2018

On-Road Remote Sensing of Heavy and Medium-duty Trucks at the Peralta Weigh Station in the South Coast Air Basin: Spring 2017

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June 2018

Executive Summary

The University of Denver conducted a four day emissions study at the Peralta weigh station on state route 91 in Southern California on both medium and heavy-duty vehicles using FEAT, a remote sensing device. Ratios of pollutants to carbon dioxide are measured and recorded for each individual vehicle that passes through the setup. Fuel specific emission information is calculated from these ratios for carbon monoxide, total hydrocarbons, nitric oxide (NO), nitrogen dioxide (NO_2), ammonia (NH_3) and infrared (IR) %opacity. Total oxides of nitrogen (NO_x) is calculated by adding NO as NO_2 and NO_2. This study adds to five previous measurements collected at this location in 1997, 2008, 2009, 2010 and 2012 shedding light on how truck emissions have changed with the introduction of the different after-treatment systems. The data is also used to show how current on-road vehicles comply with their model year specific certification standards year after year.

A total of 1,844 HDVs were measured in the four days of measurements. One FEAT sensor was placed on top of scaffolding to measure elevated exhaust vehicles (High FEAT), and a second FEAT unit was placed on the road the last three days of the campaign to capture low exhaust (Low FEAT) vehicles. The Low FEAT captured ~30% of the HDVs that passed through each day, contributing to a significant increase in vehicles measured from previous years. Compared to previous fleets at this locations, the 2012 fleet, which was comprised solely of elevated exhaust, had a model year average of 2004.0, but in 2017, the fleet model year average was 2011.1, meaning the fleet age was 2.9 years newer in 2017 than 2012.

Figure ES1 shows the fleet average gNO_x/kg of fuel (black bars, left axis) and IR %opacity (grey bars, right axis) for all years Peralta trucks have been measured. Uncertainties are standard errors of the mean calculated using the daily means. NO is plotted as grams of NO_2 with the total bar height equal to total fuel specific NO_x emissions. The fuel specific NO has decreased 61% from 1997 (NO_2 was not measured until the 2008 campaign) which is a year over year reduction of -3.9%/year. However, only ~7% of the overall reduction occurred between the 1997 and the 2008 measurements. Since 2008 emissions have experienced NO_x reductions of ~54% and an increased year over year reduction of -8.7%/year. The increased rate of reductions coincides with the introduction of selective catalytic reduction (SCRs) systems. Beginning with the 2012 measurements a growing percentage of HDVs with SCRs have entered the fleet and fleet NO_x emissions have continued to decrease.

IR %opacity has also experienced significant reductions with the largest reductions (~70%) occurring between the 1997 and the 2008 campaigns. This of course corresponded with an emphasis to reduce soot emissions culminating with the introduction of the first diesel particulate filters (DPFs) into the heavy-duty truck fleet. Since 2008, the fleet opacity average did not significantly change until the 2017 campaign, which had a further decrease of 14% from the 2012 fleet mean and is close to the values observed for the fully DPF equipped 2012 Port of Los Angeles fleet indicating that the Peralta weigh station fleet is also now fully DPF equipped. NO_2 emissions

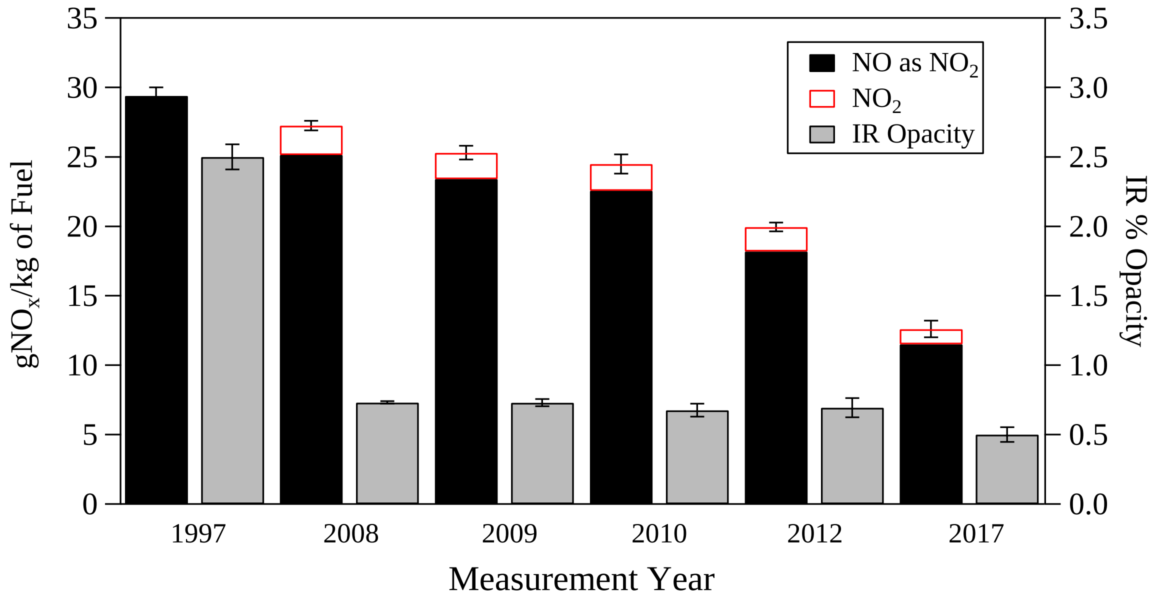

Figure ES1. Infrared %opacity (grey bars, right axis) for High FEAT only and NO as NO_2 equivalents (black bars, left axis), gNO_2 (open red bars, left axis) and gNO_x/kg of fuel (total bar height, left axis) by measurement year. Uncertainties are standard errors of the mean calculated from the daily means.

which increased in model years 2008 – 2010 as a result of first generation catalyzed DPFs have continued reductions seen in the 2012 measurements as these older catalysis lose their ability to oxidize engine out NO emissions.

With the increase use of SCRs there is an apparent influence on tailpipe NH_3. Ammonia emissions were near zero in 2012 (2011 model year and newer vehicles only accounted for 14.6% of the measurements) for all model years and SCR systems were scarce, whereas by 2017 there is a significant increase in NH_3 (mean of 0.09 gNH_3/kg of fuel) for model year 2011 and newer, which now accounts for 63% of the heavy-duty vehicles.

Along with HDVs, medium-duty vehicles (MDVs) were measured for the first time at the Peralta weigh station with the Low FEAT instrument. This now represents one of the largest emissions datasets for medium-duty vehicles (gross vehicle weight 14001-26000 lbs). On average, the model year for these MDVs was 2009.6, a year and a half older than the HDV fleet. Figure ES2 shows the apportionment of NO as NO_2 equivalent (open bars), NO_2 (solid and striped bars) and total NO_x (total bar height) by model year for MDVs (blue) and HDVs (black). Uncertainties are standard error of the mean calculated using the daily means. Both the MDVs and HDVs saw nearly identical percentage reductions in NO_x emissions from 2007 and older model year vehicles to model year 2017 (90% versus 88%). The 2017 model year MDVs had an average of 2.6 gNO_x/kg of fuel, and the average for HDVs was 3.4 gNO_x/kg of fuel. If it is assumed that 0.15 kg of fuel is consumed per bhp-hr, the newest on-road HDVs are still roughly two and a half times the certification standard and MDVs are about two times the 0.2 gNO_x/bhp-hr standard.[1]

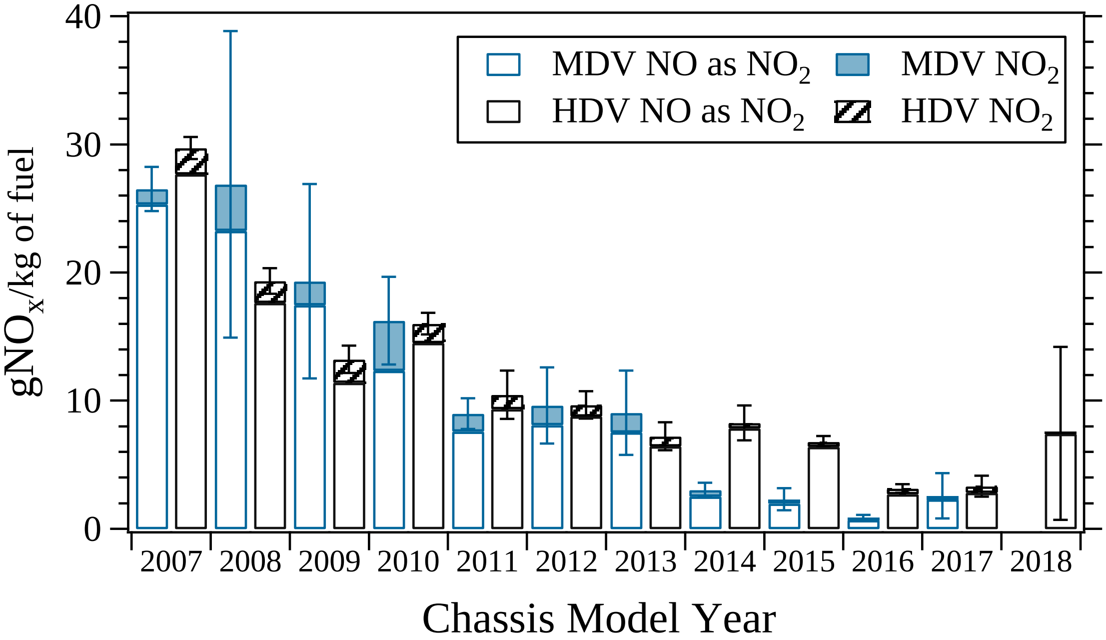

Figure ES2. Total gNO_x/kg of fuel (total bar height) for MDVs (blue) and HDVs (black) vehicles. Mean gNO_2/kg of fuel (solid or hatched) and gNO/kg of fuel as gNO_2/kg of fuel (open bars) as graphed by chassis model year. Uncertainties are standard error of the mean calculated using the daily means.

Introduction

The United States Environmental Protection Agency (EPA) has recently mandated stricter emissions standards for diesel on-road heavy-duty vehicles (HDVs) with the program represented in Table 1.[2] The standards are specifically for reduction of particulate matter (PM), non-methane hydrocarbons (NMHC), and oxides of nitrogen (NO_x). However, beginning in 2007 most diesel engine manufacturers opted to meet a Family Emission Limit (FEL) with EPA allowing engine families with FEL's exceeding the applicable 2007 NO_x standard to obtain emission credits for post 2010 engines through averaging, trading and/or banking. This allowed for some diesel engine manufacturers to meet 2010+ NO_x standards with engines that do not meet a rigid 0.2 g/bhp-hr limit subsequent to the 2010 model year.

Table 1. The 2007 EPA Highway Diesel Program.

Species	Standard (g/bhp-hr)	Phase-In by Model Year			
		2007	2008	2009	2010
NO_x	0.2	50%	50%	50%	100%
NMHC	0.14				
PM	0.01	100%	100%	100%	100%

In California the National EPA Highway Diesel Program is a part of a number of new regulations that will continue to be implemented over the next few years. The San Pedro Bay Ports Clean Air Action Plan (CAAP) banned all pre-1989 model year trucks starting in October 2008. For all of the remaining drayage trucks at the Ports of Los Angeles and Long Beach it further required them to meet National 2007 emission standards by 2012. This requirement applies to all trucks, including interstate trucks, which move containers into the South Coast Air Basin and beyond.

The California Air Resources Board (CARB) also implemented a Drayage Truck Regulation that required by the end of 2009 that all pre-1994 engines be retired or replaced and all 1994 to 2008 engines must meet an 85% PM reduction. By the end of 2013 all drayage trucks in the state had to meet the 2007 emission standards. This rule applied to all trucks with a gross vehicle weight rating of 33,000 pounds or more that move through ports or intermodal rail yard properties for the purposes of loading, unloading or transporting cargo.[3] In addition, CARB's Statewide Truck and Bus Regulations phased in most PM requirements for all trucks between 2011 and 2014 and will phase in 2010 NO_x emission standards between 2013 and 2023.[4]

Before advanced aftertreatment systems, control of NO_x and PM emissions were constrained to engine operations that traded-off the control of these two pollutants. However, advanced control and after-treatment technologies deployed in the post-2007 timeframe for compliance with the U.S. EPA and CARB heavy-duty engine emission standards do not experience this NO_x/PM trade-off. These advanced technologies include a combination of diesel particle filters (DPFs), selective catalytic reduction systems (SCRs), and advanced exhaust gas recirculation (EGR) control strategies. DPFs are typically ceramic size exclusion filters that work by physically intercepting particles from engine out exhaust and preventing them from escaping in the atmosphere.[5] SCRs specifically targets NO_x emissions by thermalizing urea to generate ammonia (NH_3) to reduce NO_x (NO + NO_2) to nitrogen and water.[6]

The site measured in this study, the Peralta weigh station, is located on the eastbound 91 freeway in the Anaheim Hills in southern California and is trafficked by long-haul and local HDVs and medium-duty vehicles (MDVs). Measurements on HDVs were first collected in 1997 at this location and with the current measurements reported on in this report will form one of the longest emissions measurement records (20 years now) for HDVs in the US. The new data collected in the spring of 2017 allows for the continuing evaluation of emission trends for HDVs, and for the first time a detailed study of MDV emissions both of which are subject to the current California standards.

Experimental

The FEAT remote sensors used in this study were developed at the University of Denver for measuring the pollutants in motor vehicle exhaust, and have previously been described in the literature.[7-9] The instrument consists of a non-dispersive infrared component for detecting carbon monoxide (CO), carbon dioxide (CO_2), total hydrocarbons (HC), and percent opacity, and two dispersive ultraviolet (UV) spectrometers for measuring nitric oxide (NO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and NH_3. The source and detector units are positioned on opposite sides of the road in a bi-static arrangement. Collinear beams of infrared (IR) and UV light are passed across the roadway into the IR detection unit, and are then focused onto a dichroic beam splitter, which serves to separate the beams into their IR and UV components. The IR light is then passed onto a spinning polygon mirror, which spreads the light across the four IR detectors: CO, CO_2, HC, and reference (opacity is determined by plotting reference vs. CO_2). The UV light is reflected off the surface of the beam splitter and is focused onto the end of a quartz fiber-optic cable, which transmits the light to dual UV spectrometers. The UV spectrometers are capable of quantifying NO, SO_2, NH_3 and NO_2 by measuring absorbance bands in the regions of 200 - 226 nm and 429 - 446 nm respectively, in the UV spectrum and comparing them to calibration spectra in the same regions.

The exhaust plume path length and density of the observed plume are highly variable from vehicle to vehicle, and are dependent upon, among other things, the height of the vehicle's exhaust pipe, exhaust volume, wind, and turbulence behind the vehicle. For these reasons, the remote sensor directly measures only ratios of CO, HC, NO, NO_2, NH_3, SO_2 to CO_2. Appendix A provides a list of the criteria for valid/invalid data. These measured ratios can be converted directly into grams of pollutant per kilogram of fuel. This conversion is achieved by first converting the pollutant ratio readings to the moles of pollutant per mole of carbon in the exhaust from the following equation:

$$\frac{\text{moles pollutant}}{\text{moles C}} = \frac{\text{pollutant}}{CO + CO_2 + 3HC} = \frac{(\text{pollutant}/CO_2)}{(CO/CO_2) + 1 + 6(HC/CO_2)} = \frac{(Q,\ 2Q',\ Q'')}{Q+1+2*3Q'}$$

Q represents the CO/CO_2 ratio, Q' represents the HC/CO_2 ratio and Q" represents the NO/CO_2 ratio. Next, moles of pollutant are converted to grams by multiplying by molecular weight (e.g., 44 g/mole for HC since propane is the calibration species), and the moles of carbon in the exhaust are converted to kilograms by multiplying (the denominator) by 0.014 kg of fuel per mole of carbon in fuel, assuming the fuel is stoichiometrically CH_2. The HC/CO_2 ratio uses a factor of two (Singer factor) times the reported HC because the equation depends upon carbon mass balance and the NDIR HC reading only quantifies about half a total carbon FID reading.[10] For natural gas vehicles the appropriate factors for CH_4 are used along with a Singer factor of 3.13. Grams per kg fuel can be approximately converted to g/bhp-hr by multiplying by a factor of 0.15 based on an average assumption of 470 g CO_2/bhp-hr.[11]

The FEAT detectors were calibrated, as external conditions warranted, from certified gas cylinders containing known amounts of the species that were tested. This ensures accurate data by correcting for ambient CO_2 levels, temperature, instrument drift, etc. with each calibration. Because of the reactivity of NO_2 with NO and NH_3 with CO_2, three separate calibration cylinders are needed: 1) 6% CO, 6% CO_2, 0.6% propane (HC), 0.3% NO and N_2 balance; 2) 0.05% NO_2, 15% CO_2 and air balance; 3) 0.1% NH_3, 0.6% propane and balance N_2. Since fuel sulfur has been nearly eliminated in all US fuels, SO_2 emissions are generally below detection limits. While vehicle SO_2 measurements are routinely collected and archived for each data campaign, since 2012 we have not calibrated these measurements and they are not included in the discussion of the results.

For the first time, two FEAT instruments were used concurrently in this campaign. One was 14'3" above the ground to capture elevated exhaust plumes (High FEAT), while a second FEAT instrument was placed on the pavement to collect emission data for low exhaust vehicles (Low FEAT). These two FEAT devices had different triggers for data collection. The High FEAT was triggered when a vehicle passed through an IR body sensor which started 1 second of data collection. The Low FEAT was triggered conventionally when a vehicle's tire passed through the Low FEAT IR beam, causing the reference signal to be blocked, and half a second of data was collected for each Low FEAT measurement. The Low FEAT uses a shorter sampling time in order to complete the sampling before the rear trailer wheels interrupt the measurements.

The FEAT remote sensors were accompanied by a video system that records a freeze-frame image of the license plate of each vehicle measured. The emissions information for the vehicle, as well as a time and date stamp, is also recorded on the video image. The images are stored digitally, so that license plate information may be incorporated into the emissions database during post-processing. A device to measure the speed and acceleration of vehicles driving past each remote sensor was also used in this study. The system consists of a pair of infrared emitters and detectors (Banner Industries) which generate a pair of infrared beams passing across the road, six feet apart and approximately four feet above the surface. Vehicle speed is calculated from average of two times collected when the front of the tractors cab blocks the first and the second beam and the rear of the cab unblocks each beam. From these two speeds, and the time difference between the two speed measurements, acceleration is calculated, and reported in mph/s. Appendix B defines the database format used for the data set.

Vehicles at this location have been measured since 1997, with six completed campaigns to date: 1997, 2008, 2009, 2010, 2012 and 2017 (see Appendix C for emissions summary of previous campaigns).[12] The 2017 data were collected similarly to the previous measurements, but with the addition of the Low FEAT. In 2017, data was collected over four days in March (20-23) from 8:00 to 14:00 on the lane reentering Highway 91 eastbound (SR-91 E) after the trucks had been weighed. Sampling took place in the exact location used for all of the previous campaigns on the single lane at the end of the station where trucks were reentering the highway. Most trucks were traveling between 10 and 20 mph in an acceleration mode to regain speed for the upcoming highway merger. This weigh station is located just west of the Weir Canyon Road exit (Exit 39).

A satellite photo showing the weigh station grounds and the approximate location of the scaffolding and FEAT instruments are shown in Figure 1. High FEAT was setup for all measurement days, whereas Low FEAT was operational for the last three days. The High FEAT detectors were positioned on clamped wooden boards atop aluminum scaffolding at an elevation of 13’3”, making the IR/UV beams and detectors at an elevation of 14’3” (see Figure 2). The scaffolding was stabilized with three wires arranged in a Y shape. A second set of scaffolding was set up directly across the road on top of which the IR/UV light source was positioned. The Low FEAT unit was setup on the ground just to the east of the scaffolding towers. Behind the detector scaffolding was the University of Denver’s mobile lab housing the auxiliary instrumentation (computers, calibration gas cylinders and generator). Speed bar detectors were attached to each scaffolding unit which reported truck speed and acceleration for the High FEAT and on tripods just after the Low FEAT. Three video cameras were placed down the road from the scaffolding, taking pictures of license plates, urea tanks and an IR image of exhaust pipes when triggered.

Exhaust thermographs were taken with an infrared camera (Thermovision A20, FLIR Systems) for qualitatively estimating the exhaust temperatures of the trucks with elevated exhaust pipes leaving the weigh station and remote controlled digital pictures of the truck’s driver side for investigating the presence of urea tanks. Both video systems were successfully operated with the IR camera system capable of imaging the exhaust systems for a majority of the trucks that had elevated exhaust systems, and a field-calibration of this IR camera allows for these images to be converted into temperatures.[13] Figure 3 shows a sample picture of a truck leaving the Port of Los Angeles, CA where the pipe is clearly visible and from which we were able to estimate an exhaust temperature.[14]

Figure 2. 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 1. Photograph at the Peralta Weigh Station of the setup used to detect exhaust emissions from heavy-duty diesel trucks.

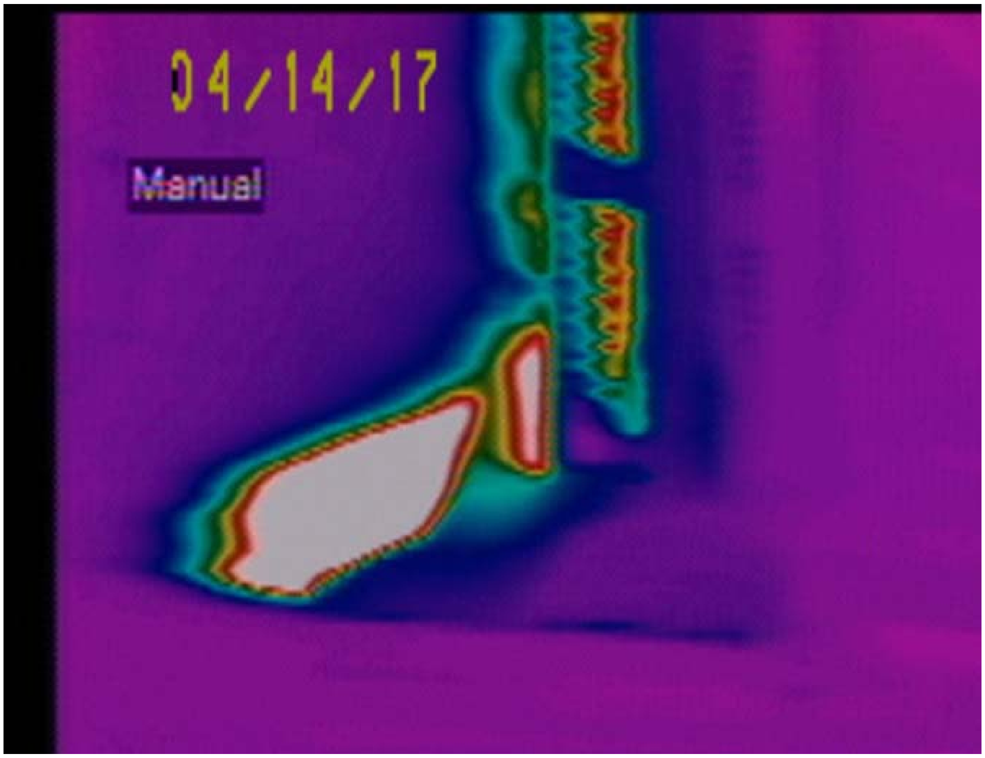

Figure 3. Thermographic image of an elevated HDV exhaust pipe. The relative scale is from ambient temperatures (the purple) to approximately 150° C for the bright red.

There currently are no emissions control equipment information provided through either vehicle registration or VIN data. With the advent of SCR systems being added to many new heavy-duty diesel trucks we have observed that the urea tanks accompanying these systems often have large blue caps visible on the driver's side of the truck. To attempt to identify trucks that have urea tanks, we setup on a tripod a consumer grade Canon digital camera that could be remotely triggered by a computer controlled garage door opener to take pictures of the driver side of the truck chassis. These images were manually reviewed afterwards to identify trucks that are equipped with a urea tank and by association some type of SCR system. Figure 4 shows an example of what these images looked like with a truck that is equipped with a urea tank.

Results and Discussion

The 2017 Peralta weigh station campaign resulted in 2315 measurements from HDVs (1844) and MDVs (471). The two vehicle classifications used for this report have been separated by gross vehicle weight > 26001 lbs. for HDVs and 14001-26000 lbs. for MDVs. Matched licenses for HDVs and MDVs by state are shown in Table 2, and Table 3 provides a summary of fleet emission averages for the High and Low FEATs as well as the entire HDV and MDV fleets. The mean emission ratios to CO_2 are shown as well as mean and median g/kg of fuel emissions for CO, HC, NO, NO_2, NO_x, NH_3, IR %opacity, and average model year, speed (mph), acceleration (mph/s), vehicle specific power (VSP) and the road slope (degrees).

Figure 4. Driver side image of a HDV with the urea tank clearly visible.

Table 2. Number of matched licenses for HDVs and MDVs by state.

State	Unique HDV	Unique MDV
AR	2	0
AZ	42	1
CA	1199	428
CO	2	0
GA	1	0
IA	1	0
IL	39	0
IN	141	5
NI	1	0
MN	1	0
NC	2	0
NE	3	0
OH	8	0
OK	9	0
OR	13	0
PA	1	0
TX	22	0
UT	1	0
WA	3	0
WI	4	0
British Columbia	4	0
Total Matched	1499	434

Table 3. Peralta weigh station data summary for 2017.

FEAT Number of Measurements	High 1408	Low 907	All HDV 1844	All MDV 471
Mean CO/CO_2 (g/kg of fuel)	0.003 (5.5)	0.006 (10.0)	0.003 (5.9)	0.006 (11.0)
Median gCO/kg	2.7	6.9	3.0	7.6
Mean HC/CO_2 (g/kg of fuel)	0.0004 (2.1)	0.0003 (1.9)	0.0004 (2.2)	0.0002 (1.03)
Median gHC/kg	1.3	0.8	1.3	0.6
Mean NO/CO_2 (g/kg of fuel)	0.004 (7.8)	0.004 (7.6)	0.004 (7.4)	0.004 (8.8)
Median gNO/kg	4.2	3.2	3.7	5.9
Mean NH_3/CO_2 (g/kg of fuel)	0.00007 (0.08)	0.0005 (0.06)	0.00008 (0.09)	0.000003 (0.002)
Median gNH_3/kg	0.01	0.02	0.01	0.01
Mean NO_2/CO_2 (g/kg of fuel)	0.0003 (1.1)	0.0003 (1.0)	0.0003 (1.1)	0.0003 (1.1)
Median gNO_2/kg	0.5	0.4	0.5	0.5
Mean gNO_x/kg Median gNO_x/kg	13.0 7.3	12.5 5.4	12.4 6.5	14.5 10.0
Mean IR %Opacity Median IR %Opacity	0.4 0.3	0.9 0.8	0.5 0.3	0.9 0.7
Mean Model Year	2010.7	2010.7	2011.0	2009.6
Mean Speed (mph)	14.0	15.2	14.0	15.8
Mean Acceleration (mph/s)	0.7	0.2	0.7	0.2
Mean VSP(kw/tonne) Slope (degrees)	4.7 1.6°	4.0 1.6°	4.7 1.6°	4.5 1.6°

2017 Heavy-duty Vehicles

There were 1368 HDVs measured with the High FEAT over four days and 476 HDVs measured with the Low FEAT over the course of 3 days. Approximately 30% of the HDVs measured over the last three days had low exhaust. The mean emission ratios to CO_2 are shown in Table 4 for solely HDVs in 2017 for the High and Low FEAT as well as mean and median g/kg of fuel emissions for CO, HC, NO, NO_2, NO_x, NH_3, IR %opacity, and average model year, speed (mph), acceleration (mph/s), vehicle specific power (VSP) and the road slope (degrees). The Low FEAT's NO_x average is 12% lower than the High FEAT, a result of the newer HDVs measured with SCR systems. 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 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 (see Appendix A) is more stringent on the lower values with a fixed percent error criteria and that is likely why the Low FEAT IR %opacity was 2.25 times the average opacity of the High FEAT for the HDVs. Figure 5 shows the comparison of the HDV fleet mean emission measurements for CO, HC, NO, NO_2, NO_x, NH_3 and IR %opacity between those measured with the High (blue filled bars) and Low (open black bars) FEAT setups.

California trucks are known to be under more stringent regulations for vehicles operating within the state; Table 5 compares California HDVs with out-of-state HDVs for CO, HC, NO, NO_2, NO_x, NH_3, IR %opacity and model year differences. Noticeably, the out-of-state vehicles, albeit much fewer, are 3.5 model years newer than the California HDVs measured, which corresponds with a 46% decrease in NO_x emissions. The newer non-Californian vehicles are more likely to have an SCR installed, meaning urea is being used, which could also explain the out-of-state HDVs having higher (186%) average fuel specific NH_3 emissions.

The overall fleet averages (grey bars) for all of the HDVs measured at Peralta are shown in Figure 6 for fuel specific CO, HC, NO, NO_x (all on the left axis), NO_2, NH_3 and IR %opacity (right axis). NO means are plotted as grams of NO while NO_2 and NO_x means are plotted as grams of NO_2. The fleet has also been segregated to compare the few natural gas vehicle (NGV) emissions (open blue bars) to the diesel fleet (red striped bars). Uncertainties are standard errors of the mean calculated from the daily means. The NGV averages are elevated, especially for CO, HC and NH_3 (a consequence of stoichiometric combustion and 3-way catalytic converters with available hydrogen for reducing NO emissions); however, there were only a small number of LNG vehicles in the entire fleet (21 out of 1844 HDVs). Unless noted, the entire fleet, including NGV vehicles, will be used in the subsequent analyses for the HDV fleet.

Heavy-duty Vehicles Historical Trends

Figure 7 shows the fleet average gNO_x/kg of fuel (black bars, left axis) and IR %opacity (grey bars, right axis) for all years Peralta has been measured. Uncertainties are standard errors of the

Table 4. Peralta weigh station data summary for HDVs in 2017.

FEAT Number of Vehicles	High 1368	Low 476
Mean CO/CO_2 (g/kg of fuel)	0.003 (5.2)	0.003 (7.7)
Median gCO/kg	2.7	5.9
Mean HC/CO_2 (g/kg of fuel)	0.0004 (2.2)	0.0004 (2.5)
Median gHC/kg	1.3	1.0
Mean NO/CO_2 (g/kg of fuel)	0.004 (7.6)	0.003 (6.8)
Median gNO/kg	1.3	2.2
Mean NH_3/CO_2 (g/kg of fuel)	0.00007 (0.08)	0.0001 (0.1)
Median gNH_3/kg	0.01	0.02
Mean NO_2/CO_2 (g/kg of fuel)	0.0003 (1.1)	0.0003 (1.0)
Median gNO_2/kg	0.5	0.4
Mean Median gNO_x/kg	12.8 7.2	11.3 3.9
Mean Median IR %opacity	0.4 0.3	0.9 0.9
Mean Model Year	2010.7	2011.9
Mean Speed (mph)	14.0	14.0
Mean Acceleration (mph/s)	0.8	0.1
Mean VSP(kw/tonne) Slope (degrees)	4.7 1.6°	4.5 1.6°

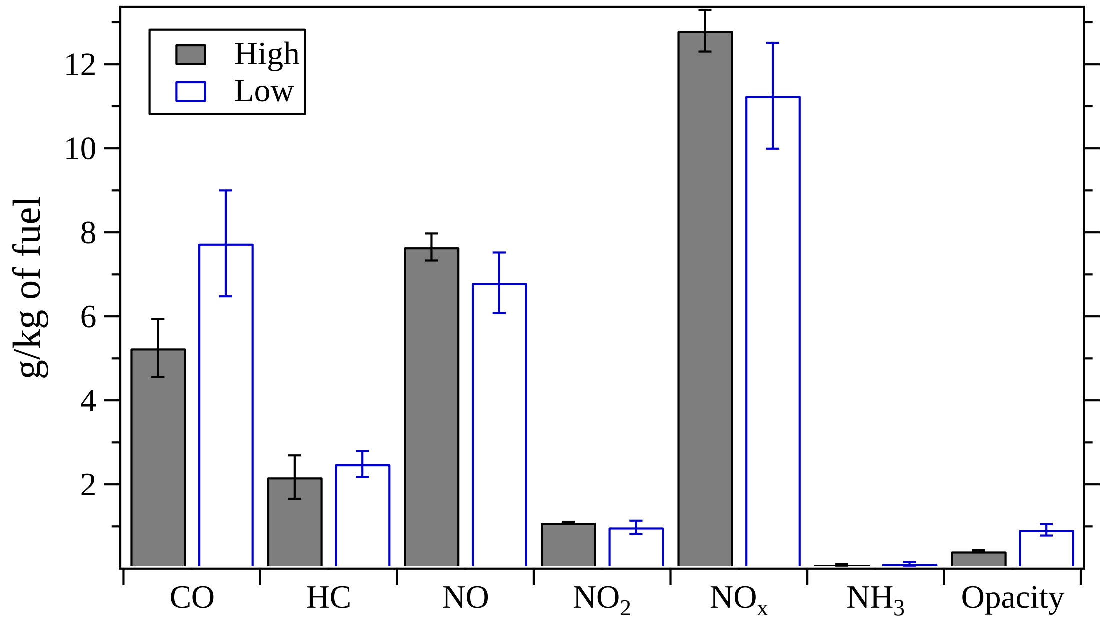

Figure 5. HDV CO, HC, NO, NO_2, NO_x, and NH_3 fuel specific emissions (g/kg of fuel) and IR %Opacity for the high (black, solid) and low (blue, open) FEAT. Uncertainties are standard errors of the mean calculated using the daily means.

Table 5. Emissions summary comparison for California and out-of-state-plate matched heavy-duty trucks. Uncertainties are standard error of the mean calculated using the daily means.

State	Trucks	Mean gCO/kg	Mean gHC/kg	Mean gNO/kg	Mean gNO_2/kg	Mean gNO_x/kg	Mean gNH_3/kg	Mean Model Year
CA	1488	5.6 ± 0.9	2.2 ± 0.5	8.2 ± 0.3	1.2 ± 0.04	13.7 ± 0.6	0.07 ± 0.03	2010.4
Other	356	6.9 ± 1.3	2.3 ± 0.4	4.4 ± 0.5	0.5 ± 0.05	7.2 ± 0.8	0.2 ± 0.02	2013.9
Δ		-21%	-0.04%	46%	58%	47%	-186%	-3.5

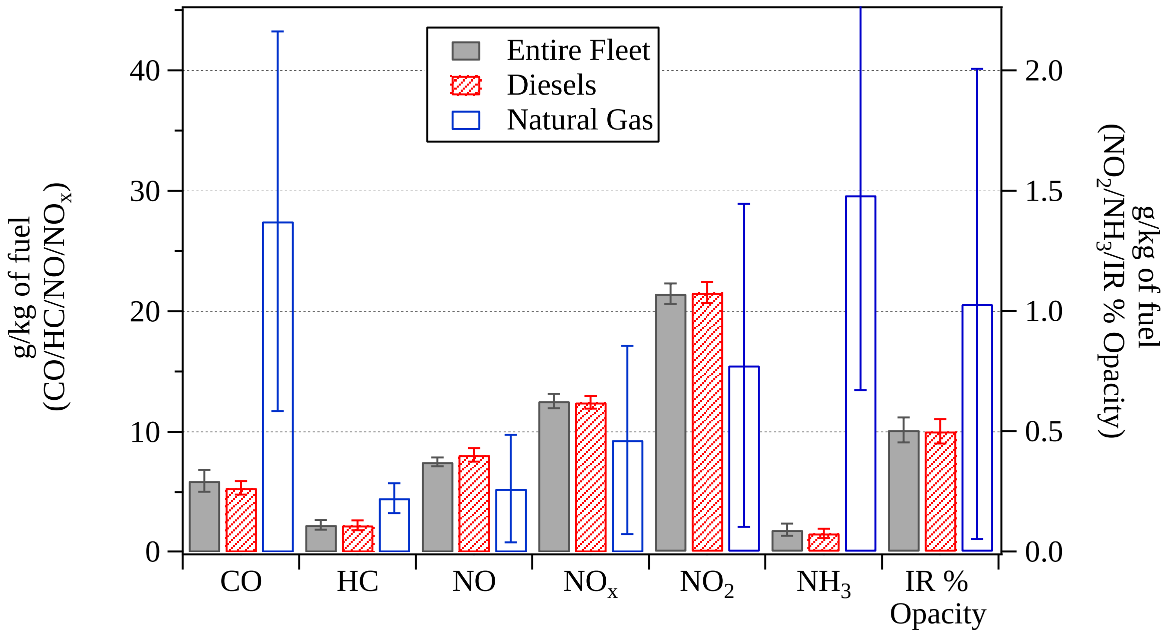

Figure 7. CO, HC, NO, NO_x (all on left axis) NO_2, and NH_3 (right axis) fuel specific emissions (g/kg of fuel) and IR %Opacity (right axis) for the entire fleet (grey, solid), diesels (red, hatched) and the natural gas portion of the fleet (blue, open). Uncertainties are standard errors of the mean calculated from the daily means.

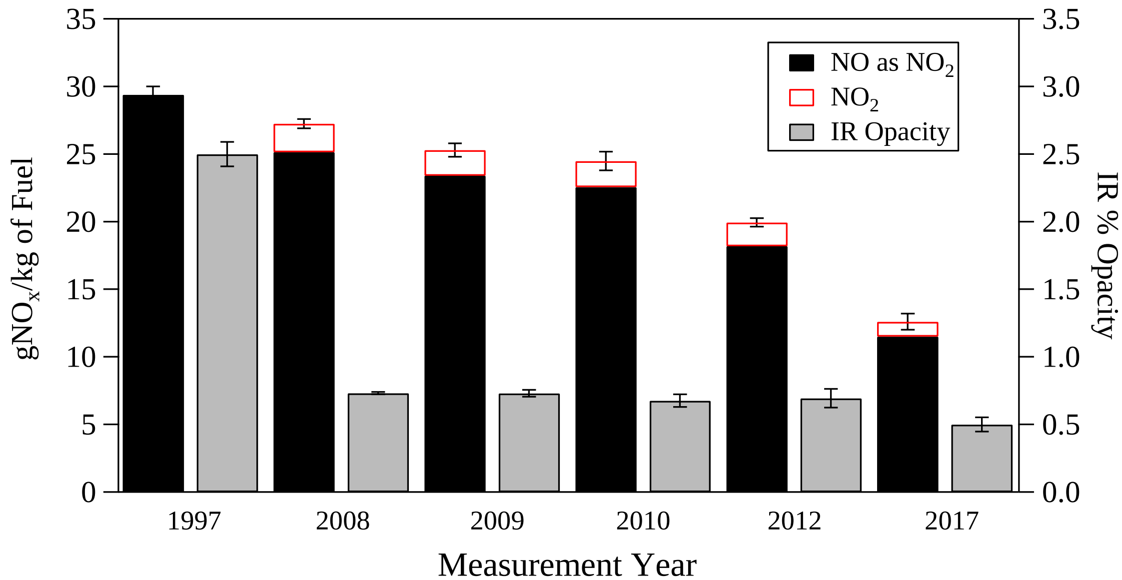

Figure 6. Infrared %opacity (grey bars, right axis) for High FEAT only and NO as NO_2 equivalents (black bars, left axis), gNO_2 (open red bars, left axis) and gNO_x/kg of fuel (total bar height, left axis) by measurement year. Uncertainties are standard errors of the mean calculated using the daily means.

mean calculated using the daily means. NO is plotted as grams of NO_2 with the total bar height equal to total fuel specific NO_x emissions. The fuel specific NO has decreased 61% from 1997 (NO_2 was not measured until the 2008 field work), and a decrease of 37% from 2012 to 2017 has occurred for total NO_x, in part due to the introduction of SCRs. The fleet measured in 2012 had more HDVs with SCRs on-board, which is why there is a reduction in NO_x from 2010 to 2012 measurement years, and with a growing percentage of HDVs with SCRs in 2017, fleet NO_x continues to decrease.[15] The reductions between 2008 and 2010 likely come from engine management changes that allowed the manufacturers to have richer air to fuel ratio engines, lowering NO_x, and relying on DPFs to control PM.

Between 1997 and the 2008 campaign, there was a 70% decrease in IR %opacity. Since 2008, the fleet opacity average did not significantly change until this last campaign, which had a further decrease of 14% from the 2012 fleet mean and is close to the values observed for the fully DPF equipped Port of Los Angeles fleet in 2012.[16] 2017 data is compared to other measurement years in Figure 7 for all HDVs measured with both High and Low FEAT. Previous studies only used the High FEAT and so for comparison purposes, the %opacity for 2017 High FEAT HDVs was 0.38 and 12.8 gNO_x/kg of fuel. The fleet has incorporated the new lower emissions technology, regulated species, such as NO_x and PM, were positively impacted. Table 6 further supports this claim, as the fleet is now mainly comprised of vehicles 2012 and newer (58% of the HDV fleet), which would have after-treatment systems responsible for decreasing the fleet average opacity and NO_x.

Table 6. Vehicles measured by model year during the 2017 measurement year separated by HDVs and MDVs.

Year	Count	
	HDV	MDV
2007 and Older	321 (17%)	191 (41%)
2008	128 (7%)	23 (5%)
2009	146 (8%)	10 (2%)
2010	93 (5%)	13 (3%)
2011	98 (5%)	15 (3%)
2012	169 (9%)	22 (5%)
2013	173(9%)	32 (7%)
2014	164 (9%)	35 (7%)
2015	175 (9%)	45 (10%)
2016	239 (13%)	52 (11%)
2017	131 (7%)	33 (7%)
2018	7 (<1%)	0 (0%)

These gaseous emissions, and IR %opacity, were analyzed further by model year and compared to the 2012 measurements. All model years depicted in subsequent figures have more than 10 HDVs. Figure 8 displays HDV gCO/kg of fuel by model year for 2012 data (black squares) and 2017 data (blue circles). Uncertainties are standard errors of the mean calculated using the daily means. Newer model years are more uncertain due to fewer vehicles.

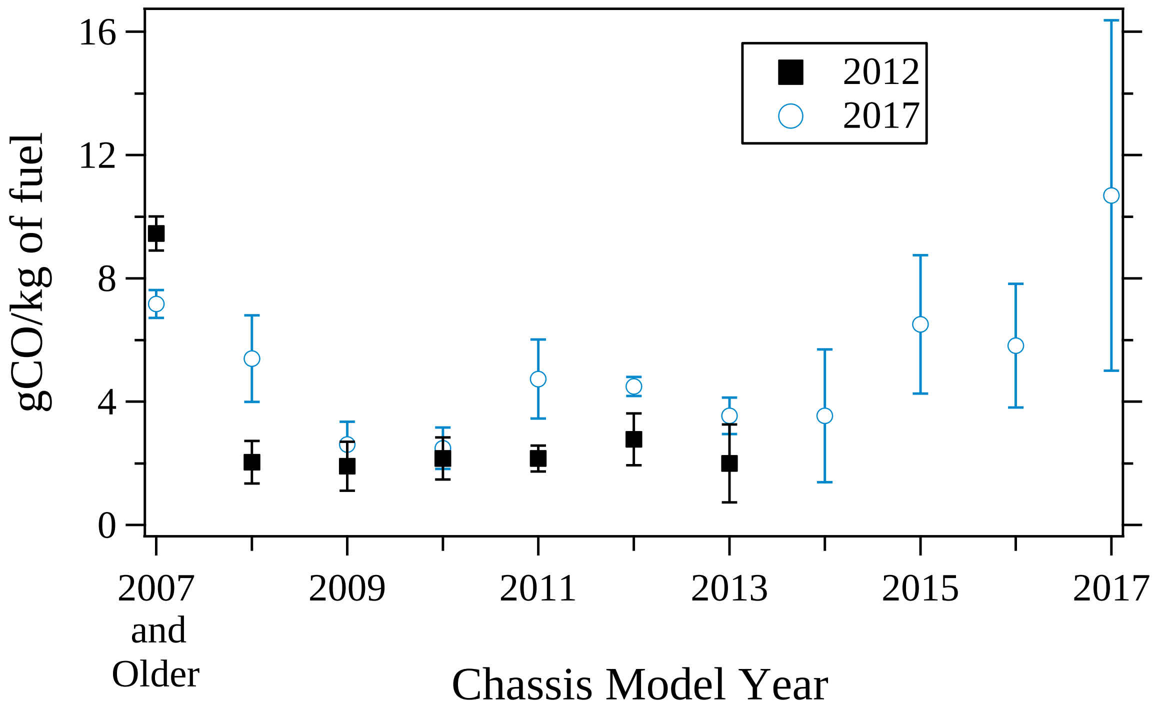

Figure 8. HDV fuel specific gCO/kg of fuel by chassis model year for 2012 (black squares) and 2017 (blue circles) data. Uncertainties are standard errors of the mean calculated using the daily means.

Figure 9 shows gNO/kg of fuel (grams of NO) by model year for 2012 (black squares) and 2017 (blue circles) HDVs with standard errors of the mean uncertainties calculated from the daily means. The 2017 data show increases for all model years from the 2012 averages. Both data sets show the reductions in NO emissions with the start of installation of SCRs between the 2010 to 2011 model years. The continual decrease in NO in subsequent model years is likely due to the increasing percentage of HDVs having SCRs. However, as the fleet of HDVs has aged from 2012 to 2017, some of those initial decreases in NO emissions have been given back.

2010 (red triangles), 2012 (black squares) and 2017 (blue circles) data for NO_2 are shown in Figure 10. Uncertainties are standard error of the mean calculated using the daily means. One unintended consequence of first generation DPFs were that their catalyzed surfaces, to aid in passive regeneration of the filter, produced elevated levels of NO_2 emissions. Without NO_x after-treatment systems these increased NO_2 emissions are clearly seen in the 2010 and 2012 measurements for the 2008 – 2010 model year trucks. [17] As these model years age, the catalyst loses its ability to

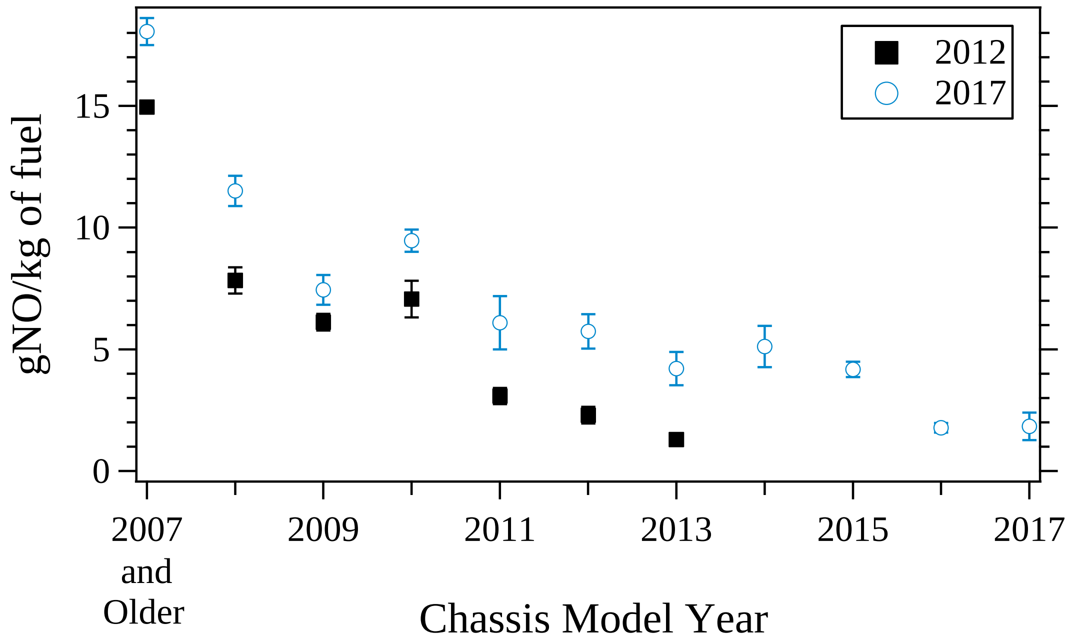

Figure 9. Fuel specific gNO/kg of fuel by chassis model year for 2012 (black squares) and 2017 (blue circles) data. Uncertainties are standard error of the mean calculated using the daily means.

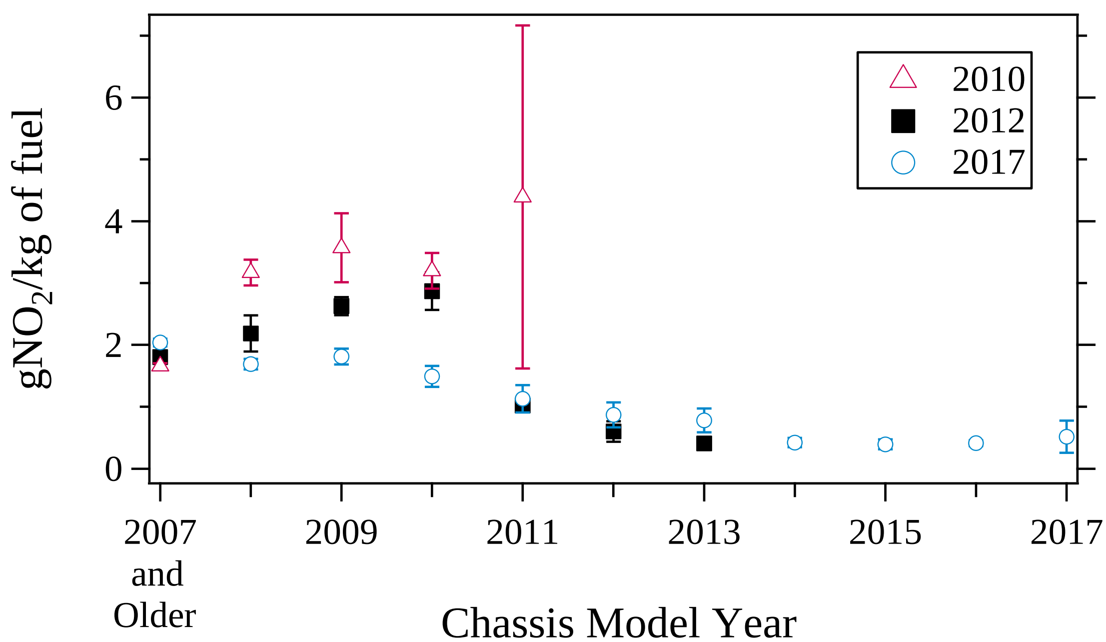

Figure 10. Fuel specific gNO_2/kg of fuel by chassis model year for 2012 (black squares) and 2017 (blue circles) data. Uncertainties are standard error of the mean calculated from the daily means.

oxidize NO to NO_2, a process known as de-greening, which corresponds to the decrease seen in NO_2 emissions for these model years in the 2017 measurements. HDVs without catalyzed DPFs (model year 2011 and newer), have a rapid decline in NO_2 from SCR systems until model year 2014 where they reach a minimum, a result of a the majority of HDVs having SCRs.

Figure 11 shows fuel specific NO_x emissions by model year, where 2012 is represented as black squares and 2017 as blue circles. Uncertainties are standard error of the means calculated using the daily means. NO_x for model year 2013 (~zero year old vehicles) in the 2012 data is identical to the average NO_x for model years 2016 and 2017 in the 2017 data. Also notable, the 2016 and 2017 model year vehicles measured in 2017 show an additional 50% reduction in their average NO_x emissions compared to model year 2015. This suggests additional improvements in the newest SCR systems. The mass ratio of NO_2 to NO_x by model year is shown in Figure 12 comparing 2012 (black squares) and 2017 (blue circles) data. Uncertainties are standard error of the mean calculated using the daily means. The ratio plot reflects the mean fuel specific emissions shown for NO and NO_2 in Figures 9 and 10 with an increase in the ratio for the 2008 – 2010 model year vehicles in the 2012 measurements.

Figure 13 is fuel specific NH_3 emissions by model year for 2012 (black squares) and 2017 (blue circles) data. Uncertainties are standard error of the mean calculated using the daily means. Here, the influence of ammonia used as the reduction agent in SCR systems is evident. With the increased presence of SCR systems, and therefore increased urea use, the ammonia slip increases from the start of SCR use in model year 2011 until 2015. However, it appears that advancements in SCR technology for the newest model year vehicles has begun to reduce the ammonia slip.[18] These levels are still much lower than currently observed NH_3 emissions in the light-duty gasoline fleet (0.4 to 0.6 gNH_3/kg of fuel).[19] In 2017, the newer model years have consistently low NO_x measurements, indicating their SCR systems are working as intended with an optimized NH_3 to NO_x ratio and at temperatures that allow this reduction to occur.

2012 (black squares) and 2017 (blue circles) data for IR %opacity by model year are shown in Figure 14. Uncertainties are standard error of the mean calculated using the daily means. It should be noted that opacity measured by FEAT is significantly nosier than for the other gaseous measurements, but it is still able to identify vehicles that emit high levels of black carbon.[20, 21] Because the remaining 2007 and older model year vehicles in 2017 are likely to have retrofit DPFs, as seen with other Californian fleets, the opacity of this fleet subsection also shows decreases from 2012 levels.[13]

Changes in certification standards have led to new technologies and combustion management in order for vehicles to achieve these standards. Although vehicles may pass laboratory certification standards, it is important to understand how the standards translate to on-road emission improvements. Long-haul HDVs at the Peralta weigh station, shown in Figure 15 for 2012 (black) and 2017 (blue) measurements have been grouped into four model year groupings the parallel the certification standards: pre-2004 HDVs that have no, or retrofit, after-treatment technologies,

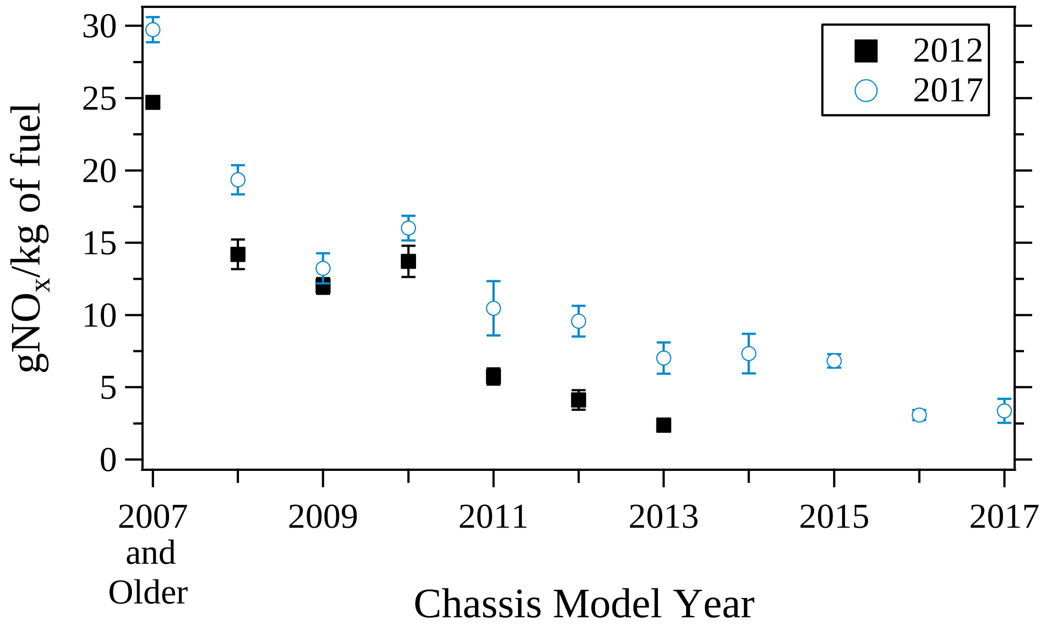

Figure 11. Fuel specific gNO_x/kg of fuel by chassis model year for 2012 (black squares) and 2017 (blue circles) data. Uncertainties are standard error of the mean calculated from the daily means.

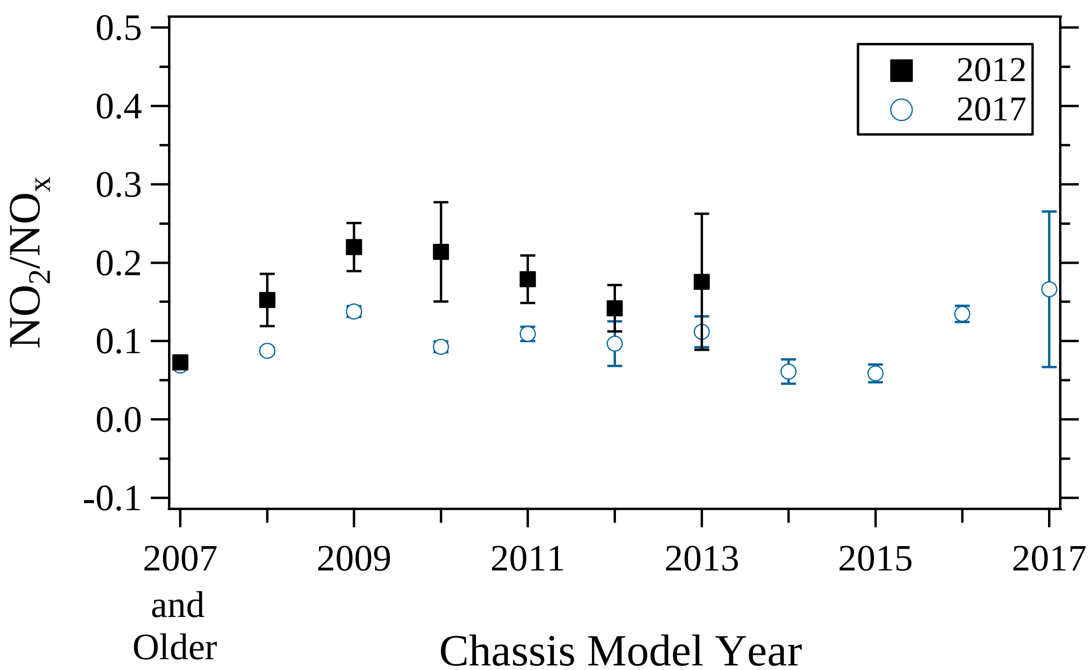

Figure 12. NO_2/NO_x mass ratio for 2012 (black squares) and 2017 (blue circles) data. Uncertainties are standard error of the mean calculated using the daily means.

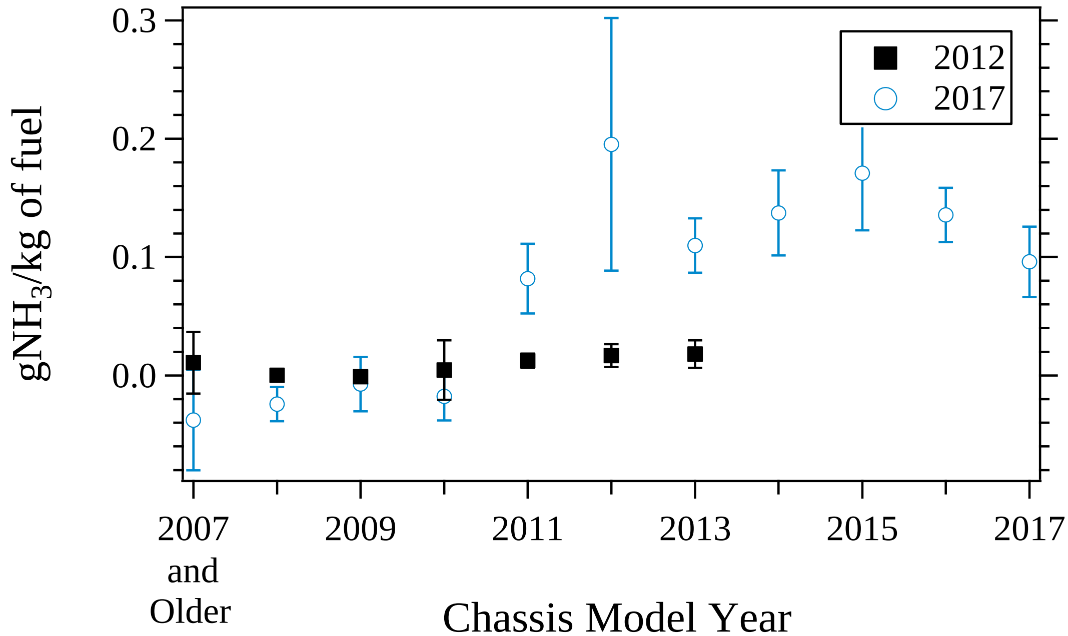

Figure 14. Fuel specific gNH_3/kg of fuel by chassis model year for 2012 (black squares) and 2017 (blue circles) data. Uncertainties are standard error of the mean calculated from the daily means.

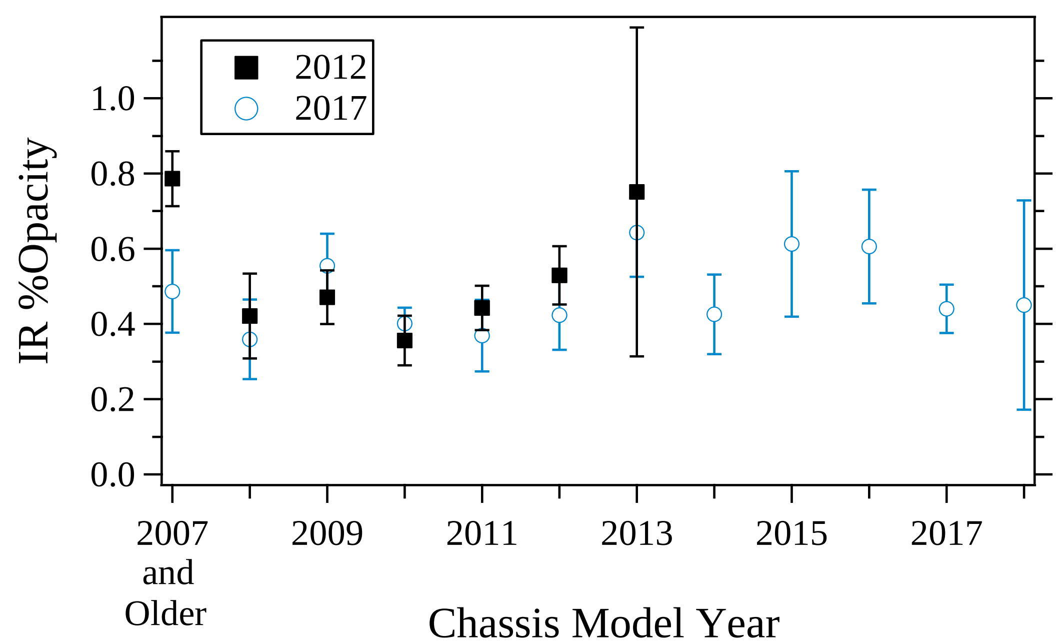

Figure 13. Infrared %opacity by chassis model year for 2012 (black squares) and 2017 (blue circles) data. Uncertainties are standard error of the mean calculated using the daily means.

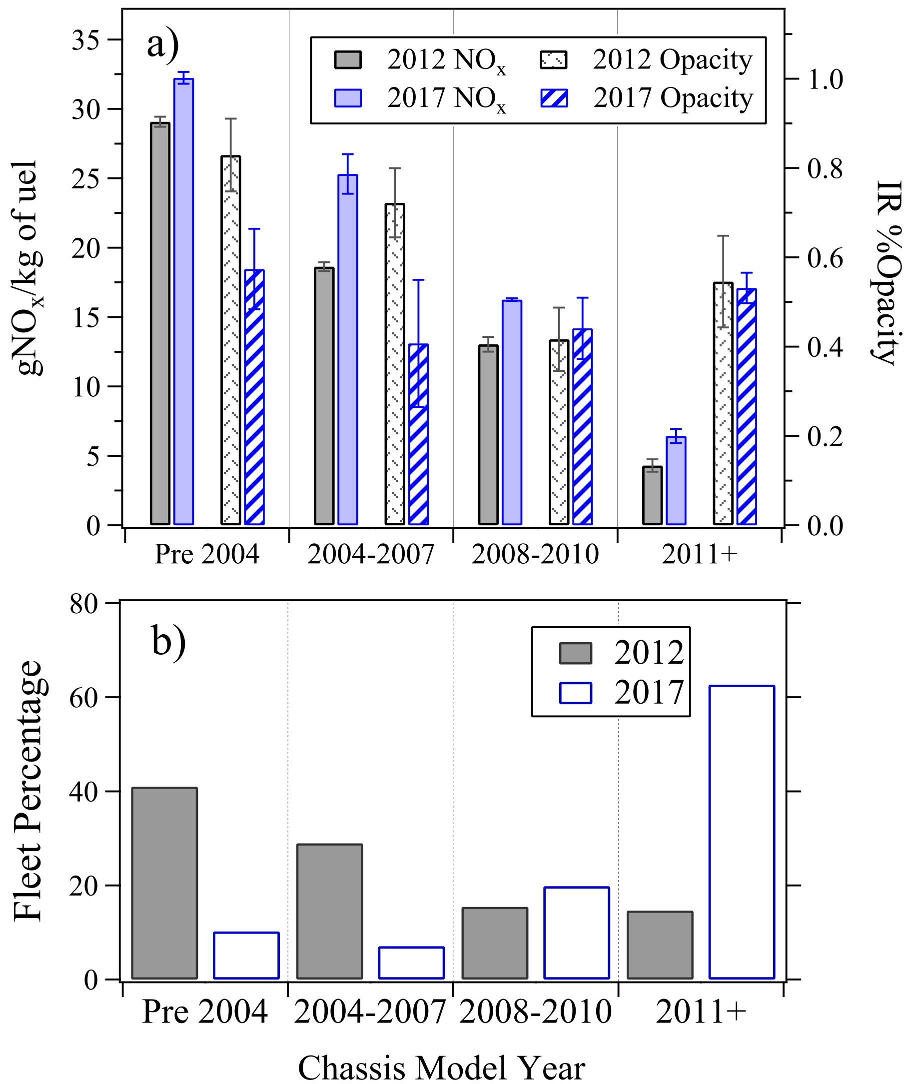

Figure 15. a) IR %Opacity (right axis, hatched bars) and gNO_x/kg of fuel (left axis, filled bars) for 2012 (black) and 2017 (blue) data grouped by model year. Uncertainties are standard error of the mean calculated from the daily means. b) Fleet percentage for grouped model years in 2012 (solid black bars) and 2017 (open blue bars) data.

2004-2007 model year vehicles that have combustion management such as EGR and retrofit activity, model years 2008-2010 that have first generation DPFs and are pre-SCR use, and 2011 and newer model years with DPFs and an increasing fraction of SCR systems. Figure 15a shows NO_x (black or blue solid bars for the 2012 and 2017 measurements respectively) and IR %opacity (black or blue hatched bars for 2012 and 2017 respectively). Uncertainties are standard error of the mean calculated using the daily means. Figure 15b shows the fleet percentage for the corresponding model year groups for the 2012 and 2017 fleets represented by black solid bars and blue open bars respectively. Consistent with the previous graphs NO_x continually decreases as technologies advance, seen in the newer model year groupings. Similarly, the IR %opacity in the

2012 measurements continually decreases for newer model year vehicles. The IR %opacity in 2017 measurements also shows significant reductions in the two oldest model year groupings indicating that the remaining older model year vehicles are likely to have DPFs installed in compliance with the California truck and bus rule. Notable in Figure 15b, the fleet in 2012 is dominated by vehicles older than model year 2004 (41%) but in 2017, the percentage of HDVs model year 2004 and older has decreased significantly to 10% which has influenced the overall emissions measured at Peralta.

2017 Medium and Heavy-duty Vehicles

The assortment of vehicles at Peralta provides an opportunity, for the first time, to gain insights into how MDVs and HDVs compare in their emissions profiles. The MDVs were categorized by fuel and compared with the HDVs in Figure 16 with the 2017 HDV diesel fleet (black solid bars) and the MDV gasoline (green striped bars) and diesel (blue open bars) fleets for all species measured. CO, HC, NO and NO_x are graphed against the left-axis and NO_2 and NH_3 are graphed against the right axis. Total fuel specific CO emissions for gas MDV fleet are four times higher than the MDV diesel fleet. Diesel engines have compression ignition engines and have significantly higher engine temperatures than gasoline engines, and thus have higher engine out NO_x than gasoline vehicles.[22] Therefore, as expected, NO_x (both NO and NO_2) are elevated for the diesel MDVs compared to the gasoline MDVs. The diesel MDVs are slightly higher than diesel HDVs NO_x due to the MDV fleet being older than the HDV fleet, but the difference is not significant for the overall average fleet emissions. For the subsequent figures, diesel MDVs will be used in comparison to the diesel HDVs.

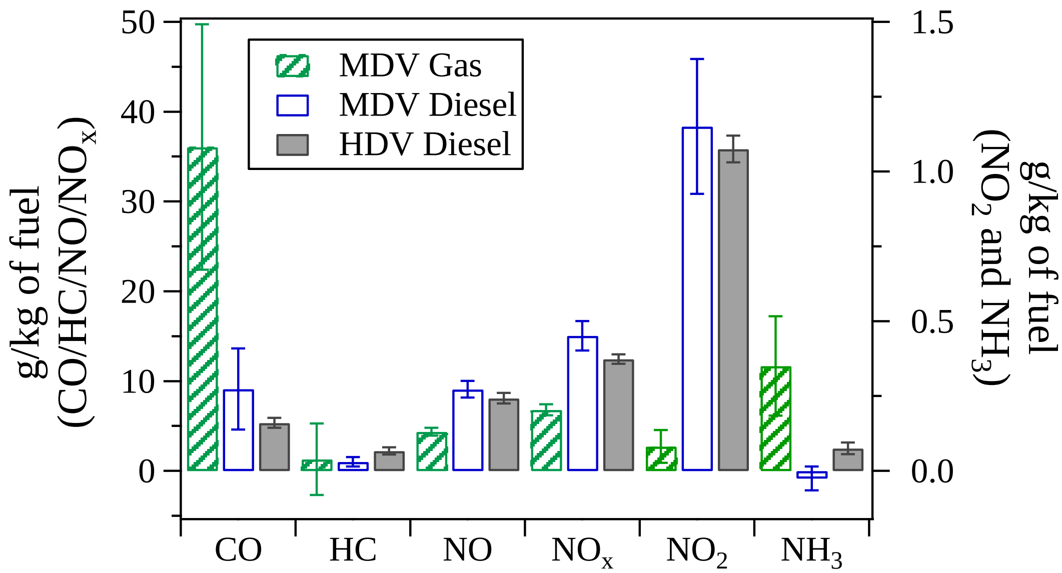

Figure 16. Fuel Specific emissions (g/kg of fuel) for CO, HC, NO and NO_x (left-axis) and NO_2 and NH_3 (right-axis) emissions fuel for gas MDVs (green striped bars, left-axis) and diesel (right-axis) MDVs (blue open bars) and HDVs (black solid bars). Uncertainties are standard error of the mean calculated using the daily means.

Figure 17 compares the MDVs (blue diamonds) and HDVs (black triangles) by model year for gCO/kg of fuel. Uncertainties are standard error of the mean calculated using the daily means. There is not a significant difference in the CO emissions for a majority of the model years between the two classes of vehicles.

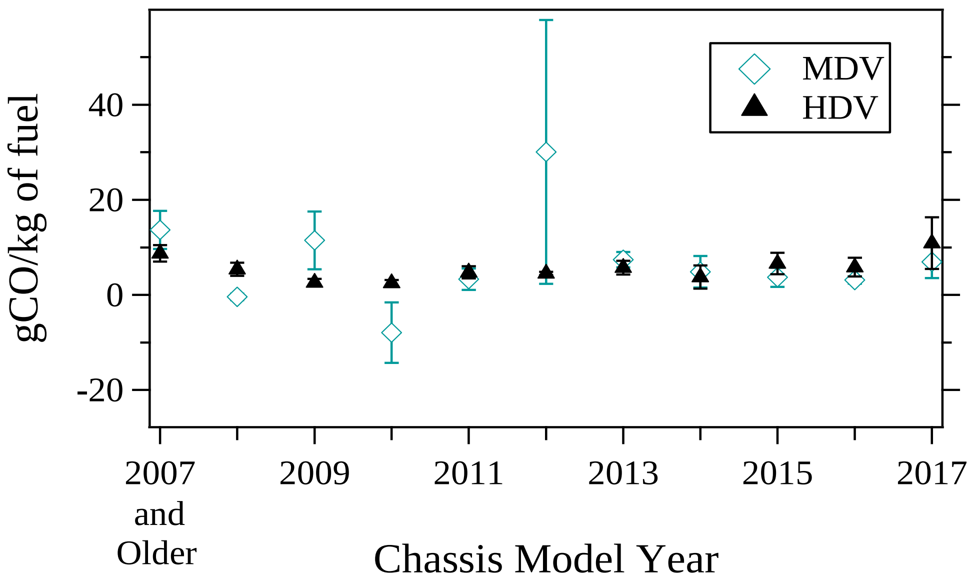

Figure 17. 2017 fuel Specific gCO/kg of fuel by model year for heavy-duty (black triangles) and medium-duty (blue diamonds) vehicles. Uncertainties are standard error of the mean calculated using the daily means.

Fuel specific NO emissions by model year are shown in Figure 18 for medium and heavy-duty vehicles represented by blue diamonds and black triangles respectively. Uncertainties are standard error of the mean calculated from the daily means. From the 2007 and older model year vehicles to model year 2017, there is a 91% and 94% reduction in NO for MDVs (16.5 to 1.5 gNO/kg of fuel) and HDVs (17.8 to 1.8 gNO/kg of fuel), respectively. Comparing the diesel MDVs to the diesel HDVs by model year, the NO emissions are statistically equivalent by model year, except for model years 2014-2016, where the decreases in HDVs emissions experience a plateau while the MDVs NO emissions continue to decline. NO_2, however, shown in Figure 19 for MDVs (blue triangles) and HDVs (black triangle), has consistent decreases by model year and no significant differences between medium and heavy-duty vehicles except for model year 2010, which is unexplained, but model years 2008 – 2010 have very few measurements. Uncertainties in Figure 19 are standard error of the mean calculated from the daily means.

Figure 20 shows the apportionment of NO as NO_2 equivalent (open bars), NO_2 (solid and striped bars) and total NO_x (total bar height). Uncertainties are standard error of the mean calculated from the daily means by model year for MDVs (blue) and HDVs (black). Noticeably, both MDVs and HDVs have a decrease in NO_x emissions between model years 2010 and 2011, when first

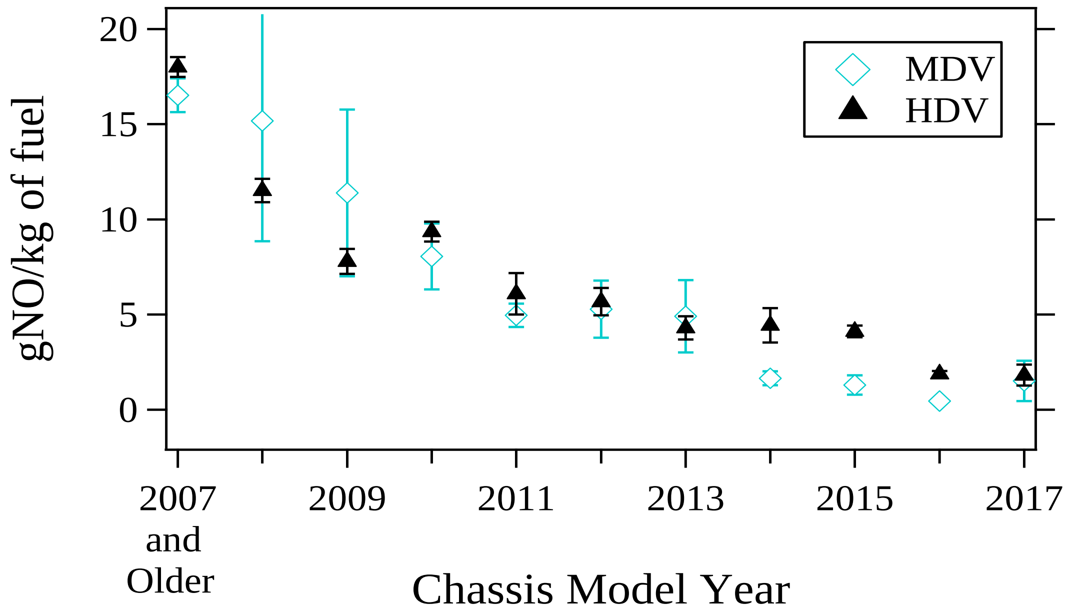

Figure 19. 2017 fuel Specific gNO/kg of fuel by model year for heavy-duty (black triangles) and medium-duty (blue diamonds) vehicles. Uncertainties are standard error of the mean calculated using the daily means.

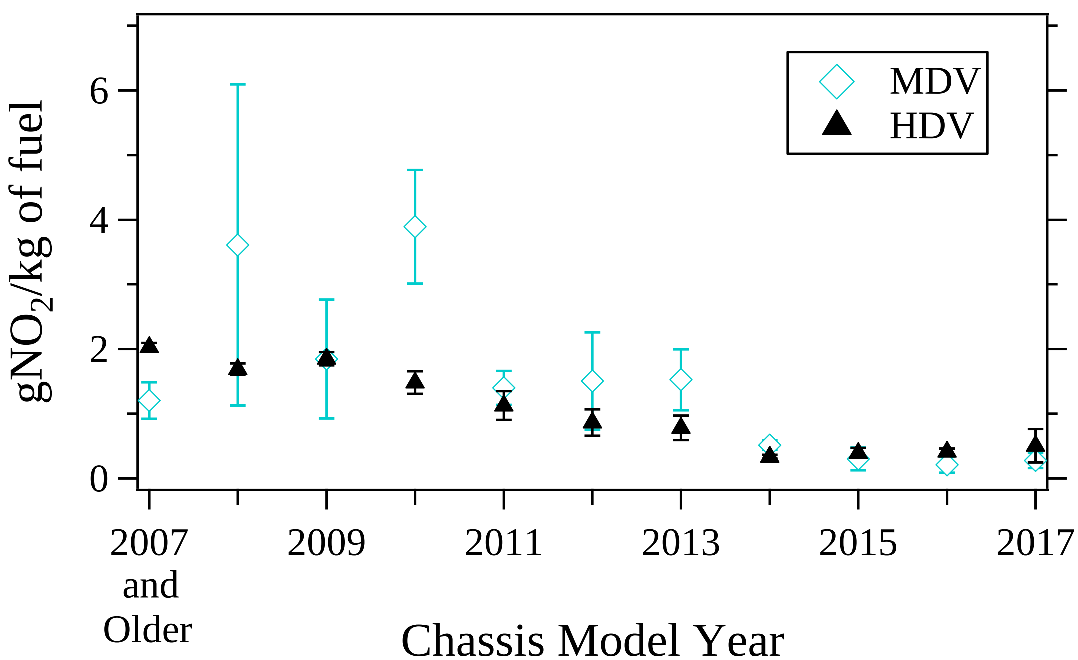

Figure 18. 2017 fuel Specific gNO_2/kg of fuel by model year for heavy-duty (black triangles) and medium-duty (blue diamonds) vehicles. Uncertainties are standard error of the mean calculated using the daily means.

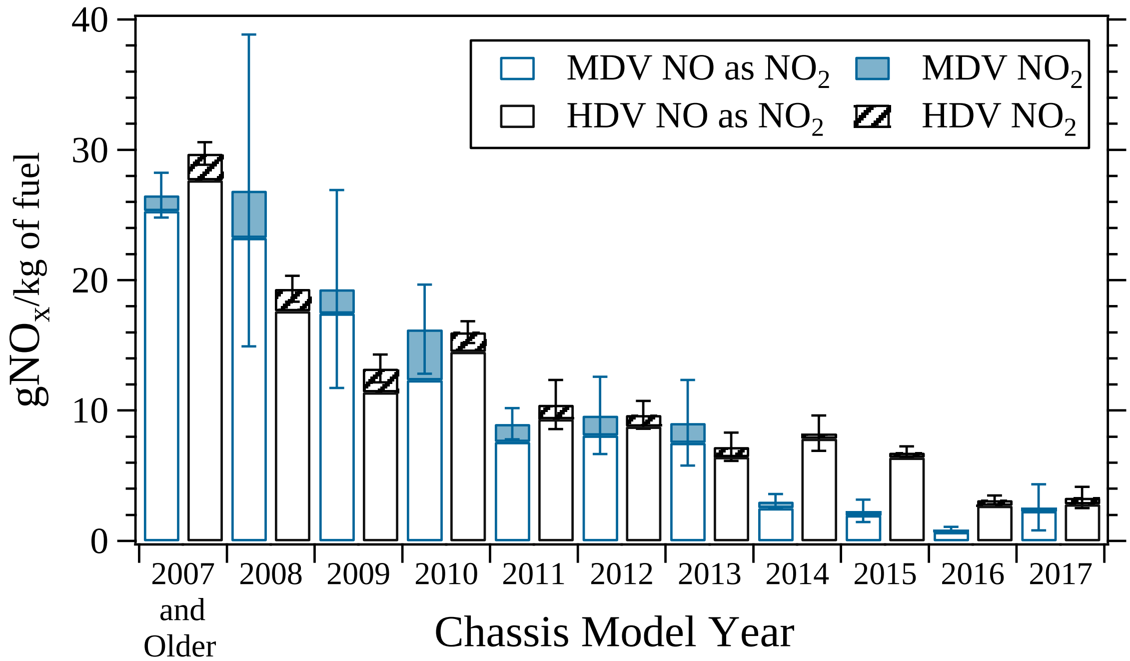

Figure 20. Total gNO_x/kg of fuel (total bar height) for MDVs (blue) and HDVs (black) vehicles. Mean gNO_2/kg of fuel (solid or hatched) and gNO/kg of fuel as gNO_2/kg of fuel (open bars) as graphed by chassis model year. Uncertainties are standard error of the mean calculated using the daily means.

generation SCRs became available, and model years 2010-2013 are consistent between these two vehicle classes. However, newer MDVs have lower NO_x emission than their HDV counterparts.

MDVs had an overall reduction from 26.5 gNO_x/kg of fuel for vehicles 2007 and older to 2.6 gNO_x/kg of fuel for model year 2017 (90% reduction), and HDVs followed suit with an 88% reduction from 29.4 gNO_x/kg of fuel for 2007 and older model year vehicles to 2017 model year average of 3.4 gNO_x/kg of fuel. Converting the newest model years' NO_x emissions for MDVs (2.6 gNO_x/kg of fuel) and HDVs (3.1 gNO_x/kg of fuel) yields observed NO_x for MDVs into g/bhp-hr as 0.39 g/bhp-hr and 0.46 g/bhp-hr for HDVs, assuming there is 0.15 kg of fuel burned per bhp-hr. Comparatively, MDVs are still 2 times the laboratory certification standard for the newest model years, and the HDVs are 2.3 times above this limit.[1] HDVs deviate from the MDVs in model years 2014-2016 for gNO_x/kg of fuel due to increase NO emissions as previously discussed in Figure 11. The exact reason for this is unknown but it is possible that these model years have a lower fraction of vehicles that fully meet the low NO_x standards that we are not able to account for.

A box and whisker plot, Figure 21, shows gNO_x/kg of fuel by chassis model year for HDVs and MDVs. The horizontal line dictates the median, the box encloses the 25th to the 75th percentiles and the whiskers denote the 10th to 90th percentiles. The measurements beyond the 10th to the 90th percentiles are shown in black triangles (HDVs) and blue diamonds (MDVs) and the model year

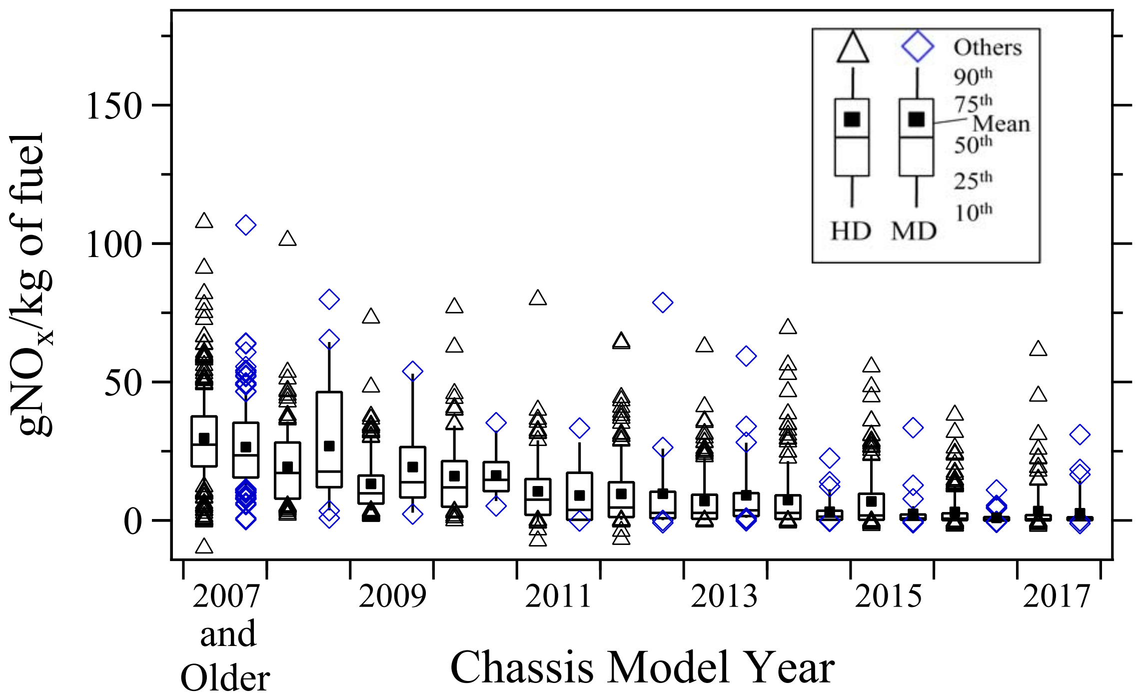

Figure 21. Box and whisker plot for gNO$_x$/kg of fuel by chassis model year for heavy-duty (HD) and medium-duty (MD) vehicles. The horizontal line dictates the median, the box encloses the 25th to the 75th percentiles and the whiskers denote the 10th to 90th percentiles. The measurements beyond the 10th to the 90th percentiles are shown in black triangles (HDVs) and blue diamonds (MDVs) and the means are represented by filled black squares.

means are represented by black squares. The 90th percentile for MDVs 2014-2016 are 47, 78 and 72% lower than the same model year of HDVs, meaning HDVs have more of these model year vehicles that are higher emitting than the equivalent model year of MDVs.

Interestingly, the increase in HDV NO$_x$ for model years 2014-2016 is also accompanied by an increase in NH_3 emissions, shown in Figure 22, where HDVs (black triangles) are elevated from the MDVs (blue squares) of those same model years. Uncertainties are standard error of the mean calculated from the daily means. Figure 23 further analyzes the 2014-2016 model year vehicles.

NO$_x$ and NH_3 deviation. Individual ammonia measurements have been plotted against their NO$_x$ reading for just model year 2014-2016 diesel HDVs. The subcategory of this fleet has been separated by engine manufacturer: Freightliner (FRHT, blue crosses), International (INTL, red squares), Kenworth (KW, black triangles), Peterbilt (PTRB, purple diamonds) and Volvo (orange Xs). The highest emitting NO$_x$ vehicles have near zero ammonia levels, similar to older vehicles that do not have an SCR installed, whereas most high NH_3 vehicles have low NO$_x$ measurements, which could represent overdosing of urea within the SCR system fully reducing NO$_x$ but with increased NH_3 slip.

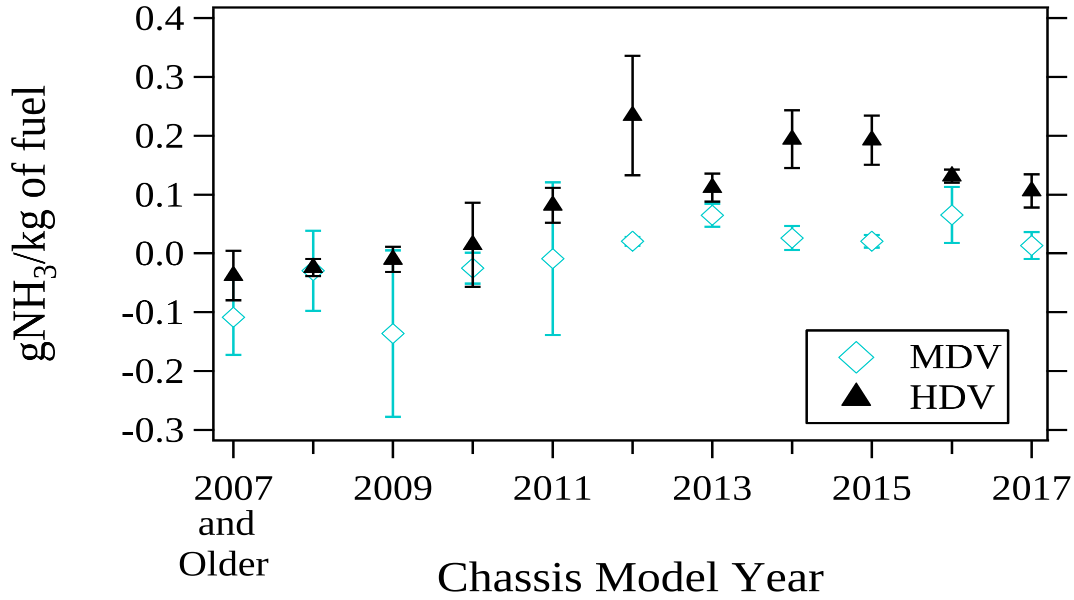

Figure 22. 2017 fuel Specific gNH_3/kg of fuel by model year for heavy-duty (black triangles) and medium-duty (blue diamonds) vehicles. Uncertainties are standard error of the mean calculated using the daily means.

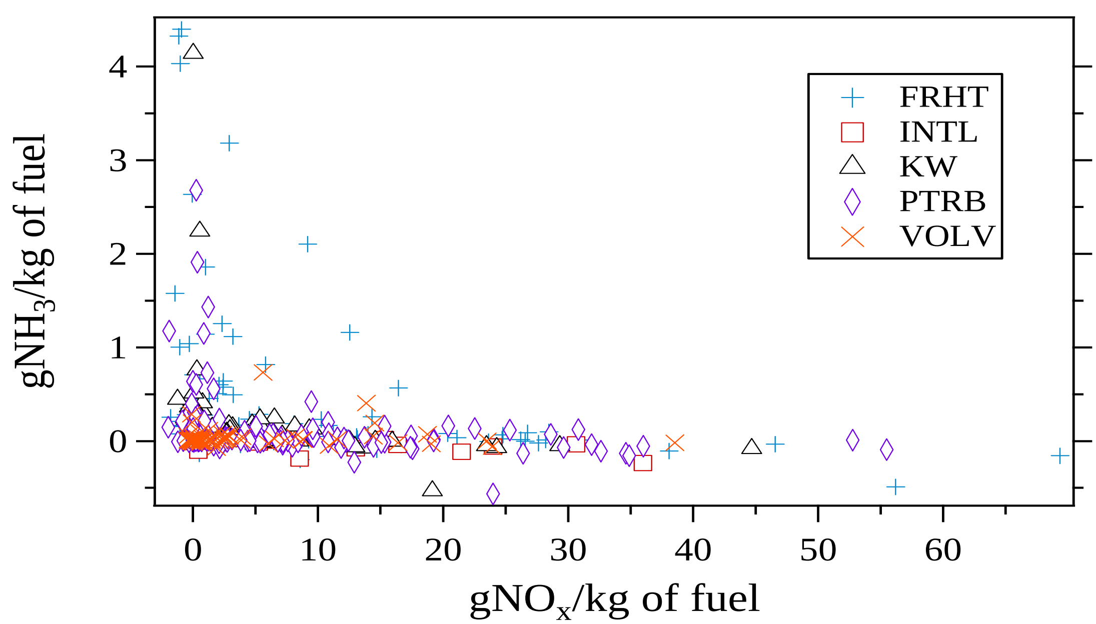

Figure 23. Individual fuel specific NH_3 emissions versus their individual NO_x emissions for diesel HDVs at Peralta model years 2014-2016. Measurements separated by manufacturer: Freightliner (FRHT, blue crosses), International (INTL, red squares), Kenworth (KW, black triangles), Peterbilt (PTRB, purple diamonds) and Volvo (orange Xs).

The diesel and gasoline MDVs have few differences in all gases measured, except for NO and NO_x, for similarly aged vehicles. NO_x and NO for model year vehicles is near zero for gasoline MDVs, whereas for diesels, the NO and NO_x emissions have been reduced for newer model years, but remains above the gasoline averages for the newest model years measured at Peralta, as expected with diesel engines. (See Appendix D for all gases by model year for gasoline and diesel MDVs).

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APPENDIX A: FEAT criteria to render a reading "invalid".

Invalid :

1) insufficient plume to rear of vehicle relative to cleanest air observed in front or in the rear; at least five, 10ms >160ppm CO_2 or >400 ppm CO. (0.2 %CO_2 or 0.5% CO in an 8 cm cell. This is equivalent to the units used for CO_2 max.). For HDDV's this often occurs when the vehicle shifts gears at the sampling beam.

2) excessive error on CO/CO_2 slope, equivalent to $\pm$20% for $CO/CO_2 > 0.069$, 0.0134 CO/CO_2 for $CO/CO_2 < 0.069$.

3) reported CO/CO_2 , < -0.063 or > 5. All gases invalid in these cases.

4) excessive error on HC/CO_2 slope, equivalent to $\pm$20% for $HC/CO_2 > 0.0166$ propane, 0.0033 propane for $HC/CO_2 < 0.0166$.

5) reported $HC/CO_2 < -0.0066$ propane or > 0.266. HC/CO_2 is invalid.

6) excessive error on NO/CO_2 slope, equivalent to $\pm$20% for $NO/CO_2 > 0.001$, 0.002 for $NO/CO_2 < 0.001$.

7) reported $NO/CO_2 < -0.00465$ or > 0.0465. NO/CO_2 is invalid.

8) excessive error on SO_2/CO_2 slope, ± 0.0134 SO_2/CO_2.

9) reported SO_2/CO_2 , < -0.00053 or > 0.0465. SO_2/CO_2 is invalid.

10) excessive error on NH_3/CO_2 slope, ± 0.00033 NH_3/CO_2.

11) reported $NH_3/CO_2 < -0.00053$ or > 0.0465. NH_3/CO_2 is invalid.

12) excessive error on NO_2/CO_2 slope, equivalent to $\pm$20% for $NO_2/CO_2 > 0.00133$, 0.000265 for $NO_2/CO_2 < 0.00133$.

13) reported $NO_2/CO_2 < -0.0033$ or > 0.0465. NO_2/CO_2 is invalid.

Speed/Acceleration valid only if at least two blocks and two unblocks in the time buffer and all blocks occur before all unblocks on each sensor and the number of blocks and unblocks is equal on each sensor and 100mph>speed>5mph and 14mph/s>accel>-13mph/s and there are no restarts, or there is one restart and exactly two blocks and unblocks in the time buffer.

APPENDIX B: Explanation of the Peralta_17.dbf database.

The Peralta_17.dbf is Microsoft FoxPro database file, and can be opened by any version of MS FoxPro. These files can also be read by a number of other database management and spreadsheet programs as well, and is available from www.feat.biochem.du.edu. The grams of pollutant/kilogram of fuel consumed are calculated assuming that diesel fuel has 860 grams of carbon per kilogram of fuel and natural gas has 750 grams of carbon per kilogram of fuel. The following is an explanation of the data fields found in this database:

License Vehicle license plate.

State State license plate issued by.

Date Date of measurement, in standard format.

Time Time of measurement, in standard format.

Co_co2 Measured carbon monoxide / carbon dioxide ratio

Co_err Standard error of the CO/CO_2 measurement.

Hc_co2 Measured hydrocarbon / carbon dioxide ratio (propane equivalents).

Hc_err Standard error of the HC/CO_2 measurement.

No_no2 Measured nitric oxide / carbon dioxide ratio.

No_err Standard error of the NO/CO_2 measurement.

So2_co2 Measured sulfur dioxide / carbon dioxide ratio.

So2_err Standard error of the SO_2/CO_2 measurement.

Nh3_co2 Measured ammonia / carbon dioxide ratio.

Nh3_err Standard error of the NH_3/CO_2 measurement.

No2_co2 Measured nitrogen dioxide / carbon dioxide ratio.

No2_err Standard error of the NO_2/CO_2 measurement.

Opacity IR Opacity measurement, in percent.

Opac_err Standard error of the opacity measurement.

Restart Number of times data collection is interrupted and restarted by a close-following vehicle, or the rear wheels of tractor trailer.

Hc_flag Indicates a valid hydrocarbon measurement by a "V", invalid by an "X".

No_flag Indicates a valid nitric oxide measurement by a "V", invalid by an "X".

So2_flag Indicates a valid sulfur dioxide measurement by a "V", Invalid by an "X".

Nh3_flag Indicates a valid ammonia measurement by a "V", Invalid by an "X".

No2_flag Indicates a valid Nitrogen dioxide measurement by a “V”, Invalid by an “X”.

Opac_flag Indicates a valid opacity measurement by a “V”, invalid by an “X”.

Max_co2 Reports the highest absolute concentration of carbon dioxide measured by the remote sensor over an 8 cm path; indicates plume strength.

Speed_flag Indicates a valid speed measurement by a “V”, an invalid by an “X”, and slow speed (excluded from the data analysis) by an “S”.

Speed Measured speed of the vehicle, in mph.

Accel Measured acceleration of the vehicle, in mph/s.

Tag_name File name for the digital picture of the vehicle.

FEAT FEAT unit location H=High and L=Low

gCO_gkg Grams of CO per kilogram of fuel consumed.

gCO_kg_err Standard error of the CO/CO_2 measurement.

gHC_gkg Grams of HC per kilogram of fuel consumed.

gHC_kg_err Standard error of the HC/CO_2 measurement.

gNO_gkg Grams of NO per kilogram of fuel consumed.

gNO_kg_err Standard error of the NO/CO_2 measurement.

gSO2_gkg Grams of SO_2 per kilogram of fuel consumed. (Note not calibrated)

gSO2_kg_err Standard error of the SO_2/CO_2 measurement. (Note not calibrated)

gNH3_gkg Grams of NH_3 per kilogram of fuel consumed.

gNH3_kg_err Standard error of the NH_3/CO_2 measurement.

gNO2_gkg Grams of NO_2 per kilogram of fuel consumed.

gNO2_kg_err Standard error of the NO_2/CO_2 measurement.

gNOx_kg Grams of NO_x per kilogram of fuel consumed.

Year Model year of the vehicles chassis.

Make Manufacturer of the vehicle.

Vin Vehicle identification number.

Series Manufacturer series of the vehicle.

Model Manufacturer model of the vehicle.

Body_style DMV vehicle body style abbreviation.

Body_type DMV vehicle body type abbreviation.

Gvw_code Gross vehicle weight code (1 – 8).

Fuel DMV fuel code (Gas, Diesel, Natural Gas)

City DMV vehicle registration city.

Zip DMV vehicle registration zip code.

Exh_temp IR thermograph converted elevated exhaust pipe temperature.

Def Visual identification of a vehicle with an visible DEF tank. (Y or blank).

APPENDIX C: Historical Emissions Summary for all Peralta Measurement Campaigns

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) Slope (degrees)	NA 1.8°	6.3 1.8°	5.8 1.8°	4.9 1.8°	6.6 1.6°

APPENDIX D: Gasoline versus Diesel MDVs at Peralta weigh station in 2017.

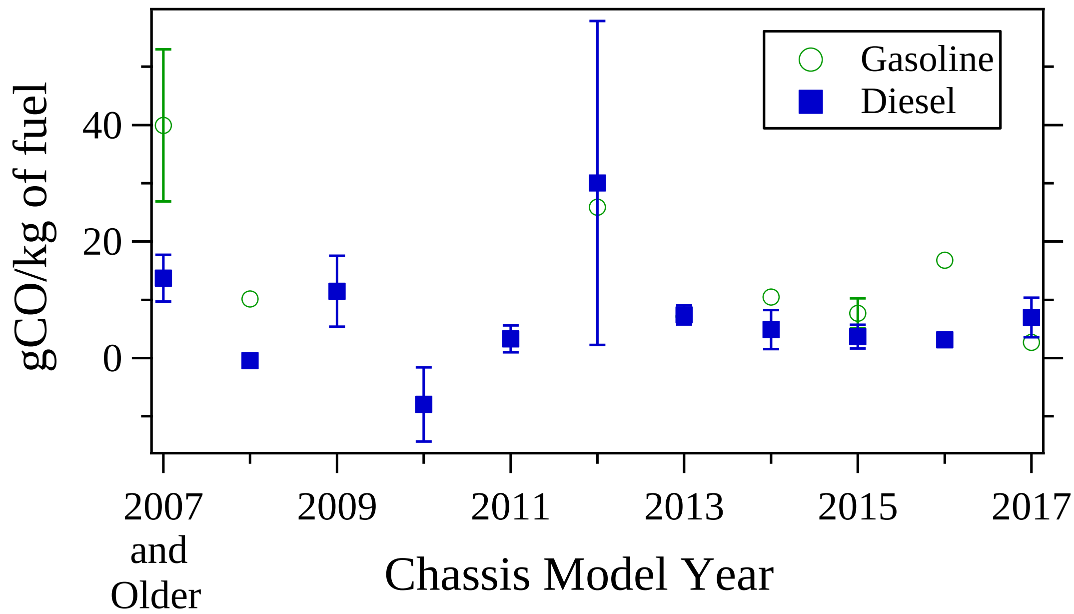

Figure C1. Gasoline (green circles) and diesel (blue squares) MDVs' fuel specific CO emissions by chassis model year. Uncertainties are standard error of the mean calculated using the daily means.

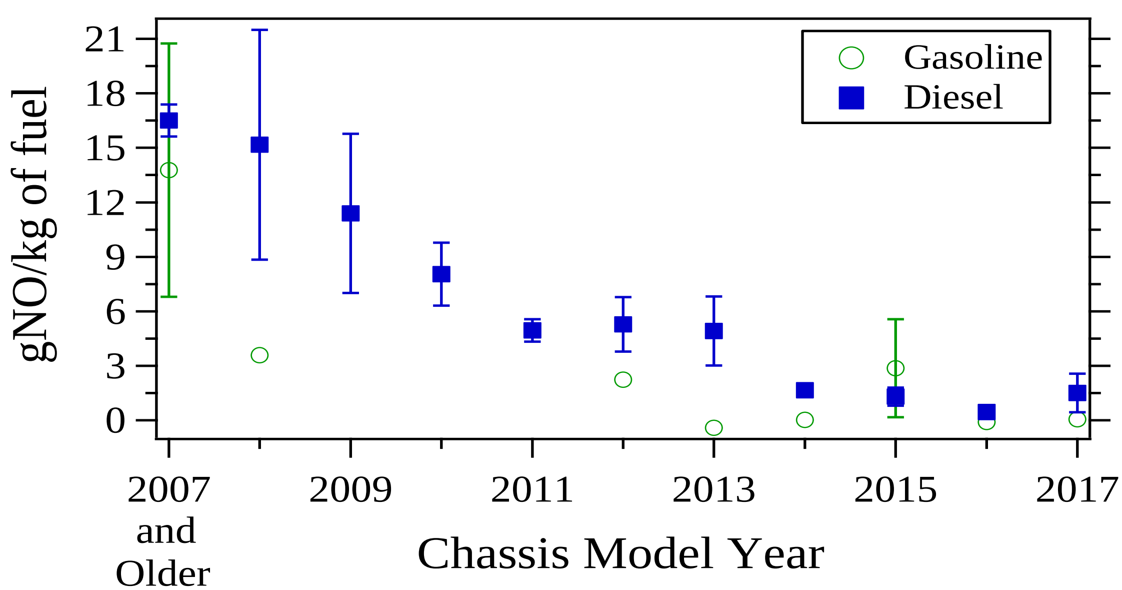

Figure C2. Gasoline (green circles) and diesel (blue squares) MDVs' fuel specific NO emissions by chassis model year. Uncertainties are standard error of the mean calculated using the daily means.

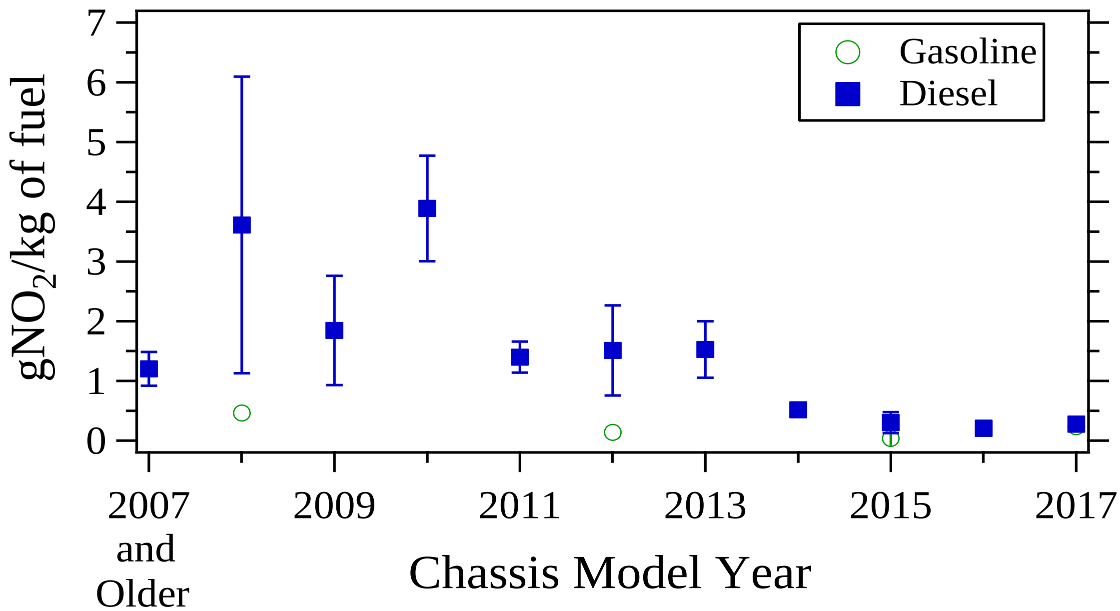

Figure C3. Gasoline (green circles) and diesel (blue squares) MDVs' fuel specific NO_2 emissions by chassis model year. Uncertainties are standard error of the mean calculated from the daily means.

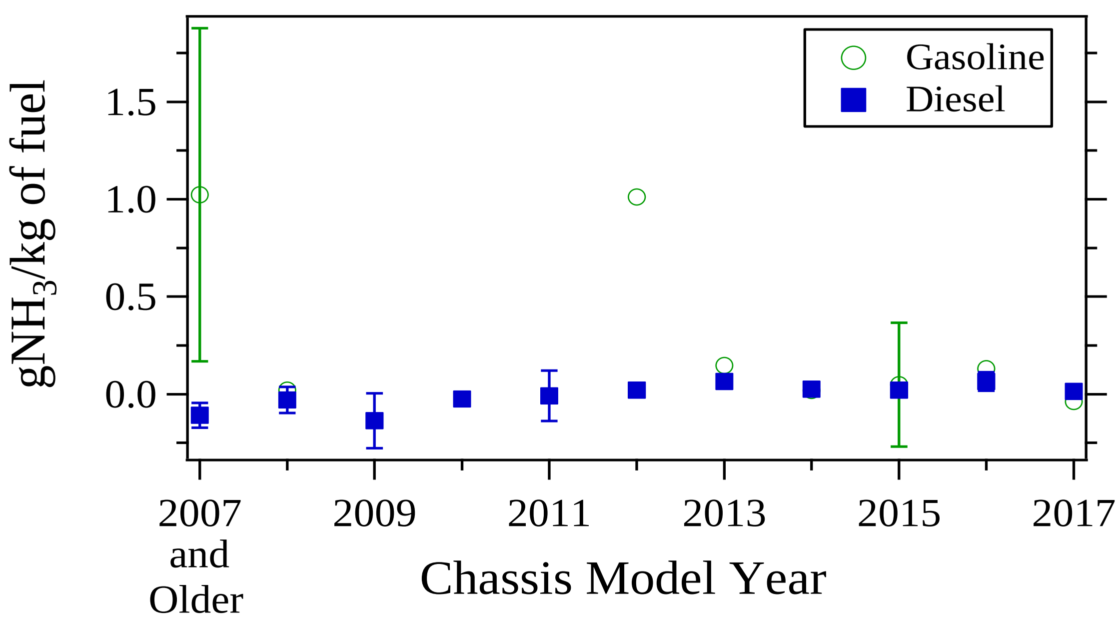

Figure C4. Gasoline (green circles) and diesel (blue squares) MDVs' fuel specific NH_3 emissions by chassis model year. Uncertainties are standard error of the mean calculated using the daily means.

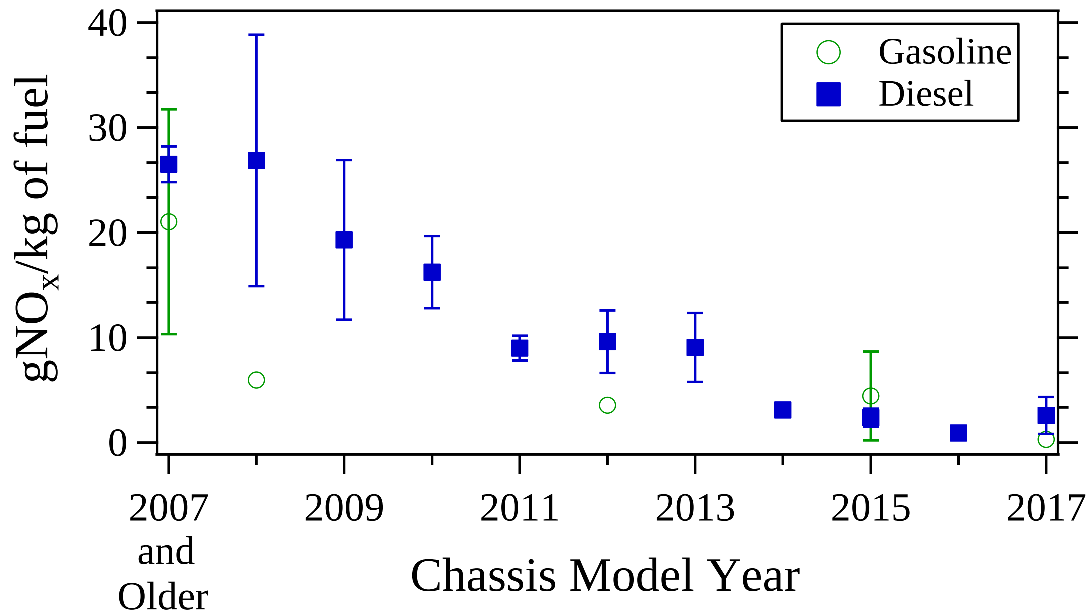

Figure C5. Gasoline (green circles) and diesel (blue squares) MDVs' fuel specific NO_x emissions by chassis model year. Uncertainties are standard error of the mean calculated from the daily means.