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Evaluation of Heavy- and Medium-Duty On-Road Vehicle Emissions in California's South Coast Air Basin

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Abstract

Emission measurements were collected from heavy-duty (HDVs) and medium-duty vehicles (MDVs) at the Peralta weigh station long-term measurement site near Anaheim, CA in 2017. Two Fuel Efficiency Automobile Test units sampled elevated and ground-level exhaust vehicles totaling 2,315 measurements. HDVs (1844 measurements) exhibited historical reductions in fuel specific oxides of nitrogen (NO_x) from the 2008 measurements (55%) with increased use of exhaust gas recirculation and selective catalytic reduction systems. However, as these technologies have aged, the in-use benefits have declined. Infrared %opacity measurements of tailpipe soot decreased 14% since 2012 with increased diesel particulate filter (DPF) use, DPF longevity and fleet turnover. 63% of the HDV fleet in 2017 was chassis model year 2011+ compared to only 12% in 2012. The observed MDV fleet (471 measurements) was 1.4 years

older than the HDV fleet with average NO_x 14% higher. A significant reduction in MDV NO_x occurred approximately 2 model years prior to similar HDV reductions (2014 versus 2016 chassis model year). MDV chassis model years 2014+ were able to meet their corresponding NO_x laboratory certification standards in-use, whereas HDVs remain slightly above this threshold. Similar MDV NO_x emission trends were also observed in data previously collected in Chicago, IL.

Introduction

Diesel powered heavy-duty (HDVs) and medium-duty vehicles (MDVs) historically comprise only a small percentage of the overall, on-road fleet (around 3% each), but contribute an increasing percentage of particulate matter (PM) and oxides of nitrogen (NO_x) emissions.¹⁻⁴ In compliance with current regulations that require the reduction of tailpipe PM and NO_x, engine control strategies and after-treatment systems such as diesel particulate filters (DPFs), exhaust gas recirculation (EGR) and selective catalytic reduction systems (SCRs) have been utilized in both HDV and MDVs for emissions control. DPFs work by way of interception and reduce tailpipe particle emissions by a high percentage, reducing human exposure to PM.⁵⁻⁸ DPFs have proven to be a beneficial addition to diesel engines, as PM can worsen respiratory and lung diseases and cause premature death, and the black carbon (BC) component of PM is a known climate forcing agent. Therefore HDVs and MDVs have installed DPFs to meet the current PM standard.⁹

NO_x contributes to ozone formation, acid rain and secondary PM formation once emitted into the atmosphere.^{10, 11} Because of this, EGR and SCRs have been introduced into diesel engines to help reduce tailpipe NO_x in two distinctive ways. Chassis model year 2008-2010

diesel vehicles rely solely on EGR to meet their corresponding NO_x standards by cooling and injecting part of the exhaust stream back into the cylinders, which reduces cylinder temperature and decreases oxygen concentrations, lowering engine out NO_x. With the newest and most stringent NO_x regulations, many chassis model year 2011 and newer diesel vehicles utilize SCRs to reduce NO_x into nitrogen (N₂) and water. These systems have tailpipe reduction efficiencies up to 95% when working at optimum conditions. This requires enough thermal energy to thermalize the reducing agent, urea, and the SCRs' catalyst is required to be above a certain temperature, typically 200-250°C depending on the catalyst, in order to overcome the activation barrier of nitrogen oxide (NO) to N₂.^{6-8, 12}

Along with these new certification standards that translate to improvements in tailpipe emissions, California has required faster in-use emissions reductions as a key component of their Diesel Risk Reduction Plan accelerating fleet turnover.¹³⁻¹⁶ This has resulted in a California fleet which is younger than those found in other states. The average age for medium and heavy-duty vehicles in the United States in 2015 was ~14 years old, whereas those observed in California are significantly newer (~6 years old).^{17, 18} The impact of the new California regulations on HDV tailpipe NO_x emissions have been monitored by multiple groups both on-road and in-lab. These groups have shown that the introduction of lower NO_x standards have resulted in reduced on-road emissions due to the use of various after-treatment systems and engine control strategies, although some researchers have shown that initial reduction levels are not persistent.¹⁸⁻²⁴

MDV emissions have received far less research attention. MDV's emissions have previously been combined into overall fleet studies, or studies that are comprised of only a few MDVs or single engine dynamometer measurements.^{3, 25-29} This lack of information forced the California Air Resources Board (CARB) to use HDV emission factors to estimate MDV

deterioration rates in their emission factor model. CARB has estimated that 23% of the truck fleet in California is made up of MDVs and that MDVs operating in California have lower mileage accrual rates and are newer, on average, than the HDV fleet.³⁰

We report here in-use emission measurements collected on both HDV and MDV fleets at the Peralta weigh station, a long-term measurement site on State Route 91 in California's South Coast Air Basin. The HDV measurements extend a data record that began in 1997, and for the first time we have also captured a significant number of emission measurements from the MDV fleet which passed through this site.

Experimental

The Fuel Efficiency Automobile Test (FEAT) technology has been used by the University of Denver to study HDVs, as previously described in the literature.³¹⁻³³ Carbon monoxide (CO), carbon dioxide (CO₂), total hydrocarbons (HC) and infrared (IR) percent opacity are measured via non-dispersive IR absorption, and nitrogen oxide (NO), nitrogen dioxide (NO₂), and ammonia (NH₃) are measured with two dispersive UV spectrometers. Collinear beams of IR and UV light are passed from the source, on one side of the road, to a detector on the other side of the roadway. UV absorbance bands at wavelengths of 195-226nm are used to quantify NO and NH₃, and 429-446nm are used for NO₂. IR %opacity is measured correlating reductions in the IR reference channel (3.9 μ m) by soot particles against exhaust CO₂. These reductions are proportional to reductions in fuel-based soot mass and number emissions provided the soot size distribution and optical properties remain constant during the sampling period. Previous data suggests that an IR %opacity of 0.5% is approximately 0.5 to 2 g of soot/kg of fuel. Ratios of CO, HC, NO, NO₂, and NH₃ to CO₂ are directly measured, and the

requirements for valid measurements have been detailed in a previous publication.³⁴ Conversion from these ratios to fuel specific data in g/kg of fuel is performed via carbon mass balance using a carbon mass fraction of 0.86 for diesel and gasoline and 0.75 for natural gas.³⁵ The FEAT measured ratios were calibrated in the field with three separate certified gas cylinders containing known amounts of 1) CO (6%), CO₂ (6%), propane (HC, 0.6%), NO (0.3%) , N₂ balance, 2) NO₂ (0.05%), CO₂ (15%) and air balance, 3) NH₃ (0.1%) , propane (0.6%), N₂ balance.

With the introduction of DPFs, the traditional use of elevated exhaust pipes for HDVs has changed and a growing number of HDVs are now manufactured with ground level exhaust. MDVs are also mainly comprised of low exhaust. Therefore, new to this campaign, two FEAT instruments were utilized to study and analyze the entire Peralta fleet. One instrument was placed on the ground to capture low exhaust vehicles, (MDVs and some HDVs, Low FEAT) and another was placed on a scaffold, putting this FEAT at 4.3 meters high and collected data from elevated exhaust pipes (HDVs, High FEAT). A picture showing the equipment setup is shown in the Supporting Information (Figure S1). Low FEAT's half second of data was triggered by vehicle wheels which block the IR reference beam, whereas High FEAT's 1 second of data collection was prompted from a block of a separate IR body sensor on the roadway for each vehicle that passed through. Each vehicle triggered measurement is attempted on both instruments but exhaust was generally only measured by the detector that corresponds to the vehicles' exhaust pipe location. Low FEAT employed a shorter sampling time in order for the measurement to finish between the tractor and trailer wheels and High FEAT's sampling time remained at 1 second as in previous studies. Front license plate images were captured for both systems to obtain non-personal vehicle information, such as make and model year, which was then linked to the vehicle's emission measurement in the final database. The speed and

acceleration were also independently measured by each system. Lastly, thermographs of elevated exhaust pipes were obtained to gather qualitative information on engine temperature for the High FEAT measurements.

The Peralta weigh station is located on State Route 91 (exit number 39, see Supporting Information Figures S1 and S2), in Southern California. The Peralta measurement site utilized the same combined uphill exit lane of the weigh station after the scales as the five previous campaigns in: 1997, 2008, 2009, 2010 and 2012.³⁶⁻³⁸ Table S1 in the Supporting Information includes an emissions measurement summary for all of the previous campaigns. In 2017, four days of data (March 20-23) were collected, three of which (March 21-23) included Low FEAT measurements.

Results and Discussion

The research conducted at the Peralta weigh station resulted in 1,368 HDVs measured with High FEAT over four days and 476 HDVs measured with Low FEAT over the course of 3 days which accounted for approximately 30% of the HDVs measured during the last three days. Table 1 shows fuel specific averages for CO, HC, NO, NO₂, NO_x, and NH₃ in g/kg of fuel, as well as average IR %opacity, model year, speed (kmph), and acceleration (kmph/s). The uncertainties are standard errors of the mean calculated using the daily means (see supporting information). The percentage of diesel vehicles that comprises each category is also displayed. There were also a small number of HDV measurements (22) powered by natural gas that account for the remaining HDV measurements.

The IR %opacity measurement validity rate is prone to decreases due to increased noise from road debris and physical interferences from vehicle parts and for these measurements only

Table 1. FEAT data summary for 2017

FEAT Number of Measurements	High 1408	Low 907	HDV 1844	MDV 471
Mean gCO/kg of fuel	5.5 ± 0.5	9.1 ± 1.7	5.9 ± 0.9	11.0 ± 2.4
Mean gHC/kg of fuel	2.1 ± 0.5	1.8 ± 0.4	2.2 ± 0.4	1.0 ± 0.3
Mean gNO ^a /kg of fuel	7.8 ± 0.3	7.6 ± 0.5	7.4 ± 0.4	8.8 ± 0.5
Mean gNH ₃ /kg of fuel	0.08 ± 0.02	0.06 ± 0.05	0.09 ± 0.02	0.002 ± 0.013
Mean gNO ₂ ^b /kg of fuel	1.1 ± 0.02	1.0 ± 0.03	1.1 ± 0.04	1.1 ± 0.1
Mean gNO _x ^b /kg of fuel	13.0 ± 0.5	12.5 ± 0.9	12.4 ± 0.6	14.5 ± 0.9
Mean IR %opacity	0.4 ± 0.02	0.9 ± 0.1	0.5 ± 0.05	0.9 ± 0.2
Mean Model Year	2010.7	2010.7	2011.0	2009.6
Mean Speed (kmph)	22.5 ± 0.2	24.2 ± 1.3	22.5 ± 0.9	25.4 ± 1.3
Mean Acceleration (kmph/s)	1.2 ± 0.3	0.4 ± 0.2	1.0 ± 0.3	0.4 ± 0.3
Diesel Vehicle Percentage	99%	95%	99%	92%

^aGrams of NO^bGrams of NO₂

60% of the Low FEAT measurements had valid opacity readings while the High FEAT had an 88% validity rate. This can bias the IR %opacity readings high as the validity criteria is more stringent on the lower values with a fixed percent error criterion and is likely why the Low FEAT IR %opacity was 2.25 times the average opacity of the High FEAT for the HDVs.

Newer HDVs have a higher percentage of vehicles with low exhaust, measured with Low FEAT, and have a corresponding 12% lower NO_x average than the High FEAT HDV mean. The Supporting Information (Figure S3) shows all other gases measured separated by High and Low FEAT, but for subsequent analyses High and Low HDV FEAT data will be combined. The HDV fleet observed at Peralta was approximately 6.25 years old, which emphasizes the turnover occurring in the California HDV fleet. However, contrary to the earlier CARB modeling assumptions, the MDV fleet observed is 1.4 model years older than the HDV fleet.

Historical Trends

The Peralta fleet has incorporated the new lower emissions technology, where regulated species, such as NO_x and PM, were positively impacted. The fleet in 2017 is mainly comprised of vehicles chassis model year 2011 and newer (63% of the HDV fleet compared to only 12% of the fleet previously measured in 2012), which would have after-treatment systems responsible for decreasing the fleet average IR %opacity and NO_x.

There are two important decreases in IR %opacity by measurement year, shown in Figure 1, where IR %opacity is represented by grey bars (right axis) and the uncertainties are standard errors of the mean calculated using the daily means. The 70% reduction from 1997 to 2008 is likely due to the early emphasis in reducing particle emissions by manufacturers and the accompanying improved PM management in newer engines, as reported in the literature.³⁹ This was followed with little change in IR %opacity until the 2017 measurements. A further reduction of 14% from the 2012 mean is accompanied by rapid infiltration of both HDVs manufactured with DPFs as well as retrofit DPFs, a response to the new regulations put in place by California on the remaining older vehicles.^{18, 40} Previous studies only utilized High FEAT technology, and for comparison, the IR %opacity for only the High FEAT measurements was 0.4 in 2017 (28% overall reduction from 2012) compared to the combined HDV mean of 0.5. This High FEAT IR %opacity level is comparable to that measured for a fully equipped DPF fleet at the Port of Los Angeles in 2012, required by the San Pedro Clean Air Action Plan, indicating that the Peralta fleet is now fully DPF equipped.³⁷

Fuel specific NO_x emissions by measurement years are also shown in Figure 1 for all HDVs, giving a historical look at implemented diesel technologies. The fleet average gNO is

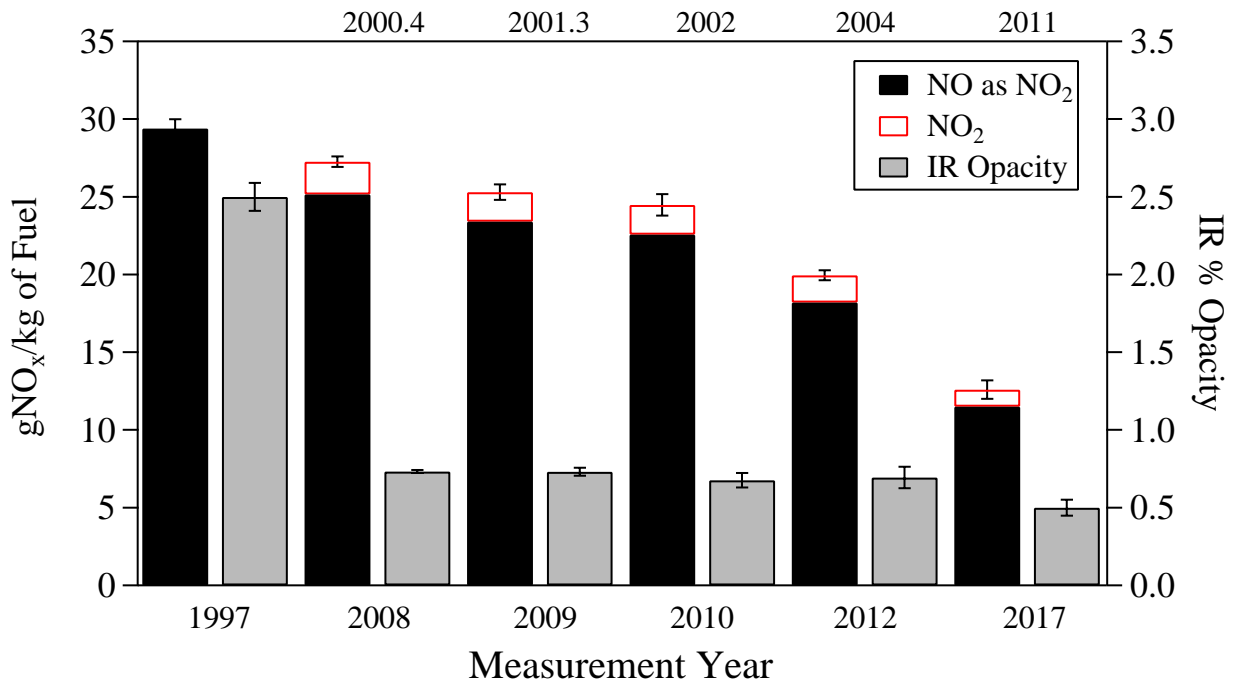


Figure 1. IR %opacity (grey bars, right axis) and gNO as NO₂ equivalents (black bars, left axis), gNO₂ (open red bars, left axis) and gNO_x/kg of fuel (total bar height, left axis) by measurement year. Uncertainties are standard errors of the mean calculated using the daily means. Fleet average model year is shown at the top of the graph above the corresponding measurement year.

plotted as NO₂ equivalents (black bars, left axis), gNO₂ (open red bars, left axis) and gNO_x/kg of fuel (total bar height, left axis). Uncertainties are standard errors of the mean calculated using the daily means. Fleet average model year is shown above the corresponding measurement year. There has been a 61% reduction in fuel specific NO from 1997 to 2017 (NO₂ was measured starting in the 2008 field work). Changes in engine management, such as enriching the air to fuel ratio and cooling the mixture via EGR, allows for lower engine out NO_x and is likely the source responsible for much of the NO_x decreases seen from 2008 to 2010. The additional reductions in NO_x measured in 2012 correspond to the initial introduction of SCRs to HDVs. Further adoption of SCRs and fleet turnover is responsible for the additional 37% reduction observed in total NO_x from 2012 to 2017.⁴¹

The reductions observed in the 2017 fleet's opacity and NO_x was a result of new technologies and combustion management changes that have helped vehicles achieve the model year certification standards. Because on-road emissions are one important metric to evaluate how well specific certification standards translate to in-use vehicles, Figure 2a) shows 2012 (black) and 2017 (blue) IR %opacity (hatched and striped bars, right axis) and fuel specific NO_x (solid and open bars, left axis) emissions for in-use vehicles grouped by model year into four categories that are consistent with the certification standards: pre-2004 chassis model year HDVs with no manufactured aftertreatment technologies, 2004-2007 HDVs with combustion management such as EGR and subject to more recent PM retrofit activities, 2008-2010 with EGR and first generation DPFs, and 2011 and newer chassis model years that are equipped with DPFs and an increased use of SCR systems. Uncertainties are standard errors of the mean calculated using the daily means. As more HDVs are equipped with aftertreatment systems and as these systems improve, mean IR %opacity and NO_x show continual declines.

2017 observed IR %opacity has decreased from the 2012 measurements for the earliest chassis model year grouped vehicles (pre-2004 and 2004-2007) that were not manufactured with any particle emission control technologies, suggesting retrofit DPFs in 2017 measured vehicles in compliance with the California Truck and Bus rule and agrees with previously observed retrofit activity at a different California weigh station.^{18, 40} Both 2012 and 2017 data for chassis model year groups 2008 – 2010 and 2011 and newer model year HDVs have similar IR %opacity for both measurement years. Therefore, the different DPF generations (2008-2010 versus 2011+) at Peralta in 2017 are performing similarly.

As previously mentioned, SCRs were phased into chassis model years 2011 and newer vehicles. Fuel specific NO_x emissions show similar decreases for both measurement years as

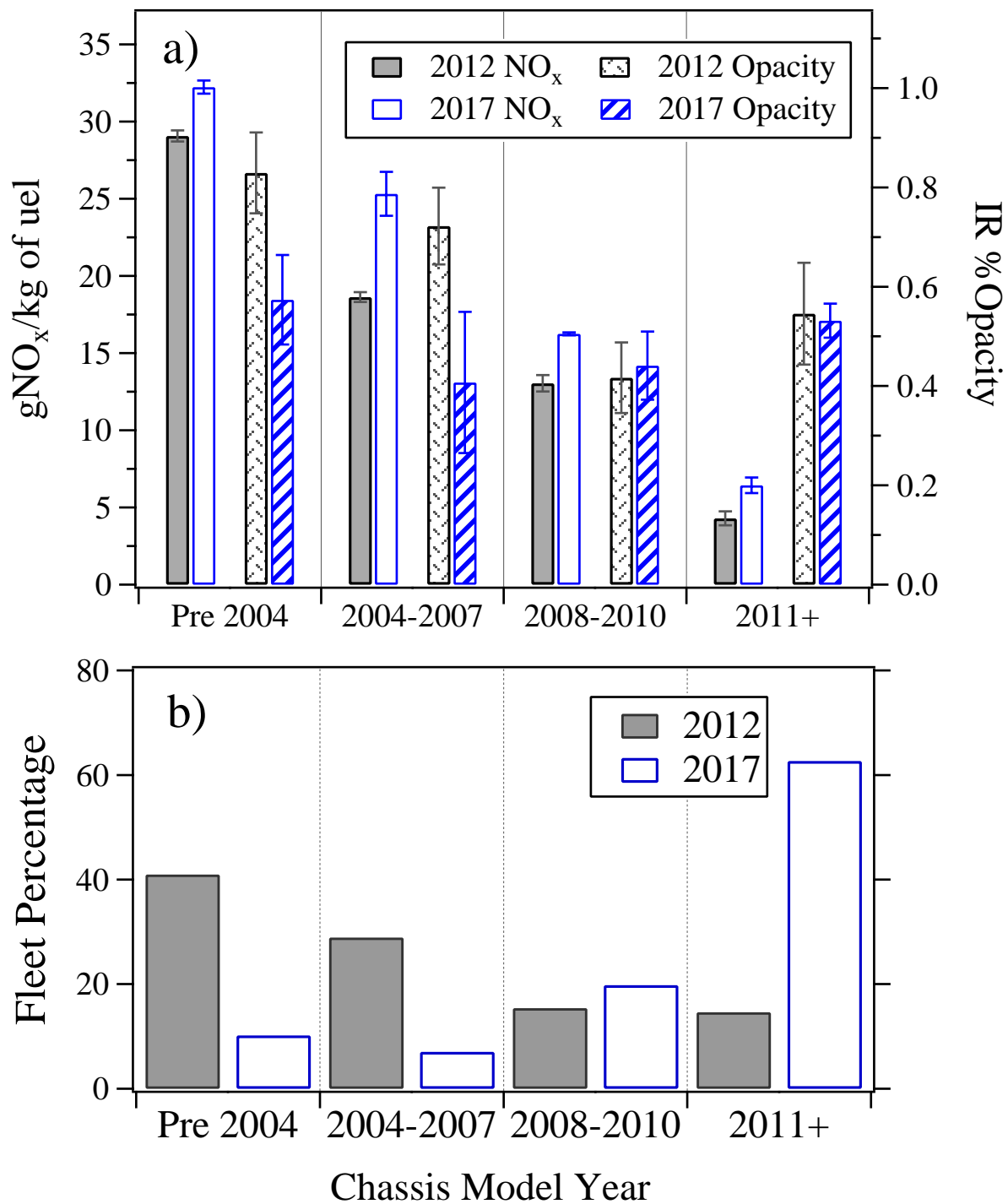


Figure 2. a) IR %opacity (right axis, hatched and striped bars) and $\text{gNO}_x/\text{kg of fuel}$ (left axis, solid and open bars) for 2012 (black) and 2017 (blue) data grouped by chassis model year. Uncertainties are standard error of the mean calculated using the daily means. b) Fleet percentage for grouped model years in 2012 (solid black bars) and 2017 (open blue bars) data.

older HDVs are replaced with model year vehicles with newer technology. The 2011 and newer model year vehicles measured in 2017 have an 80% reduction from the pre-2004 vehicles measured in 2017 (32.2 gNO_x/kg of fuel to 6.4 gNO_x/kg of fuel), an encouraging result for California's desire to reduce NO_x emissions with newer, lower emitting HDVs operating within the state. Known durability issues with EGR could be a possible explanation for the 36% increase in NO_x observed for chassis model years 2004 – 2007 (18.6 to 25.3 gNO_x/kg of fuel) and 25% increase for model years 2008 – 2010 (13.0 to 16.3 gNO_x/kg of fuel) between the 2012 and 2017 measurements. The only NO_x management these vehicles are subject to is EGR, and therefore as these vehicles age and accumulate wear, their ability to limit engine out NO_x has decreased.⁴² In 2017, chassis model years 2011 and newer also show increased NO_x emissions by 49% compared to 2012, although both of these average emissions are significantly decreased from previous model year vehicles without SCR systems (4.3 and 6.4 gNO_x/kg of fuel, respectively). Comparing 2011+ fleets are problematic because these vehicles are not all certified to the same NO_x emission level and the observed differences may simply be the result of differences in the two fleets' certification level, which cannot be obtained through any vehicle registration information. However, these observed increases in NO_x emissions with age may be a contributing factor in the noted slowdown in NO_x emission levels observed in top-down NO_x inventories.⁴³

Figure 2b shows the 2012 (black solid bars) and 2017 (blue open bars) fleet percentages for the corresponding model year categories documenting the changes that have occurred since 2012. 41% of the fleet in 2012 was pre-2004 model years, whereas only 10% of the 2017 fleet was older than model year 2004. This supports the idea that California is making progress in replacing the older HDV fleet with newer lower emitting vehicles.

California Site Comparison

Figure 3 compares the fuel specific NO_x by chassis model year measured at Peralta (red squares) to data collected using a different measurement technique at the Cottonwood weigh station (blue circles) in northern California off I-5, 17 miles south of Redding, CA.⁴⁴ At both locations the emission trends are similar with a noticeable decrease in fuel specific NO_x emissions starting in model year 2008 when EGR is used to reduce engine out NO_x . The start of SCR installations in model year 2011, and the phase-in of these systems presents another step reduction observed at both locations. Importantly, the newest model years, 2014 and newer, have nearly identical fuel specific NO_x emissions at both locations. This newest model year subsection is largely comprised of HDVs equipped with SCRs and certified to the lowest NO_x emission standards and shows consistently low NO_x measurements. From model year 2007 to 2017, there was an 88% and 89% reduction in NO_x at Cottonwood and Peralta, respectively.

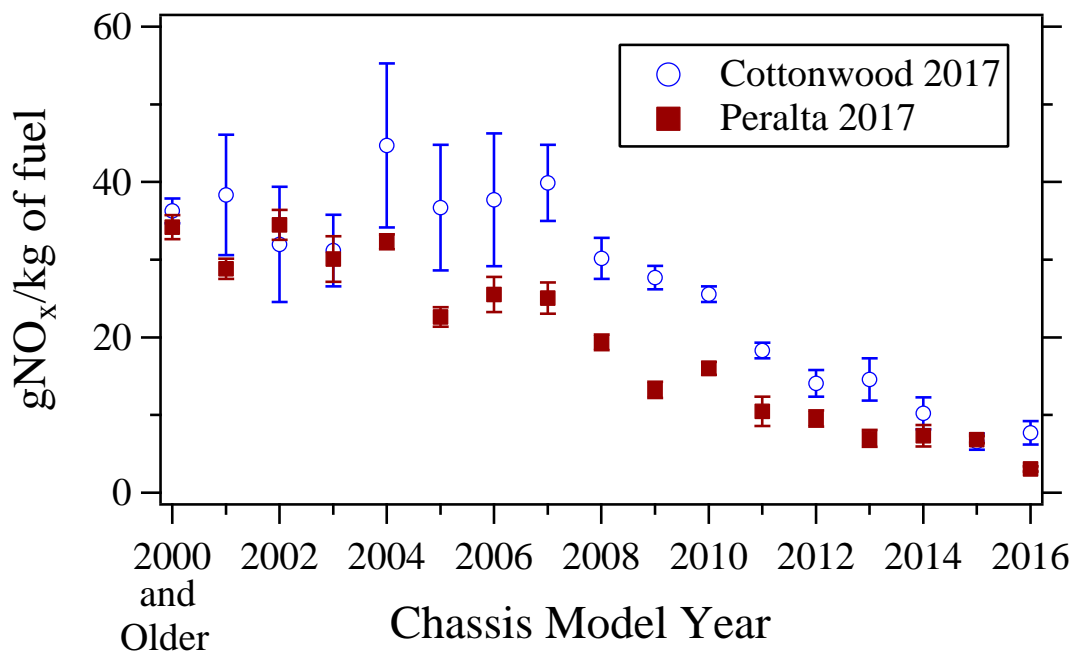


Figure 3. Fuel specific HDV NO_x by chassis model year at Cottonwood (blue circles) and Peralta (red squares) for 2017 data. Uncertainties are standard error of the mean calculated using the daily means.

There are noticeably higher fuel specific NO_x emissions observed at the Cottonwood site for the 2004 – 2013 model year vehicles. The exact reason for this is unknown, however instrument calibration issues can be ruled out, as pre-2004 and post-2013 vehicles have similar emissions within the measurement uncertainties at the two sites. The model years that deviate between the sites largely depend on EGR and engine management strategies for the control of NO_x emissions. The NO_x differences observed for model years 2011-2013 could also be the result of a higher percentage of HDVs at Peralta that have SCRs and are certified to lower NO_x emission levels. Figure 2a shows that these intermediate model years (2008-2010) at Peralta experienced increased NO_x emissions since the 2012 measurements, suggesting deterioration of the NO_x controls.

It is known that diesel engine EGR coolers can suffer from particulate fouling that can compromise their effectiveness in reducing NO_x emissions.⁴² In addition, mileage accumulation rates are likely to vary for trucks at different weigh stations due to the activity in which they are involved in and could be a contributing factor to the different NO_x emission levels observed. CARB has reported that out-of-state registered HDVs have a mileage accumulation ~30-40% higher than in-state registered HDVs depending on where the vehicle originated.³⁰ Peralta is mainly comprised of instate plated vehicles (81%) whereas Cottonwood only has 57% of its fleet registered within California. The fleet at Peralta, based on CARB's analysis, would likely have lower mileage accumulation per year than at Cottonwood due to the respective fleet's activity. To help test the speculation that NO_x differences are linked to mileage accumulation and thus wear on the EGR systems, Figure S4 in the Supporting Information shows the fuel specific NO_x emissions from Cottonwood in 2013 compared to the 2012 and 2017 Peralta data. This figure shows that the 2013 Cottonwood NO_x measurements fall between the two Peralta data sets for

most model years. This would be expected as the vehicles at Peralta have undergone a longer period of lower mileage accumulation with a predominantly in-state HDV fleet.

This mileage accumulation effect appears to be demonstrated in early SCR systems as well. Figure 2a shows NO_x emission increases at Peralta for the 2011 and newer chassis model year vehicles between the 2012 and 2017 measurements, though this comparison is limited by the number of 2011 and newer chassis model year vehicles sampled during the 2012 campaign (only 15% of the total measurements). However, there is a corresponding increase in NO_x for these model years observed for the Cottonwood fleet, which has a substantial number of vehicles model year 2011 and newer (646 measurements). Figure 4 plots fuel specific NO_x emissions against chassis model year 2008 and newer at the Cottonwood weigh station for measurement years 2013 (left, grey bars), 2015 (middle, blue bars) and 2017 (right, red bars). Open portion represent gNO_2/kg of fuel, filled portion represent the amount of NO expressed as NO_2 , and the height of each bar represents total gNO_x/kg of fuel for the given model year. Uncertainties are standard error of the mean calculated using the daily means of total NO_x . Not only is there a continual increase in model years 2008-2010 NO_x emissions, but this trend is present for 2011-2014 chassis model year vehicles as well.¹⁸ Figure S5-S7 in the supporting information are similar graphs categorized by engine manufacturer (determined from decoding the vehicles VIN), to minimize the influence of NO_x certification levels, for the 2017 Cottonwood and Peralta data sets. Because this reduces the number of vehicles in each chassis model year grouping, the uncertainties increase significantly, but all three manufacturers at both locations have fuel specific NO_x emissions that increase over time for the first-generation SCR equipped vehicles.

The observed variability patterns in NO_x emissions from newer model year repeat vehicles can help validate the degradation in EGR and SCR systems. Figure S8 in the Supporting

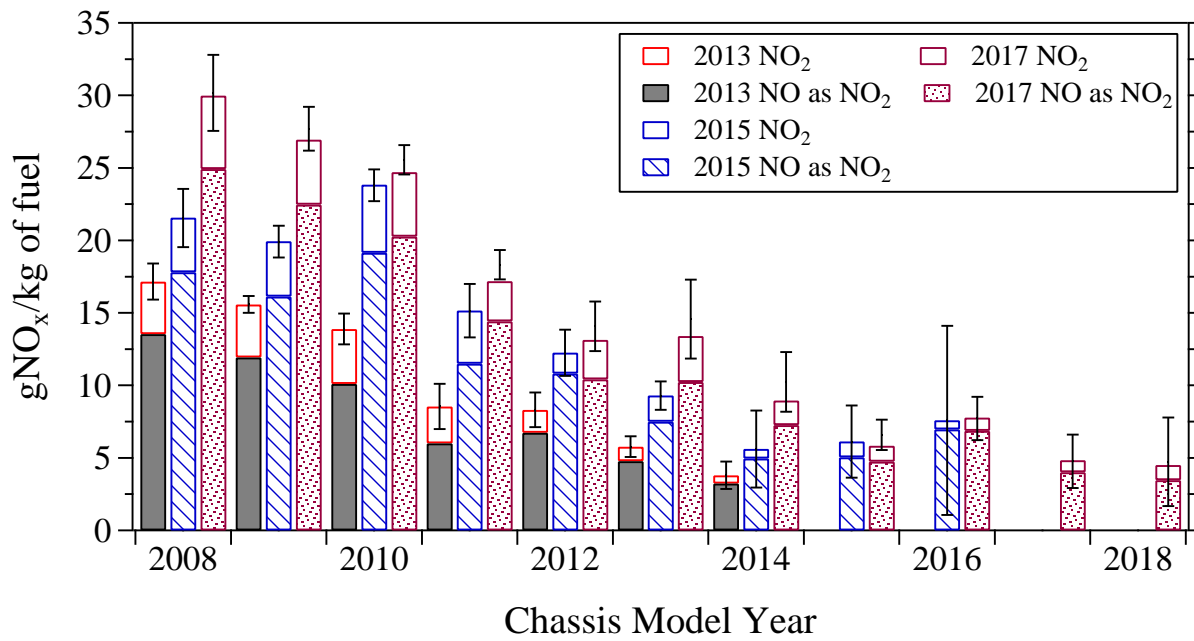


Figure 4. Fuel specific nitric oxides by chassis model year at Cottonwood weigh station for measurement years 2013 (left bars), 2015 (middle bars) and 2017 (right bars). Open portion represent gNO₂/kg of fuel, filled portion represent the amount of NO expressed as NO₂, and the height of each bar represents total gNO_x/kg of fuel for the given chassis model year. Uncertainties are standard error of the mean calculated using the daily means of total NO_x.

Information shows the 145 HDVs that were measured multiple times at Peralta. The truck number in Figure S8 is calculated using the average gNO_x/kg of fuel for each vehicle and thus higher truck numbers correspond with increased average NO_x for the particular vehicle. When assessing large databases of emissions in general, mean emissions and variability decreases moving from the oldest model years to the newest model years. However, due to the lack of engine controls in the oldest model years (2007 and older) there is actually less variability in these high NO_x emissions. In this data set, chassis model years 2008 – 2010 and 2011 – 2013 have, on average, more variable NO_x emissions, underscoring that these control technologies have the potential to dramatically lower NO_x emissions, but the reductions observed for some vehicles are inconsistent. The 2014 and newer vehicles comprise the majority of the low NO_x

measurements for trucks measured more than once, emphasizing the level of control that can be achieved for HDV NO_x controls found in the newest vehicles.

Medium versus Heavy-duty Emissions

MDVs are subject to the same regulations imposed on HDVs in California but there are no recent emissions measurement studies that include the newest model years.^{30, 39} The MDV data set presented here contains the largest number of on-road emission measurements reported to date allowing a detailed look at this fleet's emission trends. Figure 5 depicts 2017 fuel specific gNO as gNO₂ equivalents (open bars), gNO₂ (solid and striped bars) and total gNO_x (total bar height) for diesel vehicles. Uncertainties are standard errors of the mean calculated using the daily means by model year for MDVs (blue) and HDVs (black). The 2010 homologous NO_x certification standard present for 2011 and newer chassis model years, assuming that 0.15 kg of fuel is consumed per brake-horsepower hour, is also shown in a dark blue line.

From 2007 to 2017 model year vehicles, NO_x declined by 90% for MDVs (26.5 to 2.6 gNO_x/kg of fuel) and 89% for HDVs, (29.4 to 3.4 gNO/kg of fuel) as newer model years incorporated SCRs into their fleets. Both MDVs and HDVs show a significant drop in NO_x from model year 2010 to model year 2011 with the initial introduction of SCRs, and both have similar total NO_x concentrations through model year 2013. These model years are likely above the certification standard due to a combination of actions: manufacturers using credits that allowed the production of engines with higher NO_x emission levels (see Figure S9 in the supporting information) and a Federal lawsuit that delayed additional HDVs equipped with SCRs.⁴⁵ Beginning with the 2014 models, MDVs show further reductions in fuel specific NO_x emissions which are not mirrored by the HDVs (MDVs are 68% lower than HDVs model year 2014 –

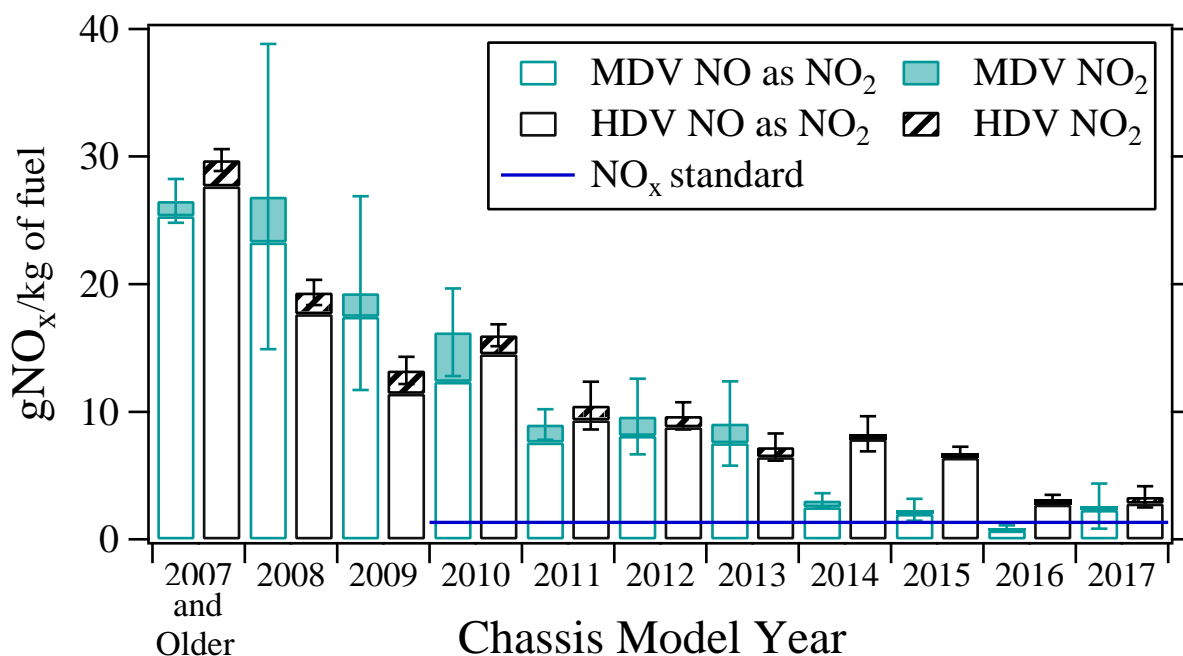


Figure 5. Total gNO_x/kg of fuel (total bar height) for MDVs (blue) and HDVs (black) diesel vehicles. Mean gNO₂/kg of fuel (solid or hatched) and gNO/kg of fuel as gNO₂/kg of fuel equivalent (open bars) as graphed by chassis model year. Uncertainties are standard error of the mean calculated using the daily means. The 2010 homologous NO_x certification standard is represented with a dark blue line assuming 0.15kg of fuel is consumed per brake-horsepower hour.

2017). HDVs remained at ~7 gNO_x/kg of fuel on average until chassis model year 2016 where a 54% reduction was achieved from 2013 vehicles. The two most abundant engine manufacturers for HDVs in 2017 at the Peralta site show a self-consistency in on-road NO_x emissions for the 2011 to 2015 chassis models (the emission difference between manufactures likely reflect differences in the fraction of non-credit engines) followed with reductions in chassis model year 2016 (see Figure S9 in the Supporting Information), whereas most MDVs show reductions starting earlier in 2014.

To assess the fleet's possible future NO_x reductions, the newest observed model years' NO_x averages (chassis model year 2016 and 2017) were calculated to be 1.6 ± 1.2 and 3.2 ± 0.4 gNO_x/kg of fuel for MDVs and HDVs, respectively. The large uncertainty for MDVs is

completely dictated by one vehicle with 31.0 gNO_x/kg of fuel (chassis model year 2017). Converted to regulation units, assuming 0.15 kg of fuel is burned per bhp-hr, MDVs observed NO_x average of 0.23 ± 0.17 g/bhp-hr is indistinguishable from the certification standard for the newest model years of 0.2 g/bhp-hr, and 0.46 ± 0.06 g/bhp-hr for HDVs is 2.3 times this same threshold.⁴⁶ These trends show that the MDVs are currently more efficient at NO_x reduction for the newest model years and are able to meet their corresponding certification standards in-use for earlier chassis model years compared to the HDVs.

Medium-duty Comparison

To understand the improvements solely in the MDV diesel fleets, the Peralta MDVs were compared to vehicles measured at an on-road measurement site in the northwest suburbs of Chicago, IL. In Chicago, only Low FEAT was used with the site measurements previously reported in the literature.^{47, 48} The Low FEAT was situated at the same location for all measurement years on the ramp from Algonquin Rd. to eastbound I-290 in 1997, 1998, 1999, 2000, 2002, 2004, 2006, 2014 and 2016. The Chicago fleet measurements at this site include a number of MDVs. The state of Illinois categorizes their license plates with suffixes of D, F or H (GVW of 14,001 to 26,000 lbs) as the last letter of the plate allowing MDVs to be extracted from these data sets (see Table S2 in the Supporting Information). Figure 6 shows the fleet average fuel specific NO, NO₂ and NO_x for Chicago's measured diesel-powered MDV fleet in 2014 (green open bars) and 2016 (blue hatched bars), as well as the Peralta 2017 diesel MDV fleet (solid grey bars). Uncertainties are the standard error of the mean calculated using the daily means.

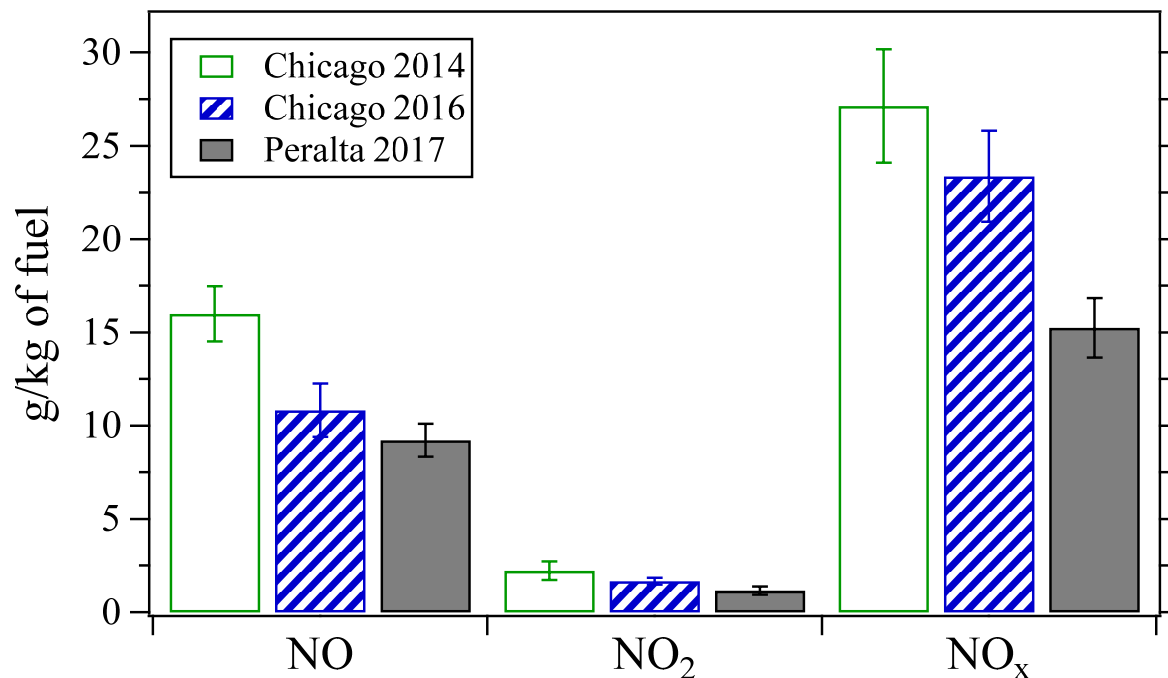


Figure 6. Chicago 2014 (green open bars), Chicago 2016 (blue hatched bars) and Peralta 2017 (grey filled bars) fleet averages for gNO/kg of fuel (g of NO), gNO₂/kg of fuel and gNO_x/kg of fuel (g of NO₂). Uncertainties are standard error of the mean calculated from the daily means.

Chicago's fleet mean model year measured in September of each year went from 2006.1 in 2014 to 2009.2 in 2016, and the spring 2017 Peralta MDV fleet had a model year average of 2009.6. As the fleets incorporate newer vehicles with SCRs, represented by a newer model year average, NO_x emissions decrease. Therefore, MDVs from both Illinois and California are continually reducing NO_x emissions from their medium-duty fleets, and the observed HDV trend, shown in Figure 1, is emulated with MDVs. However, analysis of previous Illinois data sets shows that the observed decreases in fleet averaged fuel specific NO_x emissions for the diesel MDV fleet, shown in Figure 6, have only occurred since the 2014 measurements (see Figure S10 in Supporting Information) unlike the slow but steady decreases observed in the HDV Peralta fleets (see Figure 1). The NO_x reductions correspond to a decrease in fleet age;

25% of the 2014 Chicago fleet, 40% of the 2016 Chicago fleet and 50% of the 2017 Peralta were model year 2011 and newer. Although the fleet model year composition changes, the fuel specific NO_x emissions by individual model year for all three fleets show similar trends (see supporting information Figure S11), including the lower NO_x emissions observed for the MDVs in the 2014 and newer model year vehicles. The similarity between the Chicago fleets and Peralta fleet helps demonstrate that the observed NO_x reductions at Peralta are generalizable to other MDV fleets across the United States.

Supporting Information

Supporting figures (S1-S11) and tables (S1 and S2) referenced in the text. This material is available free of charge at <http://pubs.acs.org>

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

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Supporting Information For:

Evaluation of Heavy and Medium-Duty On-Road Vehicle Emissions in California's South Coast Air Basin

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Summary of Supporting Information:

10 pages (excluding cover):

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Table S3. Chicago Historical Mean Fuel Specific Emissions for Diesel and Gasoline Medium-duty Vehicles

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Figure S1. Photograph at the Peralta Weigh Station of the setup used to detect exhaust emissions from heavy and medium-duty trucks in 2017.

Figure S2. A satellite photo of the Peralta weigh station located on the Riverside Freeway (State Route 91). The scales are located on the inside lane next to the building in the top center and the outside lane is for unloaded trucks. The measurement location is circled at the upper right with approximate locations of the scaffolding, support vehicle and camera.

Figure S3. 2017 Peralta HDV CO, HC, NO, NO₂, NO_x, and NH₃ fuel specific emissions (g/kg of fuel) and IR %Opacity for the high (black, solid) and low (blue, open) FEAT. Uncertainties are standard errors of the mean calculated using the daily means.

Figure S4. Fuel specific gNO_x/kg of fuel by chassis model year at Cottonwood in 2013 (blue circles), Peralta in 2012 (black squares) and Peralta in 2017 (orange squares). Uncertainties are standard errors of the mean calculated using the daily means.

Figure S5. Fuel specific gNO_x/kg of fuel by chassis model year for engines manufactured by Manufacturer A at the Cottonwood weigh station (top) for 2013, 2015 and 2017 measurement years and at the Peralta weigh station (bottom) for 2012 and 2017 measurement years. Uncertainties are calculated from the standard error of the mean using the daily means.

Figure S6. Fuel specific gNO_x/kg of fuel by chassis model year for engines manufactured by Manufacturer B at the Cottonwood weigh station (top) for 2013, 2015 and 2017 measurement years and at the Peralta weigh station (bottom) for 2012 and 2017 measurement years. Uncertainties are calculated from the standard error of the mean using the daily means.

Figure S7. Fuel specific gNO_x/kg of fuel by chassis model year for engines manufactured by Manufacturer C at the Cottonwood weigh station (top) for 2013, 2015 and 2017 measurement years and at the Peralta weigh station (bottom) for 2012 and 2017 measurement years. Uncertainties are calculated from the standard error of the mean using the daily means.

Figure S8. HDVs measured more than once at the Peralta weigh station in 2017. Truck number is calculated using the average gNO_x/kg of fuel for individual vehicles. The HDVs are segregated by model year: 2007 and older (black), 2008-2010 (blue), 2011-2013 (red) and 2014 and newer (purple).

Figure S9. HDV gNO_x/kg of fuel versus chassis model year for the 2017 Peralta measurements by engine manufacturer (VIN decoded). Uncertainties are standard errors of the mean calculated using the daily measurements.

Figure S10. Medium-duty fuel specific NO by measurement year in Chicago, IL. Uncertainties are standard error of the mean calculated using the daily means.

Figure S11. Medium-duty fuel specific NO_x by chassis model year for Chicago 2014 (green squares) and 2016 (blue triangles) data and 2017 Peralta data (black circles). Uncertainties are standard error of the mean calculated using the daily means.

How we estimate standard errors of the mean for our reported uncertainties:

Vehicle emissions from US vehicle fleets are not normally distributed, thus the assigning of uncertainties on fleet emission means involves a process that many readers may not be familiar with. Standard statistical methods that were developed for normally distributed populations, when used on a skewed distribution, result in uncertainties that are unrealistically too small due to the large number of samples. The Central Limit Theorem in general indicates that the means of multiple samples, randomly collected, from a larger parent population will be normally distributed, irrespective of the parent populations underlying distribution. Since we almost always collect multiple days of emission measurements from each site, we use these daily measurements as our randomly collected multiple samples from the larger population and report uncertainties based on their distribution. We calculate means, standard deviations and finally standard errors of the mean for this group of daily measurements. We report the fleet weighted means for all of the emission measurements and then calculate a standard error of this weighted mean by applying the same error percentage obtained from the ratio of the standard error of the mean for the daily measurements divided by the daily measurement mean.

An example of this process is provided below for the 2017 Peralta HDV gNO/kg of fuel measurements. While this example is for a fleet mean, we also use this technique when we report uncertainties for other statistics such as individual model years, specific fuel or technology types, and VSP. For example, each model year will have its daily means averaged and then its standard error of the mean for the daily average computed and that percent uncertainty (Daily STD Error MY/Daily MY average) will be applied to that entire model year's mean emissions.

Table S1. Example calculation of mean gNO/kg of fuel and the associated uncertainties for all HDV in 2017 at the Peralta weigh station.

Date	Daily Average gNO/kg of fuel	Number of Measurements
3/20/2017	7.92	357
3/21/2017	7.15	507
3/22/2017	6.53	454
3/23/2017	8.15	526
Average for Daily Mean	7.43	
Standard Error for Daily Mean	0.38	
Weighted Fleet Mean	7.43	
Standard Error Calculated for the Fleet Mean	0.38	
Value as reported in Table 1	7.4 ± 0.4	

Table S2. Peralta weigh station Emission Summary for Previous Measurement Years.

Study Year	1997	2008	2009	2010	2012
Mean CO/CO ₂ (g/kg of fuel)	0.008 (16.1)	0.005 (10.0)	0.005 (10.6)	0.005 (10.0)	0.004 (7.3)
Median gCO/kg	9.3	6.7	6.6	6.6	4.0
Mean HC/CO ₂ (g/kg of fuel)	0.0008 (5.0)	0.0004 (2.7)	0.0007 (4.8)	0.0007 (4.2)	0.0001 (0.6)
Median gHC/kg	3.7	2.1	2.9	2.9	1.3
Mean NO/CO ₂ (g/kg of fuel)	0.009 (19.2)	0.008 (16.4)	0.007 (15.4)	0.006 (14.7)	0.006 (11.8)
Median gNO/kg	18.0	15.2	14.3	13.5	11.5
Mean SO ₂ /CO ₂ (g/kg of fuel)	NA	0.00006 (0.26)	0.00004 (0.16)	-0.00004 (-0.22)	-0.00008 (-0.36)
Median gSO ₂ /kg	NA	0.22	0.11	-0.2	-0.28
Mean NH ₃ /CO ₂ (g/kg of fuel)	NA	0.00003 (0.03)	0.00002 (0.003)	0.000007 (0.008)	0.00002 (0.02)
Median gNH ₃ /kg	NA	0.02	0.016	0.006	0
Mean NO ₂ /CO ₂ (g/kg of fuel)	NA	0.0006 (2.1)	0.0006 (1.9)	0.0005 (1.9)	0.0005 (1.8)
Median gNO ₂ /kg	NA	1.6	1.4	1.4	1.4
Mean / Median gNO _x /kg	NA	27.3 / 25.2	25.4 / 23.6	24.5 / 22.3	19.9 / 19.1
Mean/Median IR %Opacity	2.5 / 1.9	0.73 / 0.6	0.73 / 0.6	0.68 / 0.6	0.69 / 0.5
Mean Model Year	NA	2000.4	2001.3	2002.0	2004.0
Mean Speed (mph)	NA	13.4	13.5	13.4	13.9
Mean Acceleration (mph/s)	NA	1.1	0.9	0.8	1.1
Mean VSP(kw/tonne)	NA	6.3	5.8	4.9	6.6
Slope (degrees)	1.8°	1.8°	1.8°	1.8°	1.6°

Table S3. Chicago Historical Mean Fuel Specific Emissions for Diesel and Gasoline Medium-duty Vehicles

Measurement Year	gCO/kg ^a	gHC/kg ^b	gNO/kg ^c	Vehicles	Fuel
1997	33.9 ± 4.6	6.2 ± 1.5	18.7 ± 0.9	72	D
1998	48.5 ± 16.6	16.3 ± 6.1	15.6 ± 0.4	90	D
1999	20.2 ± 3.8	4.4 ± 1.9	18.5 ± 1.4	114	D
2000	14.6 ± 1.3	1.9 ± 1.6	16.6 ± 0.6	122	D
2002	16.3 ± 2.1	1.9 ± 0.6	17.7 ± 1.3	93	D
2004	13.5 ± 3.3	3.3 ± 2.1	18.7 ± 0.7	114	D
2006	10.7 ± 0.6	0.3 ± 1.3	15.9 ± 0.6	108	D
2014	-0.4 ± 0.5	5.0 ± 1.1	16.0 ± 1.5	81	D
2016	6.8 ± 2.2	1.2 ± 1.7	13.0 ± 1.3	142	D
1997	109.4 ± 16.4	7.8 ± 3.1	13.5 ± 1.3	30	G
1998	153.7 ± 59.5	14.1 ± 7.3	11.4 ± 3.1	25	G
1999	108.0 ± 44.8	8.6 ± 7.4	15.3 ± 1.8	38	G
2000	96.2 ± 36.6	10.3 ± 10.0	10.3 ± 10.0	20	G
2002	18.1 ± 10.8	-1.5 ± 0.7	2.7 ± 1.1	20	G
2004	48.3 ± 12.4	1.4 ± 1.7	6.8 ± 3.0	26	G
2006	50.1 ± 25.2	6.0 ± 2.2	3.0 ± 1.8	17	G
2014	80.8 ± 41.7	23.9 ± 13.4	9.6 ± 3.6	19	G
2016	7.7 ± 10.3	-0.5 ± 0.4	2.8 ± 1.7	41	G

^a Calculated using a carbon mass fraction of 0.86 for both fuels and uncertainties are calculated using the daily means.

^b HC grams of propane expressed using an NDIR to FID correction factor of 2 and means are offset normalized as described in Bishop and Haugen, Environ. Sci. Tech., 25:7587-7593, 2018.

^c grams of NO



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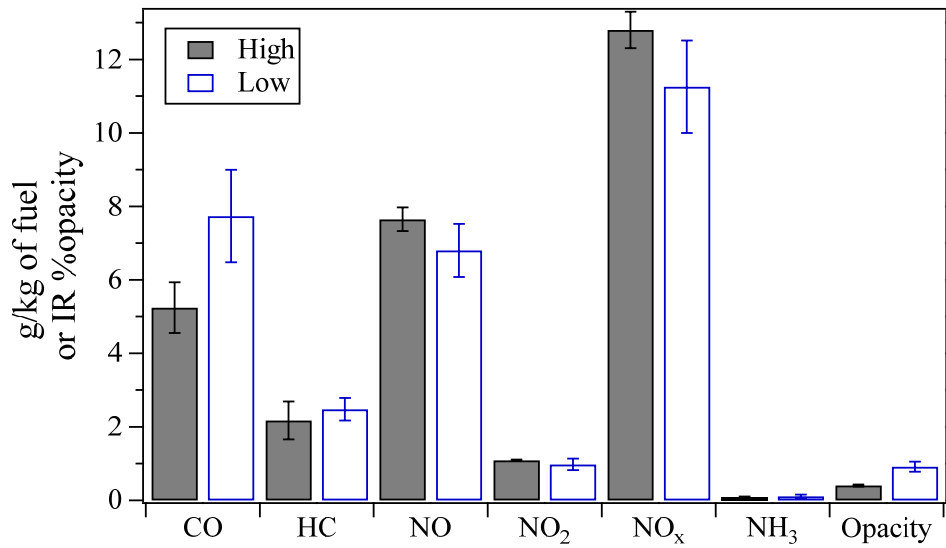


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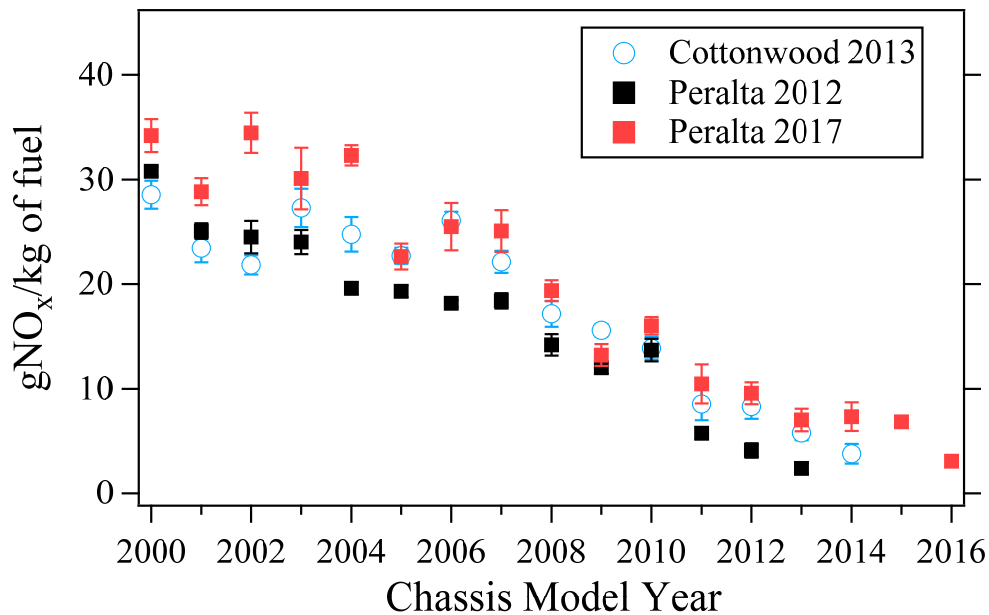


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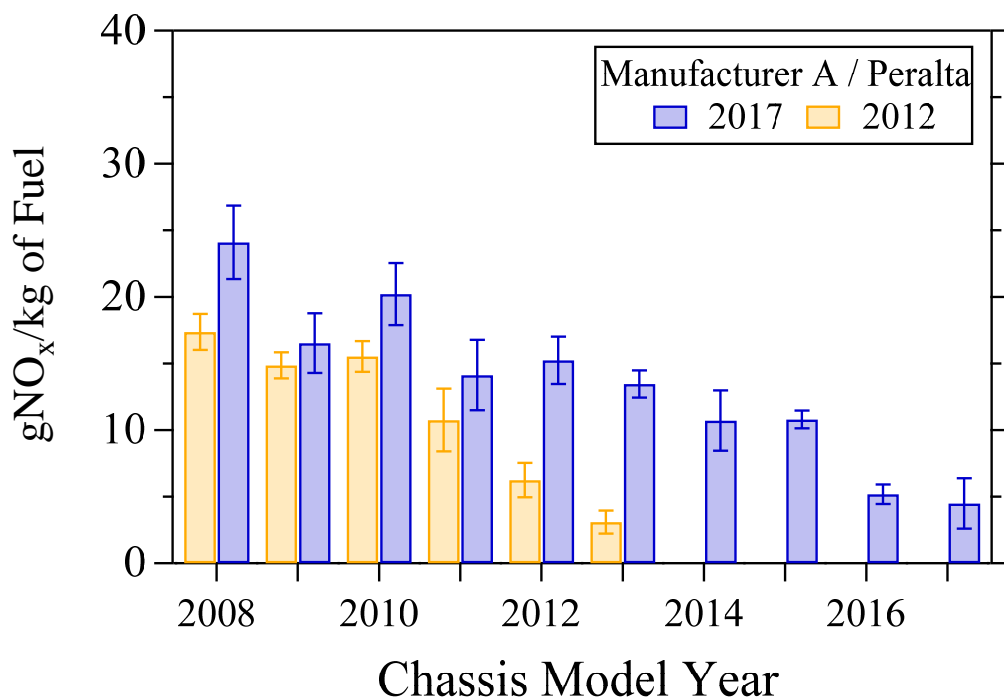
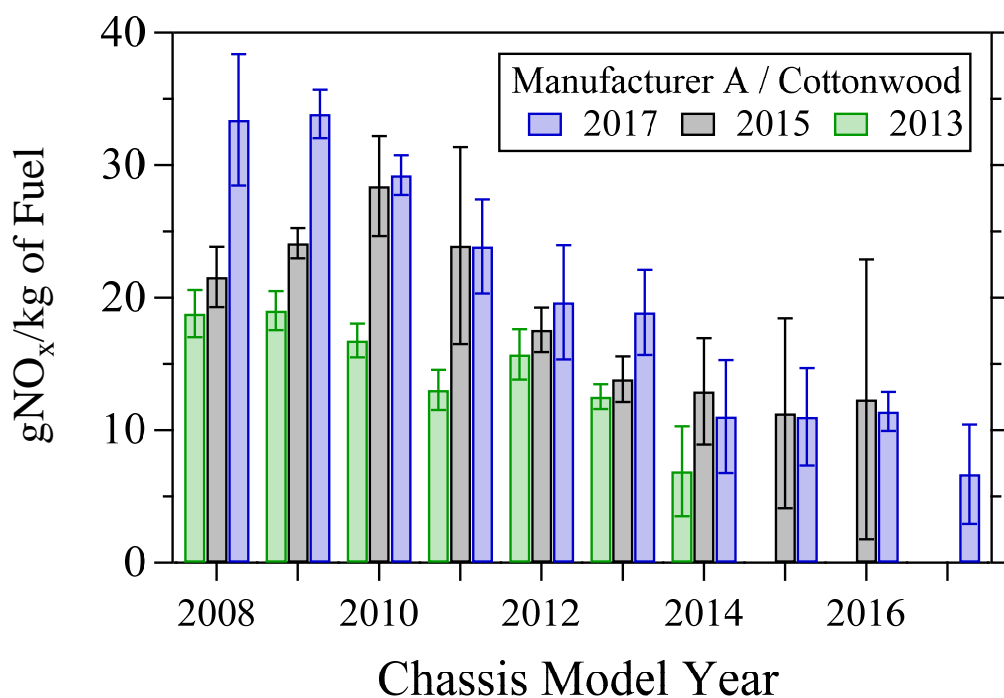


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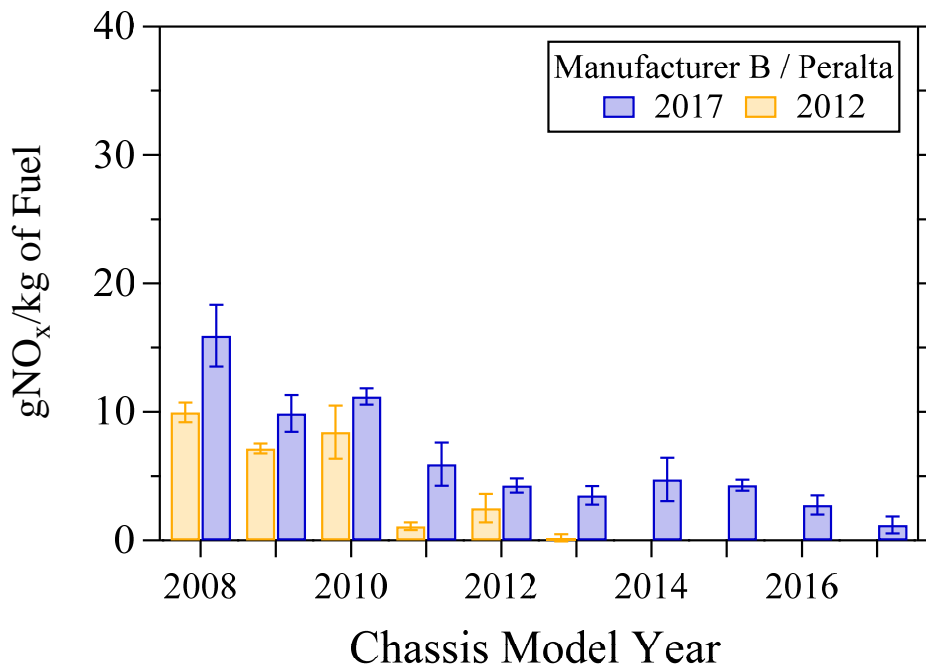
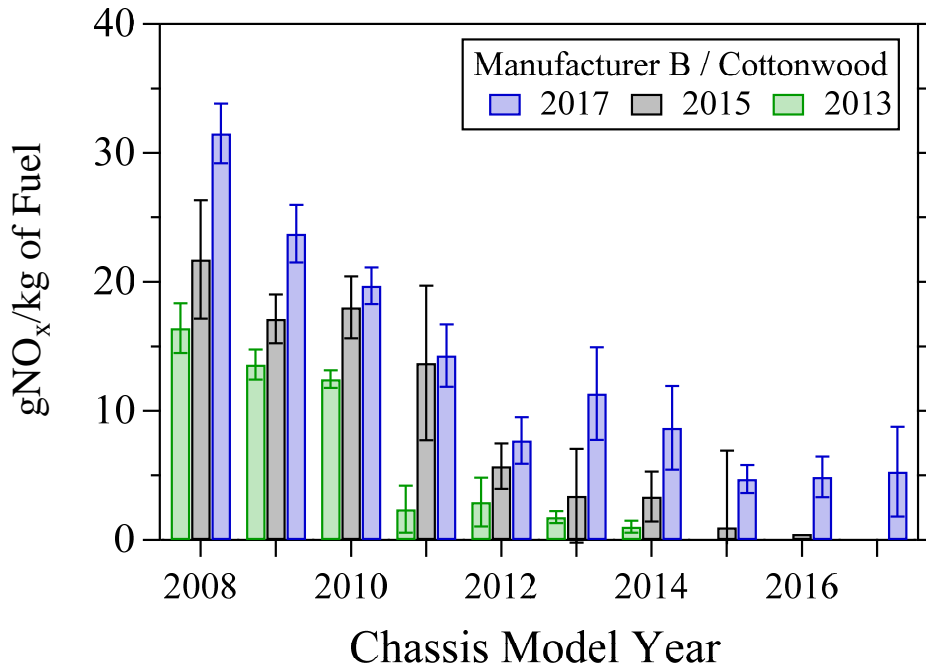


Figure S6. Fuel specific gNO_x/kg of fuel by chassis model year for engines manufactured by Manufacturer B at the Cottonwood weigh station (top) for 2013, 2015 and 2017 measurement years and at the Peralta weigh station (bottom) for 2012 and 2017 measurement years. Uncertainties are calculated from the standard error of the mean using the daily means.

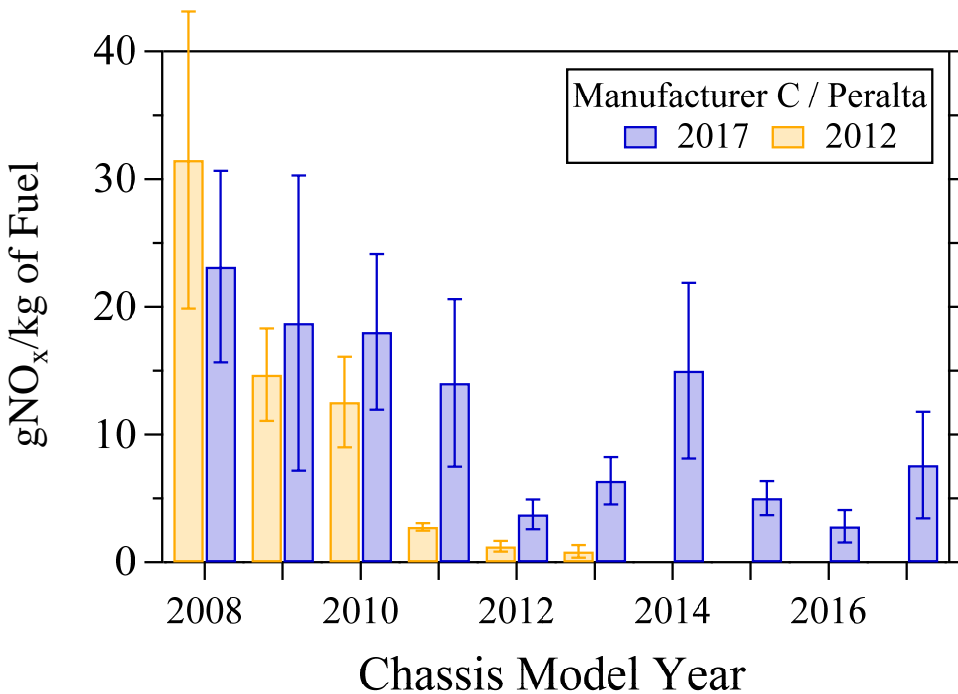
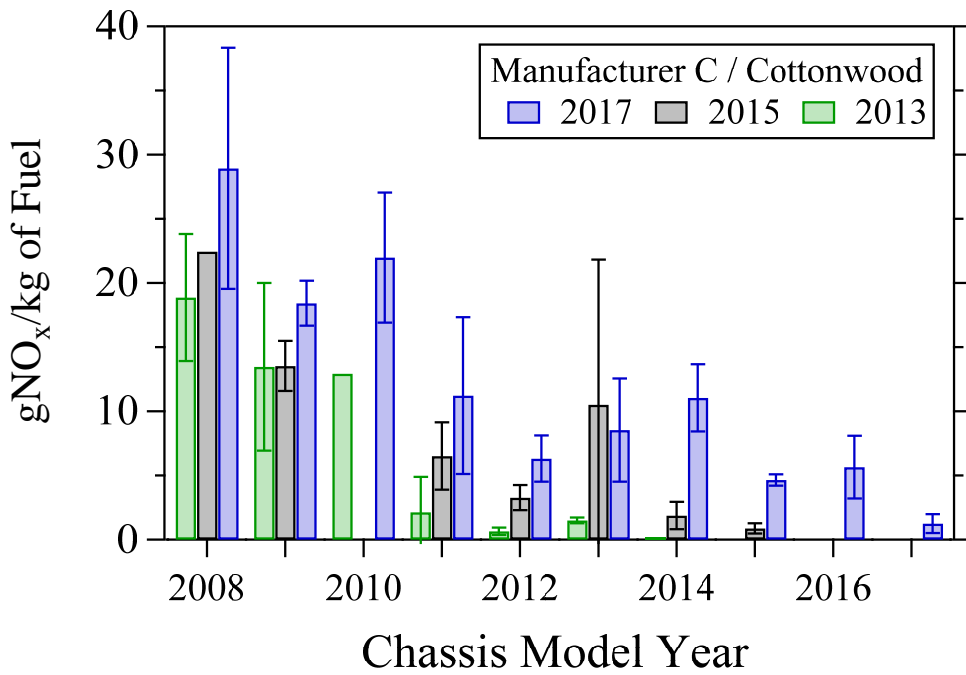


Figure S7. Fuel specific gNO_x/kg of fuel by chassis model year for engines manufactured by Manufacturer C at the Cottonwood weigh station (top) for 2013, 2015 and 2017 measurement years and at the Peralta weigh station (bottom) for 2012 and 2017 measurement years. Uncertainties are calculated from the standard error of the mean using the daily means.

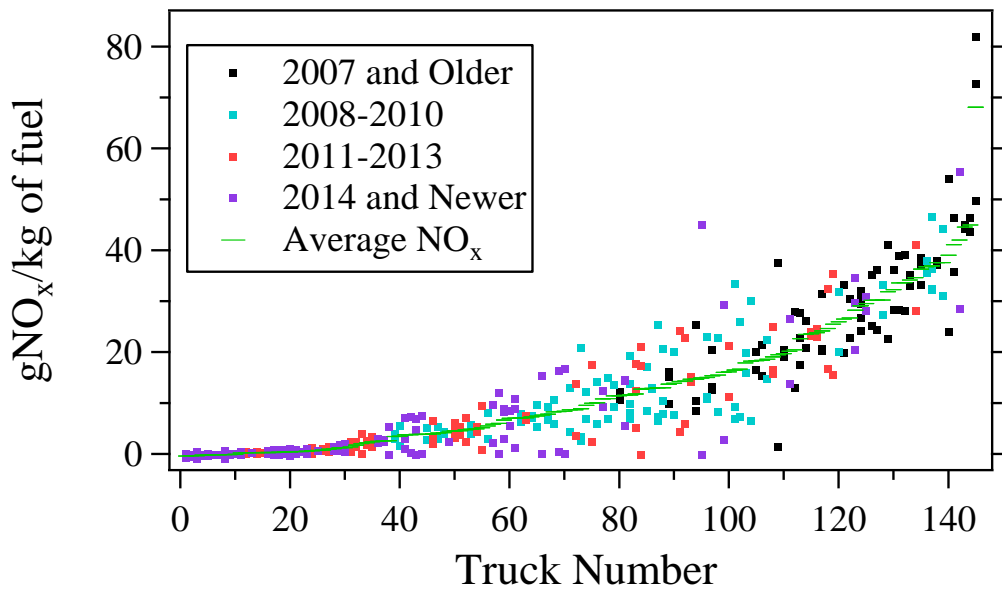


Figure S8. HDVs measured more than once at Peralta weigh station in 2017. Truck number is calculated using the average gNO_x/kg of fuel for individual vehicles. The HDVs are segregated by model year: 2007 and older (black), 2008-2010 (blue), 2011-2013 (red) and 2014 and newer (purple).

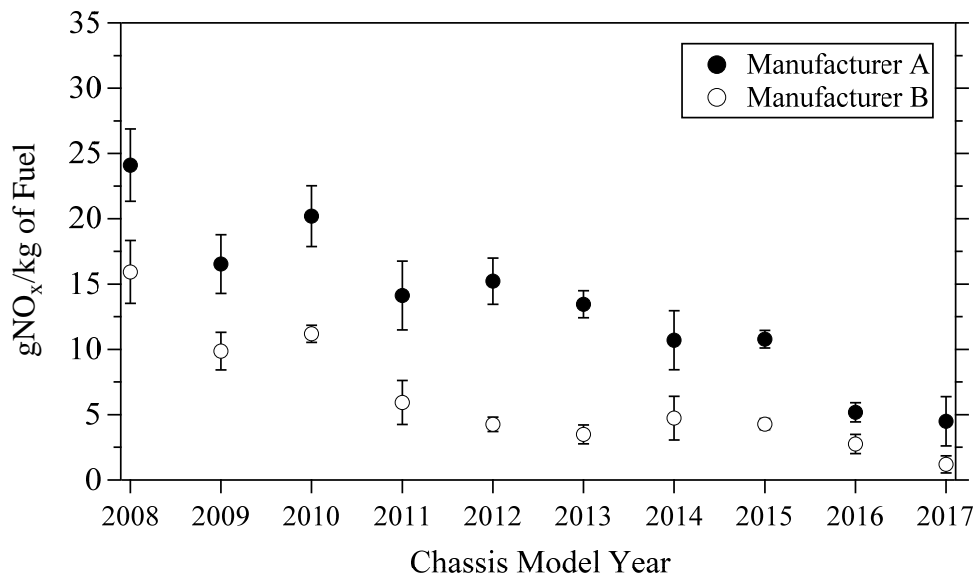


Figure S9. HDV gNO_x/kg of fuel versus chassis model year for the 2017 Peralta measurements by engine manufacturer (VIN decoded). Uncertainties are standard errors of the mean calculated using the daily measurements.

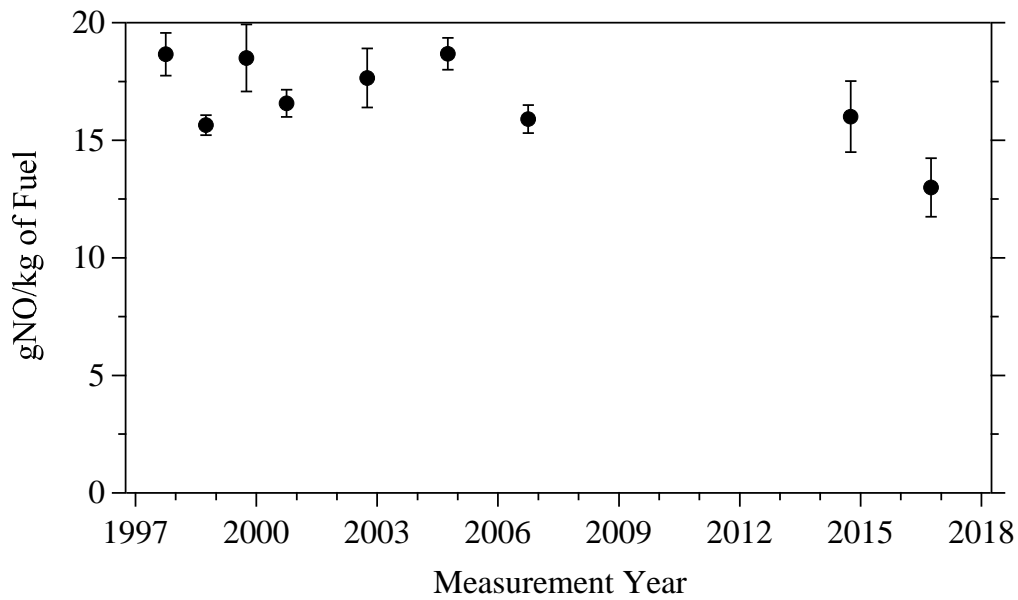


Figure S10. Medium-duty mean fuel specific NO by measurement year in Chicago, IL. Uncertainties are standard error of the mean calculated using the daily means.

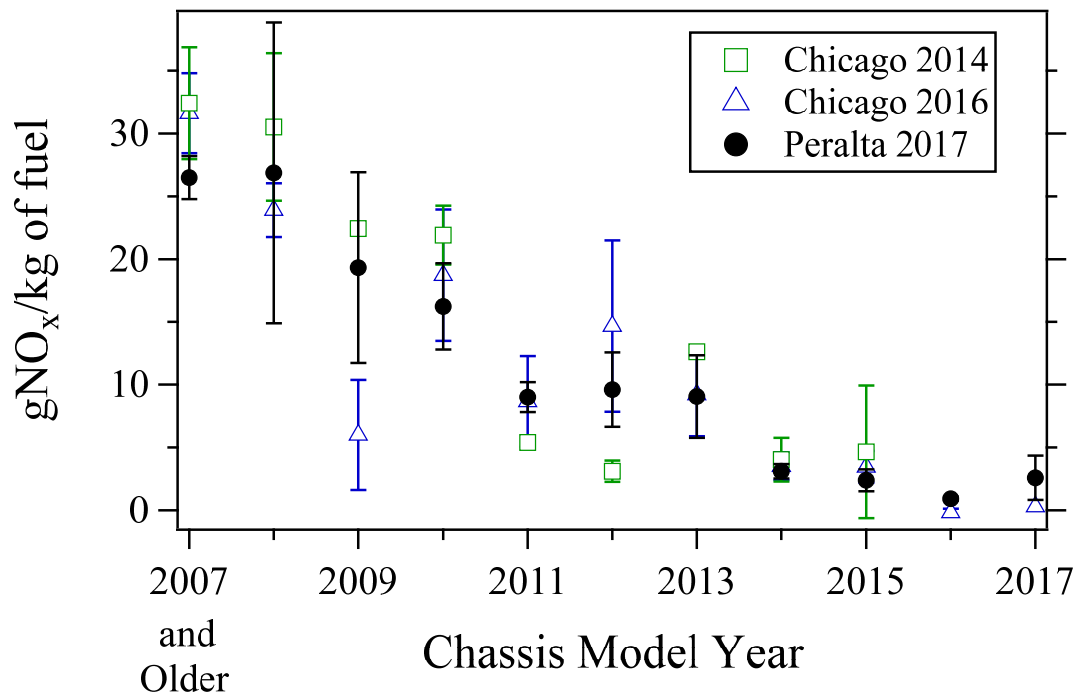


Figure S11. Medium-duty fuel specific NO_x by chassis model year for Chicago 2014 (green squares) and 2016 (blue triangles) data and 2017 Peralta data (black circles). Uncertainties are standard error of the mean calculated using the daily means.