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Authors
Preble, Chelsea V
Harley, Robert A
Kirchstetter, Thomas W

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Control Technology-Driven Changes to In-Use Heavy-Duty Diesel Truck Emissions of Nitrogenous Species and Related Environmental Impacts

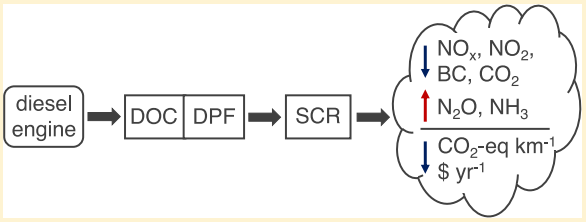
Chelsea V. Preble,*[,†,‡] Robert A. Harley,[†,‡] and Thomas W. Kirchstetter[†,‡]

[†]Department of Civil and Environmental Engineering, University of California, Berkeley, Berkeley, California 94720, United States

[‡]Environmental Technologies Area, Lawrence Berkeley National Laboratory, Berkeley, California 94720, United States

Supporting Information

ABSTRACT: Emissions from thousands of in-use heavy-duty diesel trucks were sampled at a highway and an arterial street location in the San Francisco Bay Area, spanning a time period when use of diesel particle filters (DPFs) and selective catalytic reduction (SCR) increased rapidly. At the highway site where a diverse mix of trucks is observed, SCR systems on 2010 and newer engines reduce emitted nitrogen oxides (NO_x) by 87 ± 5% relative to pre-2004 engines. SCR also mitigates DPF-related increases in nitrogen dioxide (NO_2) emissions. However, a majority of trucks had in-use NO_x emission rates that exceeded applicable emission standards. SCR systems increase emissions of nitrous oxide (N_2O) and ammonia (NH_3) from near-zero levels to 0.93 ± 0.13 and 0.18 ± 0.07 g kg^{-1}, respectively. Emissions of all nitrogenous species and especially NH_3 are skewed; 10% of trucks contribute 95% of the on-road fleet's total NH_3 emissions. Similar emission changes are observed at the arterial street site where exclusively drayage trucks operate. The environmental effects of decreased black carbon, NO_x, and carbon dioxide (CO_2) emissions and increased N_2O and NH_3 emissions due to the rapid adoption of DPF and SCR systems by the California truck fleet are: (1) a 65% net decrease in the social cost of statewide exposure to diesel truck emissions (−3.3 billion 2018 US dollars per year), and (2) a 3% net decrease in the global warming potential-weighted emission factor (−27 g CO_2-eq km^{-1}).



INTRODUCTION

Diesel particle filters (DPFs) and selective catalytic reduction (SCR) systems are commonly installed equipment on new heavy-duty diesel trucks in the U.S. starting with engine model years 2007 and 2010, respectively. DPFs can also be retrofit on older engines. Previous work demonstrated the effectiveness of these technologies in reducing emitted diesel particulate matter (PM) and nitrogen oxides (NO_x); DPFs reduce PM emissions by >90% and SCR systems reduce NO_x emissions by >75% relative to trucks operating without these controls.[1−11]

Prior work has also shown that there can be trade-offs, including increases in emissions of certain nitrogenous pollutants. As engine-out emissions of nitric oxide (NO) are intentionally converted to nitrogen dioxide (NO_2) to enable passive regeneration of DPFs, both NO_2 emissions and the NO_2/NO_x emission ratio increase.[8,12−14] These increases are of concern because NO_2 is a respiratory irritant and a direct precursor to tropospheric ozone formation. The use of diesel exhaust fluid—a solution of urea and water that is used with SCR systems to reduce NO_x emissions—can lead to increased emissions of ammonia (NH_3) and isocyanic acid.[14−18] These compounds are important precursors for secondary aerosol formation and are toxic at high concentrations. Nitrous oxide (N_2O) can be formed in SCR systems as a product of NH_3 oxidation or from thermal decomposition of ammonium nitrate that forms when NH_3 and NO_2 react.[14,19−21] While emissions of N_2O do not pose direct concerns for public health, N_2O is a potent greenhouse gas and will be an increasingly important contributor to stratospheric ozone depletion as atmospheric concentrations of chlorofluorocarbons decrease over time.[22,23]

SCR performance depends on exhaust temperature, which must be greater than ∼200 °C to ensure adequate SCR catalyst activity and effective reduction of NO_x emissions.[24] Under engine operating conditions where this temperature threshold is not met, urea injection is switched off by design to avoid the formation of deposits that may foul the SCR system and increased emissions of ammonia and other undesirable urea decomposition products.[25] With urea dosing stopped, the SCR system is inactive and NO_x emissions can be elevated. Operating modes such as cold start, idle, and low load/slow speed may not provide high enough exhaust temperatures for SCR to be active.[26]

High in-use emissions of black carbon (BC) have been noted from DPF-equipped trucks, and elevated NO_x emissions

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Figure 1. Field sampling site at the west entrance of the Caldecott Tunnel. (a) Pollutant concentrations were measured using a research van that was parked on an overpass above the highway, via a sampling line that aligned with the vertical exhaust stacks of heavy-duty diesel trucks passing by below. (b) A video camera next to the roadway recorded truck passing times and license plates.

have been noted from SCR-equipped trucks even when exhaust temperatures exceed the threshold for urea injection.[5,9,27,28] It is important to verify the performance of diesel emission control systems, not just in chassis and engine dynamometer tests but also on the road under real-world operating conditions and over time to quantify changes in performance as engines and control systems age.

The objective of this study is to quantify changes in emissions of nitrogenous species NO_x, NO_2, N_2O, and NH_3 associated with the use of modern emission control systems on heavy-duty diesel trucks. Emissions were measured from thousands of individual in-use trucks at two locations in California's San Francisco Bay Area over a period of several years when statewide regulations led to accelerated adoption of DPF and SCR systems by requiring retrofit or replacement of older engines.

METHODS

Heavy-duty diesel truck emissions were measured at the Caldecott Tunnel and Port of Oakland in the San Francisco Bay Area. These sampling sites have been used in previous studies of on-road vehicle emissions.[4,8,9,29,30] Figure 1 shows the sampling site at the western entrance of the Caldecott Tunnel on Highway 24. Emissions were measured in 2014, 2015, and 2018, during the phased implementation of statewide mandates that accelerated the use of newer engines with DPF and SCR systems. Trucks at this site were traveling eastbound on a 4% uphill grade 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. Drayage trucks accounted for 15−30% of the fleet operating at the Caldecott Tunnel, hauling containers from the nearby Port of Oakland. All truck types were included in our analysis for this location. Emissions were previously measured at the Port of Oakland in 2011 and 2013, as reported in Preble et al.[8] Additional measurements were made at this site in 2015, when all drayage trucks were required to be equipped with 2007 or newer engines. At the Port, inbound trucks were driving along a flat, designated truck route at a speed of ∼50 km h^{-1}. The phased implementation schedules for the statewide regulations that required the accelerated adoption of DPF and SCR systems by these heavy-duty diesel truck fleets over the study period are summarized in Table S1 of the Supporting Information (SI).

At both sites, a plume capture method was used to quantify emission factors from individual trucks, as described in Preble et al.[8,9] Exhaust/ambient air mixtures above the roadway were drawn into an instrumented van via a flexible aluminum duct, as shown in Figure 1. Concentrations of carbon dioxide (CO_2) and nitrogenous species were measured at 1 Hz or faster, as summarized in Table S2. CO_2 was measured with a nondispersive infrared analyzer (LI-COR, Lincoln, NE; model LI-7000). NO_x and NO were measured using two chemiluminescent detectors (Eco Physics Inc., Duernten, Switzerland; model CLD-64). N_2O was measured by cavity-enhanced near-infrared absorption (Los Gatos Research, San Jose, CA; model 913-0015). NH_3 was measured with a cavity ring-down spectrometer (Picarro, Santa Clara, CA; model G2123). Ammonia was only measured in 2018 at the Caldecott Tunnel.

Pollutant concentration peaks were integrated to calculate fuel-based emission factors, expressed in units of g of pollutant

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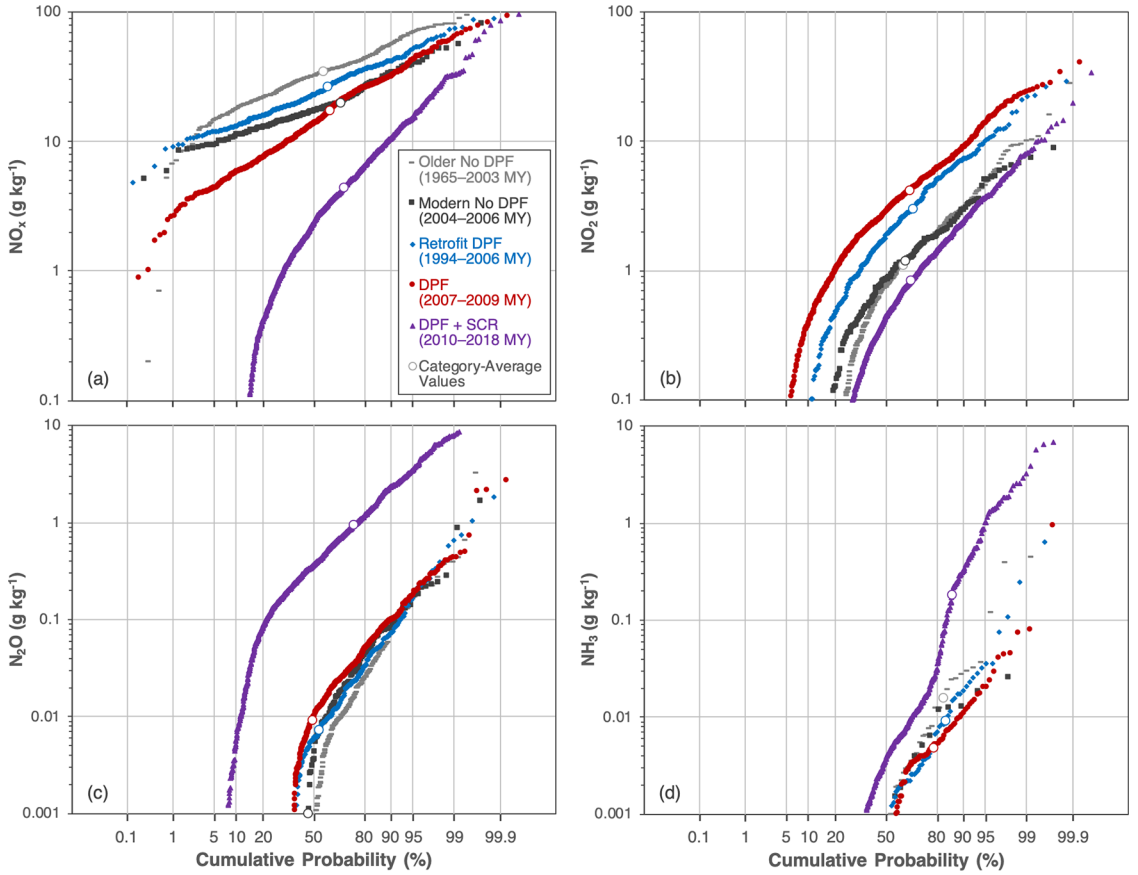

Figure 2. Cumulative probability distributions of (a) nitrogen oxides, (b) nitrogen dioxide, (c) nitrous oxide, and (d) ammonia by engine/emission control technology category. The NO_x, NO_2, and N_2O distributions are based on the combined data from sampling campaigns at the Caldecott Tunnel in 2014, 2015, and 2018. The NH_3 distributions include only data from 2018, as this pollutant was not measured in earlier years.

emitted per kg of fuel burned, using a carbon balance method:[31]

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

The emission factor for pollutant P (E_P) is calculated over the time interval $t_1 \le t \le t_2$, with t_1 and t_2 determined independently by the inflection points of each peak to account for the fact that response times for different pollutant analyzers vary. 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 factor of 44/12 converts CO_2 to carbon mass, and 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 the mass of fuel burned.[31] 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.[30] NO_2 emission factors for each truck were computed as the difference of NO_x and NO emission factors, with NO_x emission factors reported on a NO_2-equivalent basis using a molecular weight of 46 g mol^{-1}.

Emission factors were computed for trucks when the peak CO_2 concentration rose more than 7% above baseline roadway concentrations, following Dallmann et al.[4] The baseline was taken to be the concentration measured just prior to the passage of a truck. Trucks with vertically oriented exhaust stacks generally result in stronger plume captures than trucks with horizontally aligned exhaust stacks that are closer to the ground. 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.

Pollutant analyzer performance was validated by verifying the zero and span values of certified pollutant mixtures at the start and end of each day of sampling. The sample flow rates of all analyzers were verified every few days. The length of the sampling line connecting the 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 avoid NH_3 loss.

Truck license plates were recorded with a roadside video camera, as shown in Figure 1. License plates were transcribed and matched with entries in state-maintained databases: (1) the Drayage Truck Registry (DTR); (2) the Truck Regulation Upload, Compliance, and Reporting System (TRUCRS); and (3) the Department of Motor Vehicle (DMV) registration databases. Measured emission factors for each truck were linked to vehicle attributes, including chassis model year,

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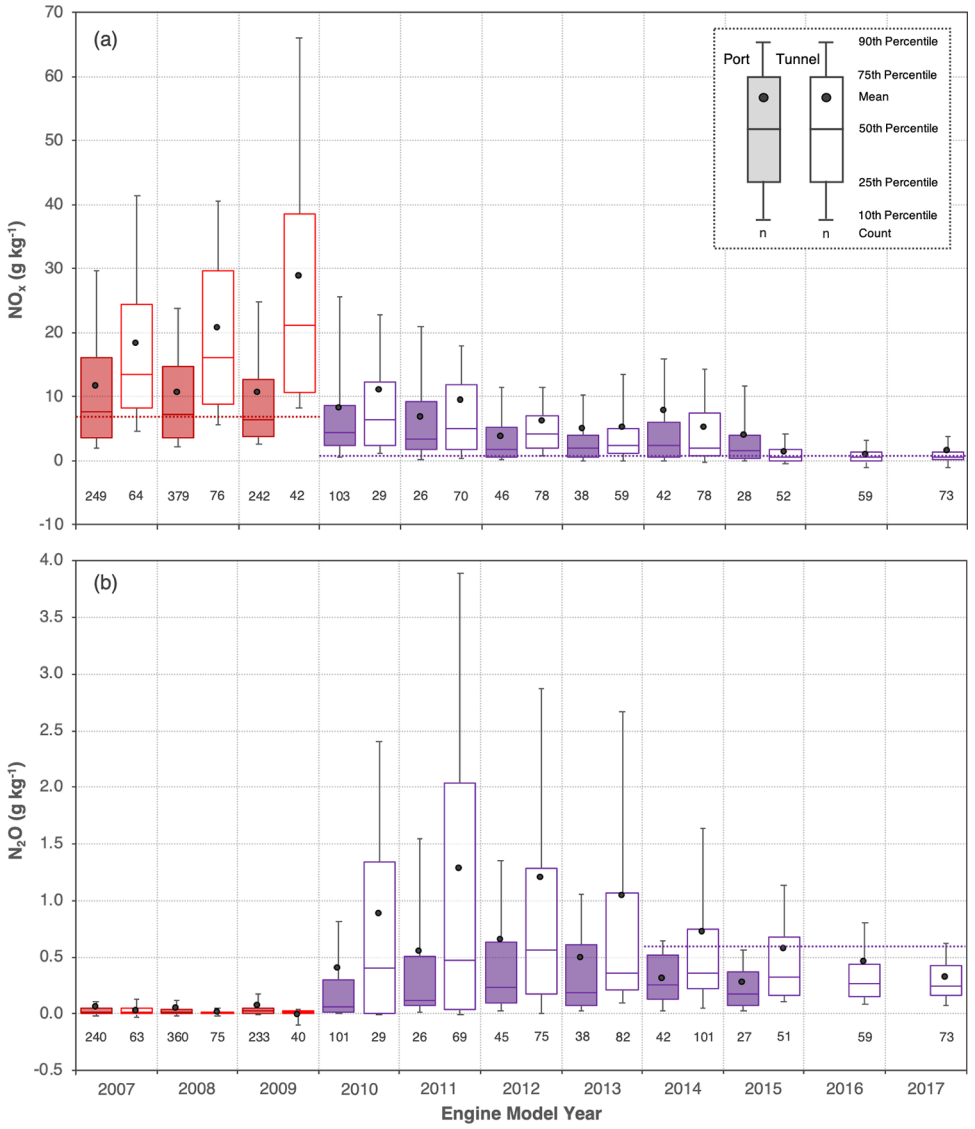

Figure 3. Distributions of measured (a) nitrogen oxides and (b) nitrous oxide emission factors by engine model year for trucks operating at the Port of Oakland in 2015 (darker boxes) and the Caldecott Tunnel in 2018 (lighter boxes). The corresponding exhaust emission standards are shown as dashed lines as comparison benchmarks (see the text).

engine model year, and installed emission control systems. If no data were available for a specific vehicle in the DTR or TRUCRS databases, the DMV registration database was used to classify trucks based on chassis model year and an inferred emission control category. Additional details about truck classification via license plate matches are included in the SI.

RESULTS AND DISCUSSION

Over the course of this study, the on-road truck fleet modernized rapidly and the use of DPF and SCR systems became common. By 2018, 91% of trucks at the Caldecott Tunnel were equipped with DPFs and 59% were also equipped with SCR systems; the median engine age was 7 years. Trucks without DPFs represented 9% of the fleet and were either exempt from (e.g., low-mileage) or out of compliance with California regulatory requirements, as summarized in Table S1. Nearly all drayage trucks at the Port of Oakland in 2015 were equipped with 2007 or newer engines with DPFs, and 25% of trucks were equipped with 2010 and newer engines that typically also have SCR systems.[9]

Trucks and emission factors are discussed below in terms of five engine model year and emission control categories: (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. These results are presented using combined data from the 2014, 2015, and 2018 field sampling campaigns at the Caldecott Tunnel and similarly combined 2011, 2013, and 2015 data from the Port of Oakland (Tables S3 and S4 in the SI). Results are also reported as fleet- and category-average values measured in a given calendar year at each site (Tables S5−S10). Unless otherwise noted, model years refer to the engine and not the truck chassis. Reported uncertainty ranges provide 95% confidence intervals for the corresponding mean values. New results from the Caldecott Tunnel measurements are the primary focus of the discussion

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that follows below; results of measurements from the Port of Oakland are included for comparison purposes.

Emission Factor Distributions and Trends. Figure 2 shows the cumulative probability distributions of nitrogenous species emission factors measured at the Caldecott Tunnel. These distributions give the likelihood on the horizontal axis that any sampled truck has an emission factor less than the corresponding value specified on the vertical axis. With these axes, log-normal distributions would plot as positively sloped diagonal lines. Median emission factor values correspond to 50% cumulative probabilities. The category-average value of each distribution is shown as an open circle.

SCR systems effectively reduce emitted NO_x relative to trucks without SCR under the driving conditions observed at the Caldecott Tunnel (Figure 2a). NO_x emissions from 2010 and newer engines with SCR are on average 87 ± 5% lower than emissions from pre-2004 engines and 77 ± 6% lower than from 2004−2006 model year engines (Figure 2a and Table S3). These emission reductions are attributable to increasingly stringent emission standards for newer heavy-duty highway diesel engines.[32]

Consistent with prior work,[8,12,13] we find that the 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 higher than baseline values for trucks without particle filters (Figure 2b). However, the average NO_2 emission factor for 2010 and newer engines equipped with SCR is 27% lower than for trucks without DPFs. Thus, under engine operating conditions observed at the Caldecott Tunnel, SCR systems completely mitigate the NO_2 increase seen for older engines equipped only with DPFs.

As shown in Figure 2c, SCR systems increase N_2O emissions from heavy-duty diesel trucks, from 0.01 ± 0.02 g kg^{-1} (i.e., near-zero) to 0.93 ± 0.13 g kg^{-1}. Similarly, the use of SCR systems increases NH_3 emissions, from 0.01 ± 0.01 to 0.18 ± 0.07 g kg^{-1}. An appreciable increase above near-zero NH_3 emission rates also occurred with the widespread introduction of three-way catalysts on light-duty gasoline-powered vehicles.[33]

An examination of the average NO_x and NO_2 emission factors measured at the Caldecott Tunnel over time reveals an approximately 45% increase from 2007−2009 model year engines between calendar years 2014 and 2018 (Figure S1 and Tables S5−S7). The NO_2/NO_x emission ratio remained unchanged over this time period. No significant change was observed over the study period at the Port of Oakland for this same category of trucks (Tables S8−S10); the most recent observations at the Port were in 2015. There was no significant change in emission rates for 2010 and newer engines at either location over the same periods, indicating that the increase may be isolated to the exhaust gas recirculation systems on aging 2007−2009 engines. These increases are different from what has been observed at other California sites. For example, Haugen et al.[7] observed significant NO_x increases over time across all 2007 and newer engines, while Bishop et al.[13] measured increases in the NO_2/NO_x emission ratio for aging 2007−2009 engines.

Figure 3 shows the distributions of measured NO_x and N_2O emission factors by engine model year. Distributions are separately plotted for trucks with 2007 and newer engines operating at the Port of Oakland in the calendar year 2015 (darker boxes) and the Caldecott Tunnel in 2018 (lighter boxes). The corresponding exhaust emission standards for NO_x and N_2O by engine model year are included as dashed horizontal lines on top of the emission factor distributions, as comparison benchmarks. NO_x emissions are limited to 0.2 g hp-h^{-1} for 2007 and newer engines based on a phased-in percent-of-sales schedule.[32] In practice, most manufacturers certified 2007−2009 engines to 1.2 g hp-h^{-1}, and the 0.2 g hp-h^{-1} emission limit was only met by 2010 and newer engines.[34] Assuming a brake-specific fuel consumption (bsfc) of 175 g hp-h^{-1}, these standards correspond to fuel-based emission factors of 6.9 and 1.1 g kg^{-1}, respectively.[35] N_2O emissions are limited to 0.1 g hp-h^{-1} for 2014 and newer engines, which corresponds to 0.6 g kg^{-1} on a fuel-normalized basis.[35−38]

NO_x emission rates for trucks with 2007−2009 engines without SCR at the Tunnel in 2018 were on average double the values measured at the Port in 2015 (Figure 3a and Tables S7 and S10). This difference between sites is more than twice as large as the increase attributed to engine aging that was observed over time at the Caldecott Tunnel, as noted above (Figure S1). This suggests that driving conditions impact emissions, where higher engine-out NO_x emissions are observed under the uphill, highway driving conditions relative to the Port's level arterial roadway. Conversely, NO_x emissions from 2010 and newer engines with SCR were ∼30% higher at the Port than at the Tunnel. This difference is entirely attributed to the higher-load uphill driving mode at the Tunnel, which leads to higher exhaust temperatures and improved SCR effectiveness in controlling NO_x emissions.

A significant fraction of each distribution shown in Figure 3a lies above the indicated NO_x emission standard at both locations and across all engine model years. Emissions are high even for those newer engines that are within the warranty and useful life periods of 5 and 10 years, respectively, assuming the mileage limits have not yet been reached.[32] On average, NO_x emission factors for trucks with 2010 and newer engines measured at the Tunnel and Port are, respectively, 4.4 and 5.8 times greater than the emission standard (Tables S7 and S10). While the on-road driving conditions of these measurements do not match the test conditions used for engine certification, it is still notable that only ∼20% of the NO_x probability distribution for 2007−2009 trucks and one-third of that for 2010 and newer trucks shown in Figure 2a meet the corresponding emission limits. Even if the threshold is raised by 50% to the not-to-exceed emission limit (0.3 g hp-h^{-1} or 1.7 g kg^{-1} assuming bsfc = 175 g hp-h^{-1}), 40% of trucks with 2010 and newer engines at the Caldecott Tunnel have in-use emissions that exceed the standard (Figure 2a).[32,35]

As shown in Figure 3b for individual engine model years, at both the Port and Tunnel locations, trucks with 2007−2009 engines have similar near-zero N_2O emission factors and trucks with 2010 and newer engines equipped with SCR have elevated emission rates. The average emission rate for SCR-equipped trucks at the Tunnel is approximately double that at the Port (Tables S7 and S10), which indicates that the faster, uphill driving conditions at the Tunnel promote more N_2O formation than the arterial street driving mode at the Port.

The average N_2O emission rate for all SCR-equipped trucks shown in Figure 2c exceeds the N_2O emission standard of 0.1 g hp-h^{-1} or 0.6 g kg^{-1}. However, this average includes 2010−2013 engines that were not subject to the N_2O emission limit. The older 2010−2013 SCR-equipped trucks have higher N_2O emissions, as shown in Figure 3b. While the average N_2O emission factors for most 2014 and newer engines at both the

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Port and Tunnel locations are below the emission limit, 10–30% of trucks exceed this standard (Figure 3b).

As noted above, trucks with SCR at the Caldecott Tunnel had elevated NH_3 emission factors, on average, relative to trucks without SCR. However, Figure 4 shows that the use of SCR does not invariably lead to high ammonia emissions. Rather, the distribution of emissions is highly skewed, as indicated by the narrow, typically near-zero boxes, means that exceed the 75th percentile, and widely extending 90th percentile whiskers. For each engine model year, ~70% of trucks had NH_3 emissions below the limit of detection (defined as the upper 95% confidence interval about the mean for trucks without SCR systems, 0.014 g kg^{-1}).

The highest NH_3 emissions are generally from SCR-equipped trucks with low NO_x emissions, as shown in Figure S2 of the SI. This relationship suggests that high NH_3 emissions may be due to the overdosing of diesel exhaust fluid in some trucks equipped with SCR that results in an excessive NH_3/NO_x ratio.[39] Another contributing factor may be an absent or ineffective ammonia slip catalyst on some SCR-equipped trucks. NH_3 emissions tend to be higher for newer engine model years, as indicated by the broader boxes and higher average values shown in Figure 4. This apparent increase suggests that a functional ammonia slip catalyst may be an increasingly important feature of SCR systems. However, ammonia slip catalysts have a potential trade-off of higher N_2O or NO emissions via the oxidation of NH_3.[19] Like NO_x, N_2O emission factors are anticorrelated with NH_3 (Figure S2). Since N_2O is regulated for 2014 and newer engines and NH_3 is not, this trade-off warrants further consideration.

Emission factor distributions of NO_x, NO_2, N_2O, and NH_3 are all skewed—a minority of trucks in the in-use fleet are responsible for the majority of the emissions of each pollutant. Figure 5 shows the cumulative distributions for each of these pollutants for the 2018 Caldecott Tunnel fleet. Measured emission factors were sorted individually for each pollutant and are plotted in the descending order, from the highest to lowest emitting, on the horizontal axis. The corresponding cumulative contributions to overall fleet emissions are plotted on the vertical axis. The NH_3 emission factor distribution is the most highly skewed, with 10% of trucks responsible for 95% of the emitted NH_3. In comparison, the highest-emitting 10% of trucks were responsible for 39% of emitted NO_x, 52% of emitted NO_2, and 63% of emitted N_2O. It is important to note that the specific trucks that comprise the top 10% of emitters can be different for each pollutant. For example, there is little overlap among the highest emitters of NH_3 and NO_x (Figure S2).

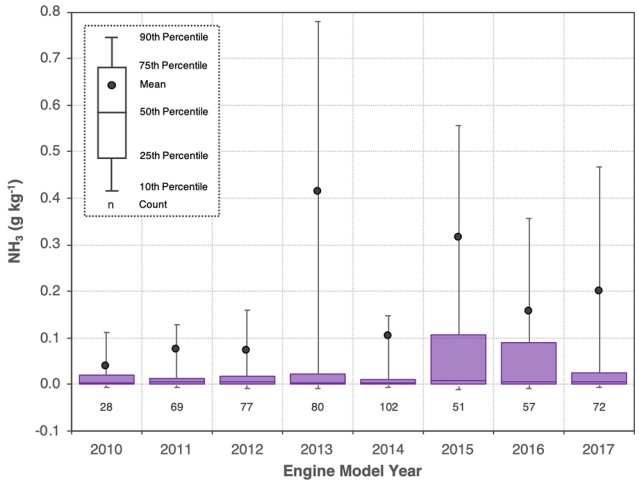

Figure 4. Box-and-whisker distributions of measured ammonia emission factors by engine model year for SCR-equipped trucks operating at the Caldecott Tunnel in 2018.

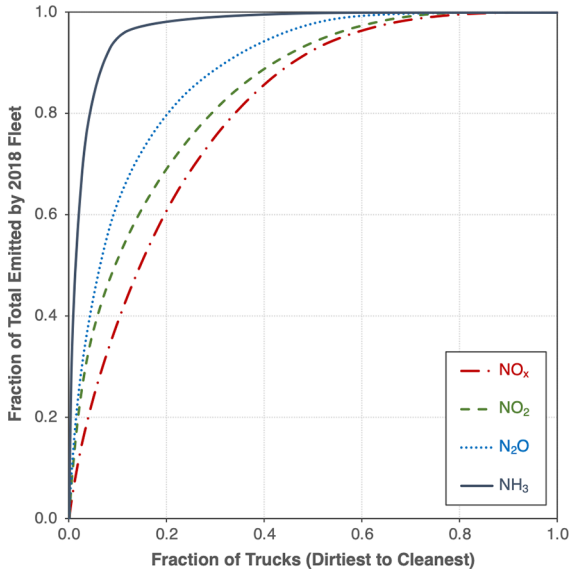

Figure 5. Cumulative distributions of NO_x, NO_2, N_2O, and NH_3 emission factors for the truck fleet measured at the Caldecott Tunnel in 2018.

Related Environmental Impacts. This study found that SCR reduces NO_x emissions by ~25 g kg^{-1} or ~80% compared to pre-2004 engines, on average across the two sampling sites (Tables S3 and S4). This reduction can be compared to concomitant increases in NH_3 and N_2O emissions from near-zero to ~0.2 g NH_3 kg^{-1} and ~0.7 g N_2O kg^{-1} for trucks with SCR. On a fuel-normalized basis, the NO_x mass emission reduction is about 150 times the increase in NH_3 and 40 times the increase in N_2O. SCR also allows for the recalibration of engines toward more fuel-efficient operating conditions, resulting in fuel savings and an approximately 4% reduction in CO_2 emissions.[40] As previously reported, DPFs reduce BC emissions by ~95% or ~1 g kg^{-1}.[9] To assess the climate and health impacts of these emission reductions in NO_x, BC, and CO_2 and increases in NH_3 and N_2O, we estimated changes in global warming potential (GWP)-weighted CO_2-equivalent emissions and social cost resulting from replacing trucks without DPF and SCR systems to trucks equipped with these controls.

Figure 6 shows the change in CO_2-equivalent mass of each climate-relevant pollutant emitted per kilometer driven (g CO_2-eq km^{-1}) when a modern 2004–2006 truck without a particle filter is replaced with a 2010 and newer truck that is equipped with both a DPF and SCR. This calculation assumed the following: the average emission factors from our two sampling sites (Tables S3 and S4); a 100-year time horizon in assessing the GWP for each pollutant, including direct and indirect aerosol effects;[22,41,42] fuel consumption of 36 L per 100 km for modern trucks without filters;[43] a 4% reduction in fuel consumption for trucks with SCR;[40] and a diesel fuel density of 0.85 kg L^{-1}.[44] Further details are provided in Table S11 of the SI.

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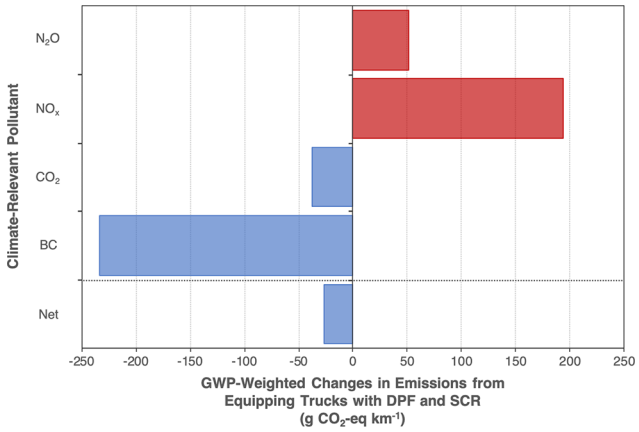

Figure 6. Change in CO_2-equivalent mass emissions per kilometer driven when a modern 2004–2006 engine without a particle filter is replaced with a 2010 and newer engine equipped with both DPF and SCR.

Though N_2O is a potent greenhouse gas, the increase in GWP-weighted emissions due to SCR-related N_2O increases is mostly offset by the SCR-enabled reduction in CO_2 emissions (Figure 6). NO_x has a negative GWP such that emission reductions lead to a warming effect.[22,42] This GWP-weighted emission increase is offset by a large reduction in BC emissions from the use of DPFs to control emitted PM. Overall, replacing a modern truck without a DPF or SCR to a newer truck equipped with DPF and SCR results in a net negative impact (-27 g CO_2-eq km^{-1}) on climate-forcing pollutant emissions. The net GWP-weighted change due to replacement of trucks from other engine/control categories with a DPF- and SCR-equipped truck depends on baseline NO_x and BC emission factors and ranges from +231 to -27 g CO_2-eq km^{-1} (Figure S3).

Both N_2O and CO_2 are long-lived and well-mixed greenhouse gases, whereas BC and NO_x are short-lived pollutants that show greater spatial variation. As a result, there is more uncertainty associated with the GWP values for BC and NO_x, in addition to complex and uncertain aerosol effects.[22,41,42] The net GWP-weighted changes in diesel truck emissions measured in this study are typically modest and within ±10% of the baseline CO_2-equivalent emission rate; the retrofit DPF category is the exception, with an approximately 30% increase above baseline when replaced by a 2010 and newer truck with DPF and SCR (Figure S3). The increase in N_2O emissions may be of greater concern with respect to future depletion of the stratospheric ozone layer.[23]

NO_x and NH_3 are precursors to secondary PM (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. The increment in NH_3 emissions from SCR-equipped trucks could offset a small fraction of the environmental benefits of much larger decreases in emitted NO_x and BC from trucks equipped with DPF and SCR systems, especially in urban areas.

To understand the relative environmental impacts of heavy-duty diesel truck emissions, we calculated the social cost of DPF- and SCR-related changes in BC, NO_x, NH_3, and CO_2-equivalent emissions from the on-road fleet operating in California. All costs are reported in terms of 2018 U.S. dollars (USD). This analysis assumed the following: annual marginal emissions by county from the Estimating Air Pollution Social Impact Using Regression (EASIUR) online tool, adjusted to the 2018 USD, 2018 populations, and a midpoint relative risk value;[45−53] average emission factors from this study; marginal cost of 42 USD per ton of emitted CO_2;[54] and fuel consumption and vehicle miles traveled by county in 2018 from California's EMFAC2017 web database.[55] These assumptions have been described in greater detail in the SI and are summarized in Table S12. The statewide social cost by the pollutant is the sum of county-level values. Figure 7 shows the impact of converting the statewide fleet from entirely 2004–2006 engines without particle filters to newer trucks equipped with both DPF and SCR systems. Climate impacts are represented together by the CO_2-equivalent bar, and direct air pollution exposure impacts are given by the separate NH_3, NO_x, and BC bars.

Control of diesel PM and NO_x via particle filters and selective catalytic reduction offers the largest benefit to the social cost of exposure to heavy-duty diesel truck emissions (Figure 7). The increase in the social cost of NH_3 emissions from SCR-equipped trucks is negligible compared to the much larger decrease in social costs from NO_x and BC emission reductions. Moreover, the CO_2-equivalent impact on the net social cost is small such that any uncertainty in the GWP values of NO_x and BC would not have a large impact on the net social cost of these emission changes. As noted earlier, isocyanic acid increases with SCR.[16−18] Figure 7 does not include the social cost of these emissions, but the expected impact would reduce the overall net benefit of including DPF and SCR systems on the statewide fleet of on-road heavy-duty diesel trucks. It is important to note that these estimates of social cost are limited to the value of avoiding premature death due to long-term exposure to fine PM and do not include morbidity impacts. Additionally, the values reported here do not include the additional, though smaller, mortality impacts of exposure to ozone.[56] These estimates offer previews of the significant air quality benefits that can be expected statewide in California and nationally when all trucks are equipped with these emission control technologies.

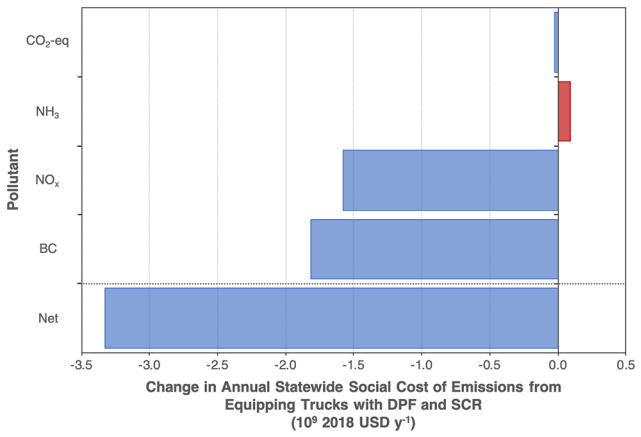

Figure 7. Change in annual social cost (2018 USD per year) of heavy-duty diesel truck emissions in the state of California resulting from converting the on-road fleet from modern 2004–2006 engines without diesel particle filters to 2010 and newer engines equipped with both DPF and SCR systems. Additional assumptions are summarized in Table S12 of the SI.

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■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.9b04763.

Summary tables of statewide regulation implementation schedules, instrumentation used, fleet- and category-average emission factors by sampling year at each location, compiled average emission factors by engine/emission control category at each location across all sampling years, assumptions for global warming potential and social cost analyses, and CO_2-equivalent emission rates by engine/emission control category (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: cvpreble@berkeley.edu.

ORCID

Chelsea V. Preble: 0000-0002-6489-5718

Notes

The authors declare no competing financial interest.

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