g kg^{-1})	AE33 BC (g kg^{-1})
No DPF	1960–2005	20.8 ± 10.5 (n = 14)	2.6 ± 1.6 (n = 14)	0.12 ± 0.10 (n = 14)	0.11 ± 0.13 (n = 12)	0.00 ± 0.01 (n = 4)	0.33 ± 0.29 (n = 14)	0.27 ± 0.27 (n = 13)
Retrofit DPF	1999–2006	19.6 ± 3.7 (n = 37)	1.6 ± 0.9 (n = 37)	0.08 ± 0.05 (n = 37)	0.01 ± 0.04 (n = 35)	0.00 ± 0.00 (n = 8)	0.73 ± 0.77 (n = 36)	0.63 ± 0.71 (n = 35)
DPF	2007–2009	22.9 ± 3 (n = 200)	5.0 ± 0.9 (n = 200)	0.22 ± 0.05 (n = 200)	0.02 ± 0.01 (n = 194)	0.00 ± 0.00 (n = 84)	0.62 ± 0.29 (n = 197)	0.52 ± 0.25 (n = 195)
DPF + SCR	2010–2023	5.5 ± 0.6 (n = 2794)	1.0 ± 0.1 (n = 2794)	0.19 ± 0.03 (n = 2794)	0.79 ± 0.12 (n = 2774)	0.17 ± 0.05 (n = 1718)	0.07 ± 0.02 (n = 2737)	0.06 ± 0.02 (n = 2718)