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Investigate the Durability of Diesel Engine Emission Controls

Gary A. Bishop

Molly J. Haugen

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Gary A. Bishop and Molly J. Haugen

Department of Chemistry and Biochemistry
University of Denver
Denver, CO 80208

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California Air Resources Board
Chris Ruehl Project Coordinator
101 I Street
Sacramento, CA 95814

Disclaimer

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Abstract

The University of Denver has collected six data sets, each including approximately 1,200 fuel specific emission measurements, from two California fleets: a drayage fleet at the Port of Los Angeles and a long-haul interstate fleet at the Cottonwood weigh station. Collected between 2013 and 2017, they have been used to follow the introduction of diesel particulate filters (DPF) and selective catalytic reduction (SCR) after-treatment systems in heavy-duty trucks to control particulate and oxide of nitrogen (NO_x) emissions. The Port fleet, a fully DPF equipped fleet by 2012, has steadily aged (+3.3 yrs. since 2103) and a small number of trucks were found with high particle emissions. NO_x emissions have slowly increased (21 to 27 gNO_x/kg of fuel) and lower operating temperatures are likely the reason that newer SCR equipped Port vehicles (2011 & newer) have not helped to lower these emissions. The Cottonwood fleet has experienced a steady fleet turnover and with the newer fleet (-1.7 yrs.) both particulate (0.22 to 0.08 gPM/kg of fuel) and NO_x emissions (20.3 to 16 gNO_x/kg of fuel) have declined. Newer SCR equipped vehicles at Cottonwood gives the promise of an additional factor of 3 reduction in fuel specific NO_x emissions by 2023.

Heavy-duty vehicles (HDVs) used in transportation have been a growing energy consumption segment in both the United States and the rest of the world. Combined with the consistent emission reductions experience in light-duty fleets HDVs, despite comprising only a few percent of the total transportation fleet, are responsible for a growing fraction of oxide of nitrogen emissions (NO_x) and particulate matter (PM) emissions and continue to be a target for regulations to limit or eliminate these emissions. Past HDV emission regulations in the U.S. have met limited success as regulations in the 1990's to lower PM and NO_x emissions saw real improvements in PM emissions but were not as successful in reducing NO_x emissions.

Beginning with 2007 model year engines, new regulations were enacted that would eventually require an order of magnitude reduction in both NOx (to 0.2 g/bhp-hr) and PM (to 0.01 g/bhp-hr) emissions. The demands of these reductions have necessitated the development of new engine management systems and aftertreatment devices not previously used in HDVs. The two most notable are the diesel particulate filter (DPF) for PM control and selective catalytic reduction systems (SCR) for NO_x control. The introduction of new emission control technology always brings with it the questions of how well will it perform and how durable it will be. The following discussion of recent research carried out by the University of Denver involves collecting emission measurements from HDVs to provide information to help study these and other questions.

These measurements utilized a new and novel on-road measurement system dubbed OHMS (On-road Heavy-duty Measurement System) that measures the integrated exhaust from HDVs with elevated exhaust pipes using a modified events tent as an exhaust containment system. The approach utilizes a 50-ft. long and 15-ft high tent structure under which the truck drives and, as the exhaust disperses in the roof of the tent, it is captured by a perforated pipe which integrates the trucks emissions as it drives through the tent and that delivers the exhaust sample to a small suite of analyzers in a mobile lab parked at the exit of the tent. The system used in this study is capable of simultaneous measurements of carbon dioxide (CO_2), carbon monoxide (CO), total hydrocarbons (THC), nitric oxide (NO), total NO_x, nitrogen dioxide (NO_2) by difference (NO_x – NO), total PM, particle number concentration (PN) and black carbon (BC).

The method determines fuel specific emission rates of pollutants from the ratio of pollutant to CO_2 for each vehicle. From these ratios using carbon balance, we can calculate the mass emissions for each pollutant per mass or volume of fuel consumed. The system was also configured to determine the speed and acceleration of a vehicle at the entrance and exit of the tent, and was accompanied by three video systems used to record the license plate of the vehicle, infrared images of elevated exhaust pipes to estimate operating temperature and to look for the presence of urea tanks indicating that the vehicle is equipped with a SCR system. Vehicle license plates were matched with state registration databases when available to provide non-personal vehicle information.

The University of Denver has successfully conducted three data collection campaigns for HDVs using the OHMS system at two sites in California in the spring of 2013, 2015 and 2017. The first was located at the exit from Trapac, LLC. container operations at berths 136 - 147 at the Port of Los Angeles in Wilmington, CA. The second was at the California Highway Patrol's Cottonwood scales along I-5 in northern California just south of Redding CA (see Figure ES1). These sites provided contrasting fleets with the Port location having a short-haul drayage fleet that had only recently been required to retire any HDVs with an engine not meeting the 2007 certification standards. The Cottonwood location consisted of an interstate long-haul fleet subject to more traditional fleet turnover changes. The first provided an opportunity to follow the aging process on emissions from a relatively new vehicle fleet while the later would observe the fleet emission trends during the introduction of new technology vehicles via fleet turnover.

Figure ES1. State map showing relative locations of the two California sampling sites.

Table ES1 lists the sampling dates and the measurements overview for the three data collection campaigns that have been conducted since 2013. This has resulted in a total of 7,076 HDV emission measurements and vehicle information being compiled for study. This comprises one of the largest in-use emissions data sets collected to date on HDVs. These databases, as well as any previous data our group has obtained for HDVs can be found at www.feat.biochem.du.edu. With any long term study it is not always possible to control all of the variables from year to year that can impact the data sampling and this study is no exception. Our Port location experienced changes in each of the last two sampling periods as Trapac modernized their facility in 2015 with a new physical exit location and an automated exit process. A speed bump was added across the end of the exit lanes between the 2015 and 2017 campaigns slowing the tent exit speeds of the vehicle. The new exit facility added an additional exit lane that was little used in 2015 but was fully operational in 2017. That along with the addition of the speed bump reduced the number of measurement attempts and is why the last years Port measurements have fewer trucks. At Cottonwood there were no physical changes from year to year but high winds limited the data collection in 2015 and Patrol operational considerations in 2017 reduced the number of HDV with driving modes that optimized successful measurements.

The two fleet's age distributions are moving in opposite directions from each other. Since the first measurements were collected in 2013 the fleet sampled at the Port of Los Angeles has increased in age by approximately 3.3 years as the fleet's mean model year only increased from 2009.1 to 2009.8 over the five year period. The current fleet's dominant chassis model years are 2008 and 2009 models that were purchased prior to the San Pedro Clean Ports Clean Air Action Plan 2010

Table ES1. Program Sampling Schedule and Measurement Totals.

Location	Sampling Dates	Readable Plates	Unique Vehicles	Total Measurements
Port of Los Angeles	April 22 – 26, 2013	1263	954	1220
Port of Los Angeles	March 23 – 27, 2015	1595	999	1456
Port of Los Angeles	April 3 – 7, 2017	797	628	795
Port Totals	15 Days	3655	2581	3471
Cottonwood Scales	May 6 – 10, 2013	2316	1739	1866
Cottonwood Scales	April 8 – 10, 2015	879	792	694
Cottonwood Scales	April 10 – 14, 2017	1153	969	1043
Cottonwood Totals	13 Days	4348	3500	3603

deadline to upgrade to a 2007 PM compliant engine. In 2013 these models made up 70% of the measurements and in 2017 these two models still represented 57% of the measurements. In contrast the fleet at the Cottonwood weigh station has gotten steadily newer as it has turned over. In 2013 the mean model year of 2005.6 corresponded to an approximate fleet age of 7.4 years. In 2015 the mean model year observed was 2008.1 (~6.9 years old) and in 2017 that further improved to 2011.3 (~5.7 years old) or an overall improvement of 1.7 years newer.

Figure ES2 is a bar graph showing the fuel specific emission measurements for the three data collection campaigns for all of the gaseous species means for CO, HC, NO (moles of NO), NO_2 and NO_x (moles of NO_2) for our two sampling locations. The uncertainties plotted are standard errors of the mean calculated from the daily means. At the Port the only consistent trend is for increasing NO_x emissions; ~25% since the 2013 measurements. We have found that NO_x emissions at the Port are generally higher and less affected by model year (see Figure ES3) than similarly aged vehicles at Cottonwood as the Port's activity cycle and subsequent lower operating temperatures are likely not conducive to successful SCR operation. CO and HC emissions at the Port are sensitive to the number of natural gas powered vehicles measured as they have characteristically higher emissions of CO and HC (CH_4) than diesels and the means for both of these species rose (4.5% of the measurements in 2015) and fell (only 1% of the 2017 measurements) with the number of CNG vehicles in the database. These natural gas powered vehicles are included in the fleet averages.

For the HDVs measured at Cottonwood overall all of the gaseous species showed reductions over the five year period, though HC and NO_x did not have consistent trends in this regard. The observed increases in NO_x emissions in 2015 were the result of unexplained systematic increases for all model years. The 2017 measurements by model year are more consistent with the 2015 measurements and the reductions in the mean are a result of the age decrease of the fleet with newer and lower emitting HDVs replacing older and higher emitting HDVs. This indirectly indicates that SCR performance at Cottonwood is significantly better than at the Port (see Figure ES2).

Figure ES4 shows the mean fuel specific PM and BC emissions which are plotted on the left axis and the mean PN/kg of fuel emissions plotted on the right axis. Both locations saw decreases in

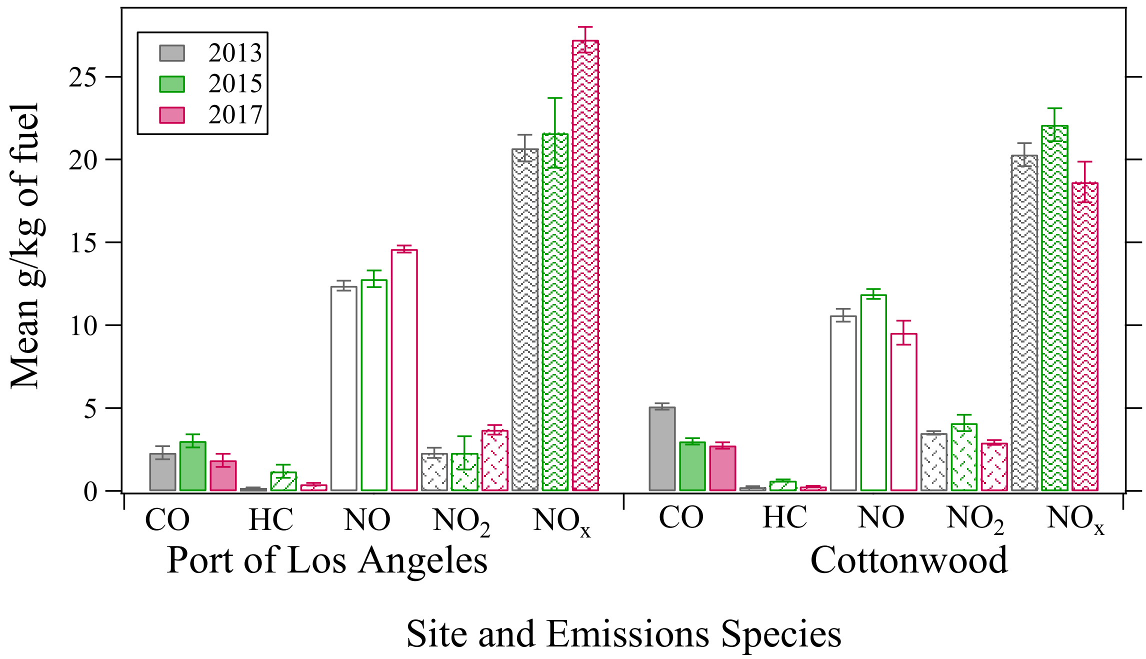

Figure ES2. Mean fuel specific emissions for CO (solid), HC (diagonal), NO (open), NO_2 (hatched) and NO_x (wavy) at the Port of Los Angeles (mean model year 2009.1 to 2009.8) and Cottonwood Weigh Station (mean model year 2005.6 to 2011.3) for 2013 (grey-left bar), 2015 (green-middle bar) and 2017 (red-right bar) HDV fleets. Uncertainties are standard error of the mean calculated from the daily means.

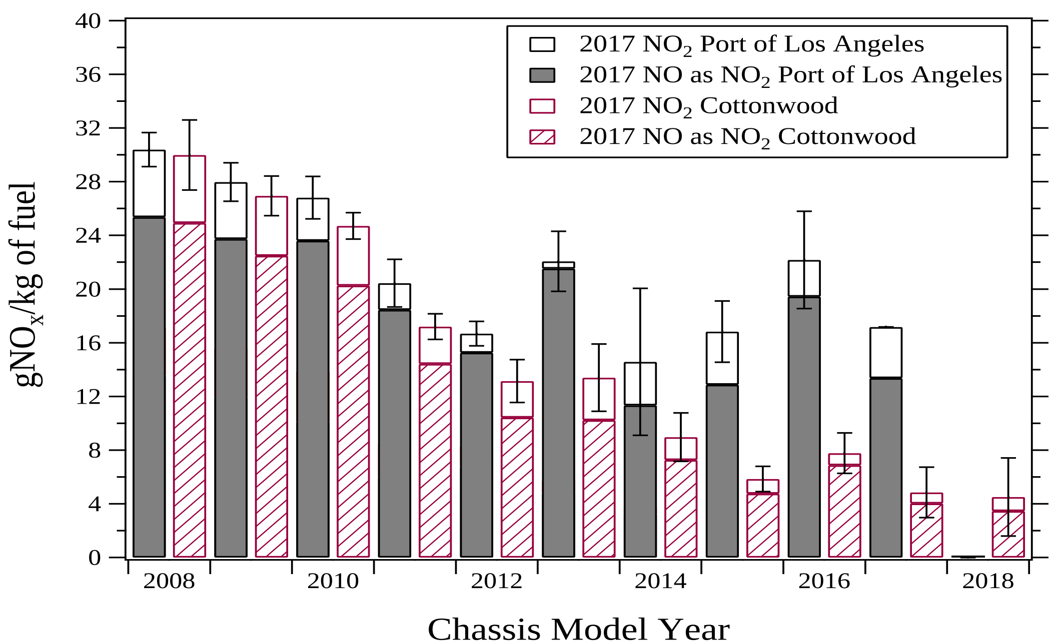

Figure ES3. gNO_x/kg of fuel for 2017 data for the Port of Los Angeles (grey-left bars) and Cottonwood (red-right bars). Filled/hatched portions are gNO/kg of fuel as NO_2 and open portions are gNO_2/kg of fuel. Uncertainties are standard errors of the mean for the total gNOx/kg of fuel calculated from the daily measurements.

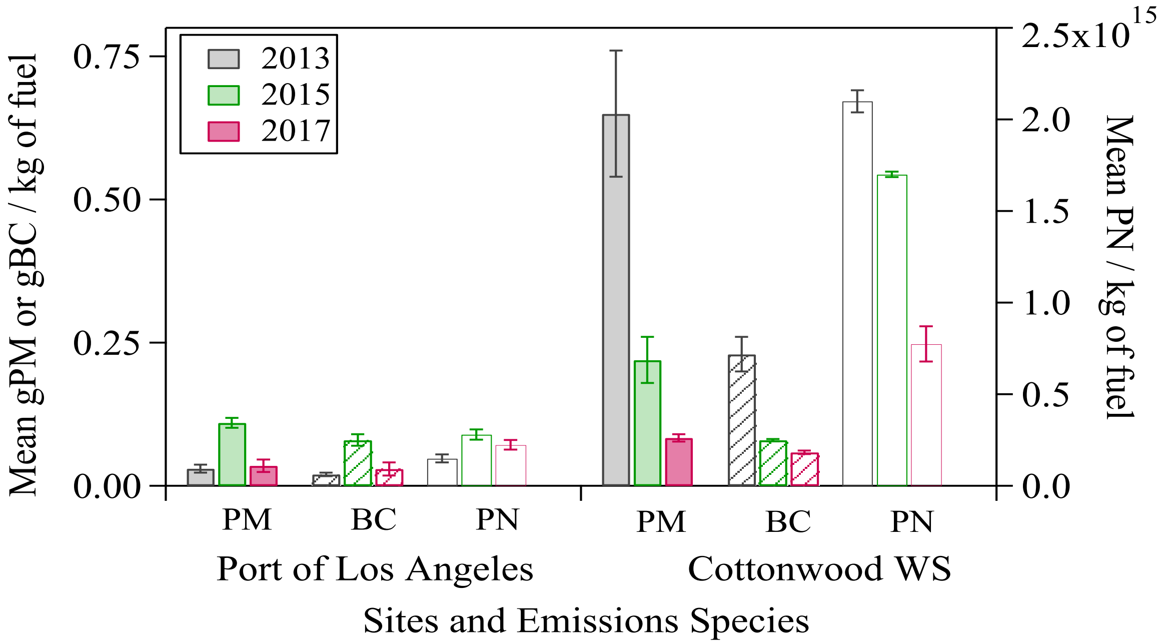

Figure ES4. Fuel specific mean emissions for PM (solid, left axis), BC (diagonal, left axis) and PN (open, right axis) at the Port of Los Angeles and Cottonwood Weigh Station for 2013 (grey-left bar), 2015 (green-middle bar), 2017 (red-right bar) HDV fleets. Uncertainties are standard errors of the mean calculated from the daily means.

particle emissions over the 2015 measurements but for likely different reasons. After the Port's particle emissions experienced significant increases in 2015 due to an increase in the number of high emitters in the 2008 to 2010 chassis model years, the 2017 data saw those high emitter fractions significantly reduced to levels nearer those observed in 2013 with fuel specific PM, BC and PN emissions decreasing 64%, 63% and 20% respectively (0.11 to 0.04 gPM/kg of fuel, 0.08 to 0.03 gBC/kg of fuel and 2.8 x 10^{14} to 2.2 x10^{14} PN/kg of fuel). Figure ES5 is a box and whisker plot for fuel specific PM emissions for the three measurement campaigns at the Port with a split y-axis. The box denotes the 25th to the 75th percentile and the whiskers are the 10th to the 90th percentiles. The mean is represented by a filled square and the horizontal line indicates the median. Individual measurements outside the 10th and 90th percentiles are signified with symbols. This graph illustrates the similarities in the Port's 2013 and 2017 campaigns interquartile ranges for model years 2008 to 2010 and a similar number of measurements beyond the 90th percentile. For model years 2008 and 2010 the upper range of the measurements are generally similar for all of the measurement years), however, the 2015 measurements have more numerically. The exception is the 2009 model year where the 4 measurements at the extreme end of the distribution are all from one truck. One potential explanation for fewer high emitting vehicles in 2017 at the Port of Los Angeles is that the Air Resources Board increased roadside compliance testing (including at the Port and Cottonwood concurrently with the 2015 and 2017 OHMS campaigns) and the issuance of statewide citations since 2015 have increased significantly which may have encouraged corrective maintenance or relocation for some of the high emitting trucks observed in 2015. Of the 38 HDV observed in 2015 with fuel specific PM emissions greater than 0.5 only 4 were observed

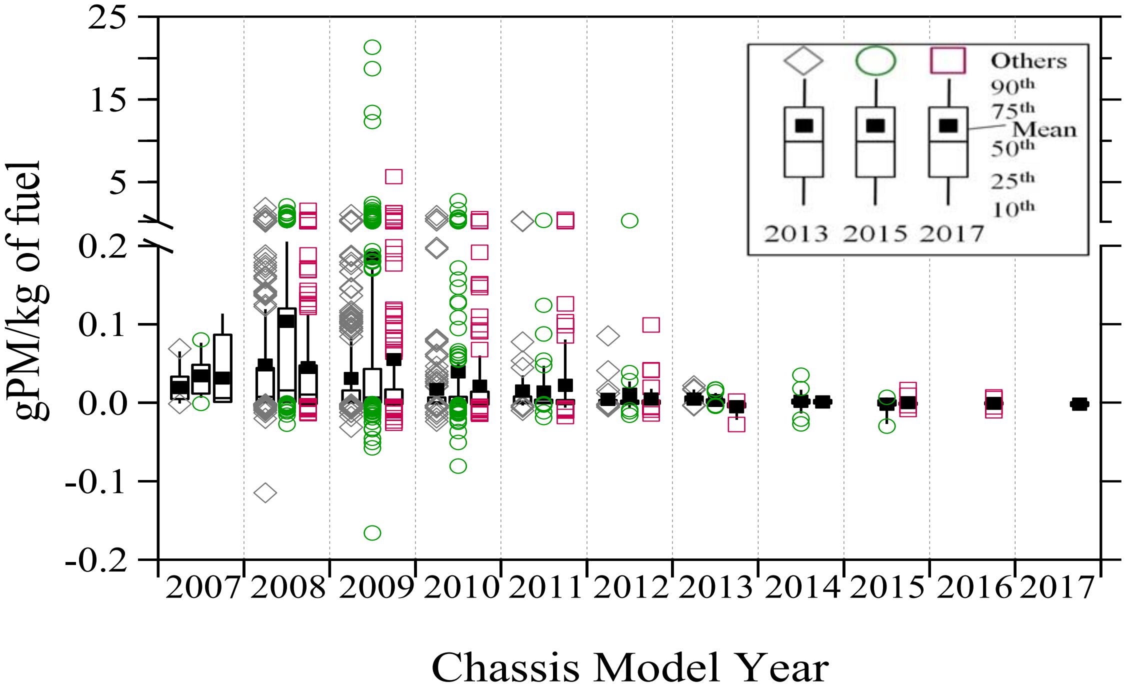

Figure ES5. Box and whisker plot for the Port of Los Angeles gPM/kg of fuel emissions by chassis model year for the 2013 (diamonds), 2015 (circles) and 2017 (squares) data. The box represents the 25th, 50th and 75th percentiles, the whiskers span the 10th and 90th percentiles and the individual measurements that fall outside these percentiles. The filled square is the mean.

again in 2017. One was the highest emitting vehicle measured in 2015 and while its two repeat measurements in 2017 were essentially zero there is some question as to whether it is the same truck as the video images of the trucks front are noticeably different. Two of the remaining three vehicles still had elevated PM emissions (0.26 and 0.25 gPM/kg of fuel) though lower than observed in 2015.

At Cottonwood the combination of a newer fleet, driven by higher turnover, and DPF retrofitting of the remaining older vehicles continued a consistent reduction in particle emissions (see Figures ES4 and ES6). Reductions of almost a factor of 3 over the 2015 fuel specific PM (0.22 to 0.08 gPM/kg of fuel) emission levels, a 57% reduction for PN (1.7x 10^{15} to 7.7 x 10^{14} PN/kg of fuel) emissions and smaller but continued reductions for BC (0.077 to 0.056 gBC/kg of fuel) emission levels were observed. Since 2013 we have observed decreases of 87%, 76% and 64% for fuel specific PM, BC and PN emissions respectively. These sustained reductions have brought the Cottonwood fleet's mean particle emissions to levels that are approaching those observed at the Port indicating that the vast majority of HDVs operating through the Cottonwood scales are now DPF equipped.

Figure ES6 is a box and whisker plot for gPM/kg of fuel emissions by chassis model year for the three data sets collected at the Cottonwood weigh station using a double split y-axis. The box denotes the 25th to the 75th percentile and the whiskers are the 10th to the 90th percentiles. The mean is represented by a filled square and the horizontal line indicates the median. The individual

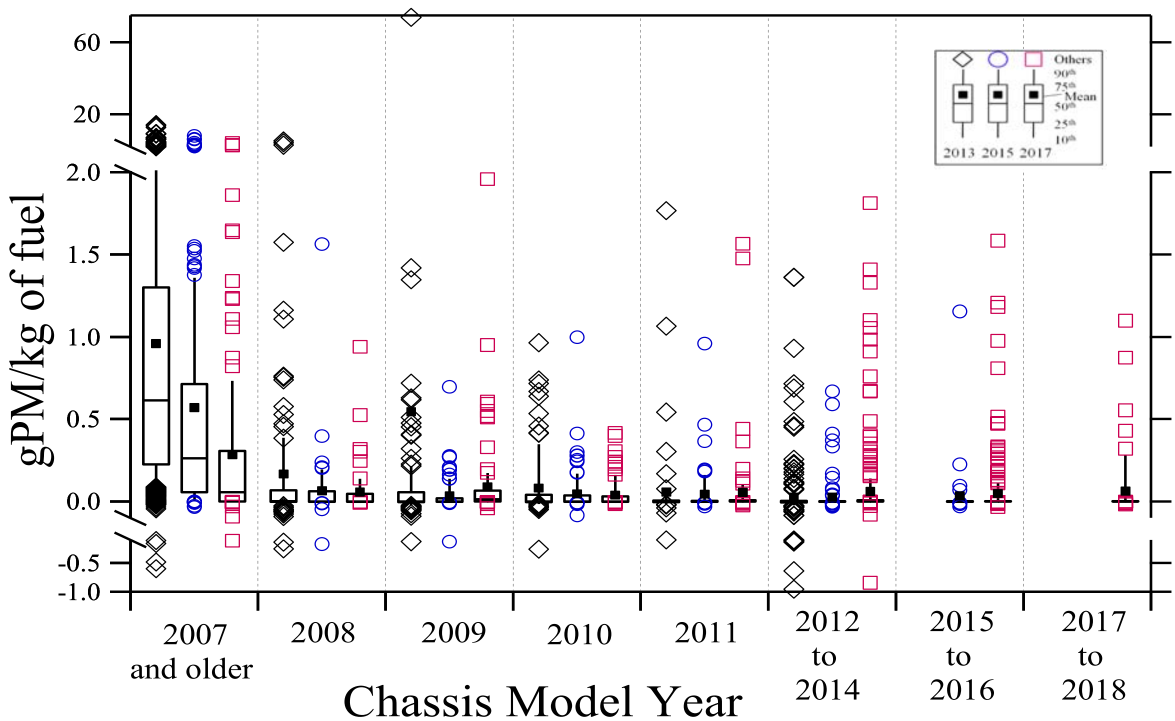

Figure ES6. Box and whisker plot for the Cottonwood weigh station gPM/kg of fuel emissions by chassis model year for the 2013 (diamonds), 2015 (circles) and 2017 (squares) data. The box represents the 25th, 50th and 75th percentiles, the whiskers span the 10th and 90th percentiles and the individual measurements that fall outside these percentiles. The filled square is the mean.

measurements outside the 10th and 90th percentiles are signified with symbols. There are noticeable reductions from the 2007 and older group, though the range of observed fuel specific PM emissions is similar for each year's data set, there are significant reductions in the number of these higher readings. This has dramatically shrunk the size of the interquartile range for each successive measurement campaign and lowered mean emissions for this age group by more than a factor of 2. Mean emissions for the 2008 and newer models are all low, however, there is a question as to why a small number of 2012 and newer model year vehicles have relatively high PM emissions.

A skewed emissions distribution, where a minority of vehicles are responsible for a large fraction of the emissions, is one characteristic of modern vehicle fleets where tailpipe emissions are generally tightly controlled. Figures ES7 and ES8 document the evolution of the emissions distribution at our two sampling sites. Figure ES7 shows the fraction of the fleet that is responsible for the corresponding cumulative fraction of the total PM emissions at the Port of Los Angeles for the three data sets. Deviation from the 1:1 line (a normal distribution) indicates that fewer vehicles are responsible for a larger percentage of the total PM emissions. The 2015 Port fleet had the most skewed emissions distribution as fewer vehicles with high PM emissions were responsible for a larger fraction of the total gPM/kg of fuel. One high emitting vehicle in 2015, measured four times, was responsible for 40.6% of the total PM emissions. As displayed in Figure ES5 the 2017 fleet

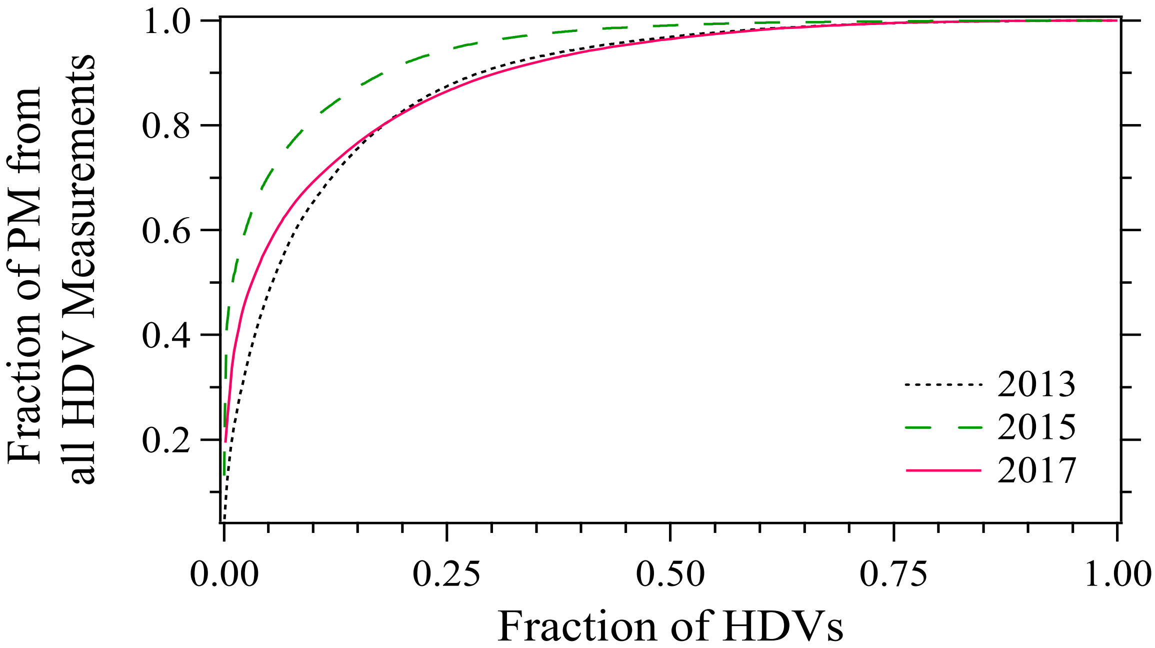

Figure ES7. Cumulative fraction of gPM/kg of fuel from the cumulative fraction of HDV measured at the Port of Los Angeles for 2013 (black dotted line), 2015 (green dashed line) and 2017 (red solid line).

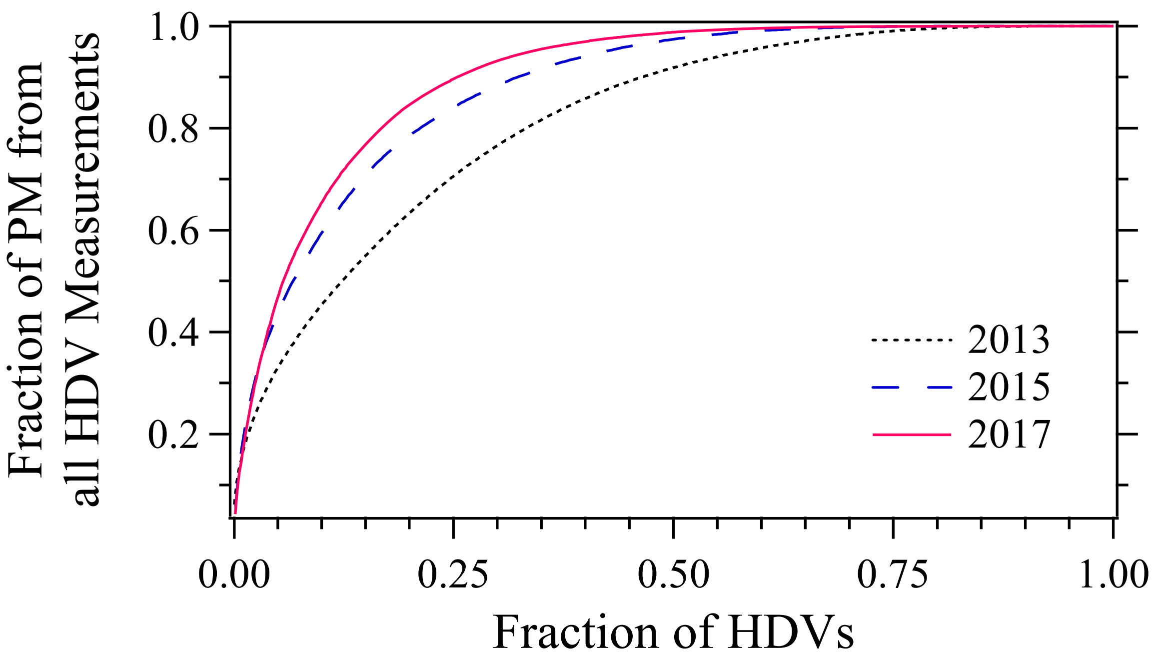

Figure ES8. Cumulative fraction of gPM/kg of fuel from the cumulative fraction of HDV measured at Cottonwood for 2013 (black dotted line), 2015 (blue dashed line) and 2017 (red solid line).

returned to an emissions distribution that is more like the emissions distribution observed in 2013 and has more evenly distributed PM emissions across all HDVs.

At Cottonwood, Figure ES8, the fleet PM emissions distribution is becoming increasingly skewed due to the retirement of pre-DPF vehicles, either through turnover or by retrofitting older vehicles with DPFs. With consistently low PM emitting vehicles dominating the fleet the mean PM emissions have a growing dependence on fewer vehicles.

In the future we still expect these two fleets to be on different age paths. Prior to the OHMS measurements at the Trapac exit the University of Denver collected remote sensing measurements in 2008 – 2010 and in 2012 (Bishop et al., Environ. Sci. Tech., 46, 2012, Bishop et al., Environ. Sci. Tech., 47, 2013). Figure ES9 combines the two data sets to show our Port of Los Angeles sites change in the fleet's mean model year (right axis) and age (left axis) by measurement year. The San Pedro Clean Ports Clean Air Action Plan appears to have only temporarily interrupted the previous business model of HDVs at the Ports of Los Angeles and Long Beach which was based on using the oldest and cheapest vehicles in the fleet for the short haul operations. Since 2010 the Port fleet has gotten progressively older (5 years from 2010 and 3.3 years since the first OHMS measurements in 2013), though it is still younger than the pre-control fleet the trend suggests it will likely revisit those highs again. The State of California's Truck and Bus Rule will undoubtedly eliminated most of the Ports pre-2011 trucks, however, by 2023 there should be an ample market of used 2010 compliant vehicles. If this turns out to be the case then actively enforcing the certification compliance of these vehicles will determine if the emissions reductions achieved in 2010 can be maintained. We do know that SCR equipped vehicles do not perform up to certification standards at our Port monitoring site (see Figure ES3) and so NO_x reductions are likely to not be at the levels anticipated by the new standards barring significant improvements in low temperature NO_x reductions technologies.

We would expect the fleet at Cottonwood to continue to ebb and flow with the economies of the times. During good times the fleet will likely continue to get younger while possibly suffering some setbacks during the downturns. We believe that particle emissions at the weigh station will likely decrease a little more as the last of the pre-2008 trucks are retired but the current fleet is very close to levels seen at the Port of Los Angeles in 2013 indicating a total DPF equipped fleet. As the fleet at Cottonwood continues to turn over and become an all SCR equipped fleet we would expect NO_x emissions to continue their downward trend. The lowest emitting model years at Cottonwood (2015 & newer, see Figure ES3) indicate that it is possible for fuel specific NO_x emissions to decrease an additional factor of 3 (~18 gNO_x/kg of fuel to ~5 gNO_x/kg of fuel) which will be driven by the States Truck and Bus rule. Current SCR technology, when operational, is more than capable of delivering the large NO_x reductions called for in the certification standards and we expect this technology to continue to improve its performance as more experience is gained with designing and building it for HDVs.

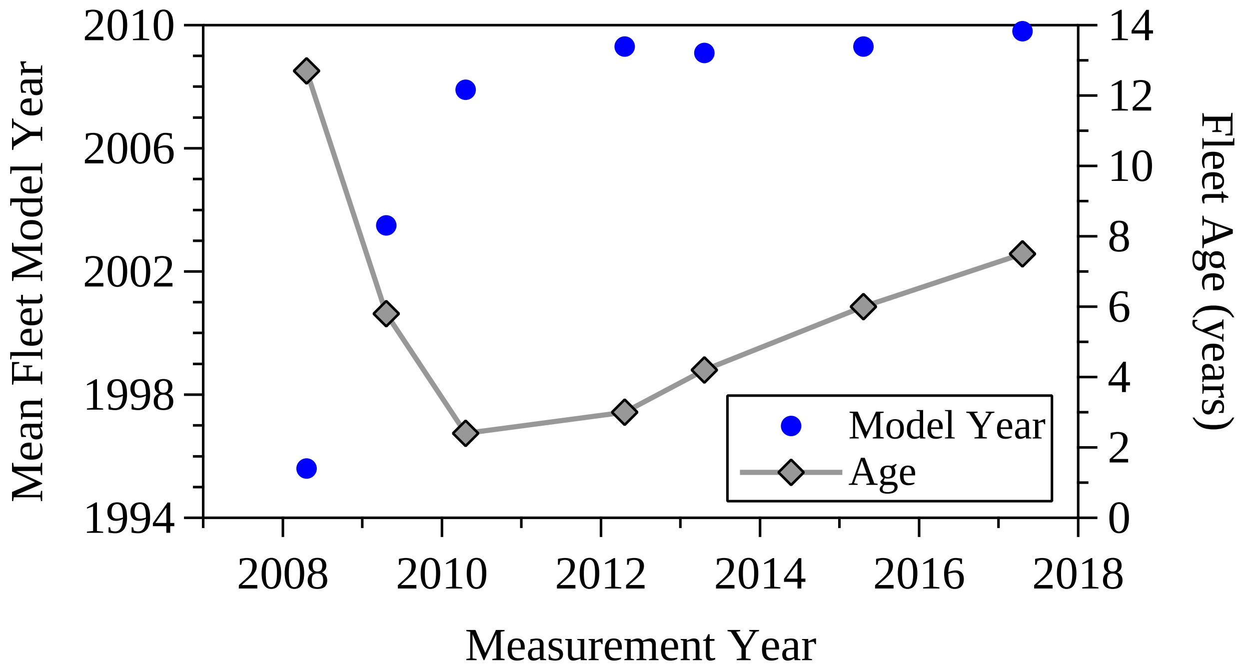

Figure ES9. Mean fleet model year (●, left axis) and age (◆, right axis) by measurement year for all of the data collected at the Port of Los Angeles measurement site.

Introduction

Humankind imposes many and varied impacts on the natural environment and, in the United States, transportation and its effects will always be on the list of the most important. The United States is the largest consumer in the world of transportation energy, consuming more than 25% of the world's total in 2012.[1] Light-duty cars and trucks numerically dominate the US transportation fleet but heavy-duty vehicles (HDV) have become the fastest growing segment. Combined these two groups consume more than 85% of all the transportation fuels.[2] Combined with the consistent emission reductions experience in light-duty fleets HDVs, despite their being a small fraction of the fleet, are responsible for a growing fraction oxide of nitrogen emissions (NO_x) and particulate matter (PM) emissions and continue to be a target for regulations to limit or eliminate these emissions.[3, 4]

Despite more than 50 years of regulating vehicle emissions, they are still a significant source of carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_x) and ultrafine particulate matter (PM).[5] HDV in particular have been a point of emphasis in new regulations to significantly reduce NO_x and PM emissions. Federal and California regulations, beginning with 2007 heavy-duty engines, required an order of magnitude reduction in PM to 0.01 grams/brake-horsepower hour (g/bhp-hr) to directly combat black carbon (BC) emissions considered to be a serious health threat.[6-8] In addition, beginning with 2010 heavy-duty engines, regulations requiring the phase-in of new HDV meeting a 0.2 g/bhp-hr NO_x emission limit have also been implemented.

For HDV these regulations have been met with the adoption and implementation of new and advanced after-treatment systems. The two most important advancements being the diesel particulate filter (DPF) for PM and BC control and selective catalytic reduction (SCR) systems for NO_x emissions control. Both of these technologies have proven themselves to be more than capable of meeting the certification standards of the new regulations but there are always concerns about how robust the systems will be in realistic everyday usage. One way to investigate the efficacy and reliability of vehicle emission control systems is to make repeat emission measurements of HDV over time and document the changes observed. This approach has been successfully used for light-duty vehicles at multiple sites across the US and for HDV at the Port of Los Angeles and the Caldecott tunnel.[9-14]

This research report covers the results of a multi-year study of HDV emissions at two California locations using a new and novel measurement technique which we hope will provide insights into how DPFs and SCRs age. As light-duty fleet emission distributions have become increasingly skewed it is expected that the HDV fleet will follow suit.[15] Quantifying the frequency of HDV that develop an emissions problem, and the higher emissions level that results, cannot easily be forecast. Fleet distribution information requires methods that can collect reasonably sensitive emissions data from a large number of HDV that are representative of the on-road population. This last requirement may the most important in that, if any systematic method evolves to modify or disable the new emissions control systems, the modified systems will likely not be found with testing programs that have to recruit individual vehicles.

Experimental

OHMS Measurement System

The On-road Heavy-duty Measurement System (OHMS) measurement method is composed of an exhaust collection system, an exhaust measurement system and a vehicle monitoring component. The exhaust collection system consists of a modified events tent, large enough for HDV to drive under, to contain exhaust from trucks with elevated exhaust stacks. The tent used in this study was 50 ft. long, 15 ft. wide, and 18 ft. high at its peak (see Figure 1). The vehicle's passenger side of the tent has a ¾ length side wall to help trap the exhaust based on the fact that typical HDVs almost always have one elevated exhaust stack on the right hand side behind the passenger side of the cabin. The driver's side tent wall is left open so as not to obstruct the driver's view of the traffic. The completely open side wall also helps to reduce the tent's wind profile. Each of the tent's legs were secured to the ground with either water barrels or cement weights.

Figure 1. A photograph of the OHMS setup at the Cottonwood weigh station in northern California. The exhaust intake pipe is in the upper left part of the tent and two of the water barrels are visible next to the right front tent leg. The orange road barrel just to the right of the mobile laboratory contains the camera used to take the picture of each vehicles license plate.

Anchored to the roof of the tent along the passenger side of the vehicle is the exhaust air intake pipe (see Figure 2). It consists of a 50 ft. long piece of 4” diameter light-weight, thin wall irrigation pipe secured with rope to the underneath side of the tent roof with air intake holes drilled every foot for a total of 50 holes. The hole diameters gradually decrease in size from ~1in at the entrance to the tent to ¼in at the exit and are generally angled toward the roadway. At the tent exit the pipe is attached to a short section of pipe with two 90º elbows that move the air flow to the outside wall of the tent and point it toward the ground where, after an additional 5ft of pipe, it is connected to an inline fan (Fantech FG 4XL, 135 cfm). One final piece of pipe about 2ft long is added after the fan through which the analyzer sampling lines are inserted into the exhaust air stream. As a truck drives through the tent the exhaust contained in the tent is drawn through the holes throughout the length of the tent. When the vehicle speed matches the pipe’s air speed, exhaust sampled from a previous hole is continuously added to with new exhaust at each successive hole. The air intake pipe has an estimated residence time of approximately 8s and the vehicle emissions are rapidly diluted in the process by approximately a factor of 1000. In this way the perforated tube integrates the diesel exhaust over whatever drive cycle the truck drives under the tent roof. The design goal was a typical on-road acceleration cycle that this tractor might use when driving in any urban area.

Figure 2. Photograph showing a closer view of the exhaust sampling pipe anchored to the roof of the tent. The inline fan is the metal oval between the two sections of pipe.

The emission analyzers are housed in the University’s mobile lab parked next to the tent (see Figure 1) and consist of a Horiba AIA-240 CO and CO_2 analyzer, two Horiba FCA-240 THC/NO analyzers for the gaseous pollutants and for particulate measurements a Dekati Mass Monitor (DMM 230-A) and a Droplet Measurement Technologies Photoacoustic Extinctiometer (PAX). Appendix A contains the instrument manufacturer’s specifications for each of the analyzers. The Horiba AIA-240 measures CO and CO_2 using non-dispersive infrared absorption. The determination of total hydrocarbons (THC) is made with one of the Horiba FCA-240 instruments using a flame ionization detector (FID). This analyzer is also used to measure NO using the ozone chemiluminescent reaction. The second Horiba FCA-240 is only used for a second NO measurement and is configured to measure total NO_x ($NO + NO_2$). This is accomplished with the addition of a reaction chamber supplied by the manufacturer in the analyzer that converts all nitrogen dioxide (NO_2) to NO which is then measured using ozone chemiluminescense.

The Dekati DMM is used for total particle mass (PM) and particle number (PN) measurements and contains an inertial 6-stage impactor with a mobility channel for aerodynamic size and a corona charger with an online particle density measurement for particle mobility size information. These two components combined with a number of additional assumptions enable density calculations of the particles required for conversion from measured current values to report total particle mass in $\mu g/m^3$ and number concentration. The DMM samples over a particle size range from 0 to 1.2 µm and particles larger than 1.2µm are not measured.

The PAX consists of a reciprocal nephelometer which measures the light scattering for all particles and a photoacoustic cell for absorption measurement of only black particles to determine BC mass concentration. A modulated diode laser simultaneously measures the scattering and absorption of particles. The standard 870 nm wavelength is highly specific for BC particles with little absorption from other gases or aerosols. As the laser beam is directed through the aerosol stream, absorbing particles heat up and transfer energy to the surrounding air producing pressure waves detected by a microphone in the photoacoustic cell. All of the analyzers sample continuously at 1Hz, but only the PM, PN and BC data are continuously recorded and saved.

Figure 3 is a schematic diagram (not drawn to scale) of the exhaust sampling system, vehicle monitoring components and data collection computers. The gaseous analyzers are fed by a twin piston pump (KNF NeuBerger) which delivers 55 l/min of exhaust via ¼ in. Teflon tubing. The compressed sample is routed through a water condensation trap to dry the sample before it is passed through the analyzers. The particulate instruments contain their own sampling pumps and are fed by a separate ¼ in. copper tube.

Additional information collected on each vehicle measured includes a front license plate picture, speed and acceleration rates, external exhaust pipe thermographs and a digital picture of the driver's side of the vehicle. The license plate of each vehicle is captured using a camera positioned in front of the tent inside a road barrel. The camera, when triggered, captures an image of the front of each vehicle. The images are stored digitally and the transcribed plates were incorporated into the emissions database. The license plates were matched against a number of state registration records as availability dictated and non-personal vehicle information was retrieved and added to the emissions database.

Speed and acceleration were measured on each vehicle at the entrance and exit to the tent. Speed sensing bars (Banner Industries) consisted of a pair of infrared beams passing across the road, 6 ft. apart and approximately four feet above the roadway. OHMS set-up utilized two pairs of speed sensing bars (entrance and exit) reporting two sets of speeds and accelerations. Vehicle speeds are

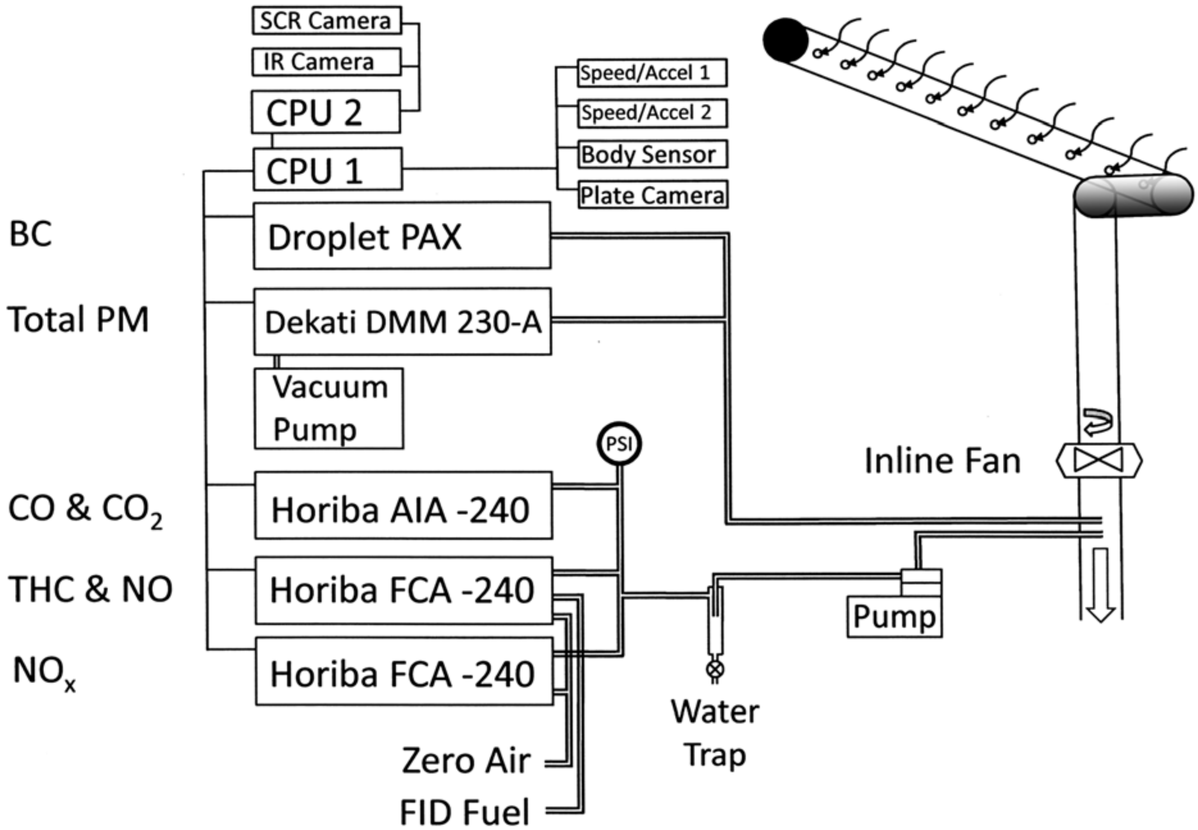

Figure 3. Schematic drawing (not to scale) of the OHMS exhaust sampling, analysis and vehicle emissions data collection systems.

reported in units of mph and were calculated from the average of the two reported times collected when the front cab of the tractor blocks the first and second beam, and then the rear of the cab unblocks each beam. The acceleration at the entrance and exit are reported in units of mph/s.

An infrared camera (Thermovision A20, FLIR Imaging) was used to capture thermographs of elevated exhaust pipes to qualitatively record operating temperature (see Figure 4). An additional computer system and software were installed to store the captured thermographs from the infrared camera. Thermographs were captured of the passenger side of each truck. The thermographs were initially compared to a laboratory calibration using a stainless steel exhaust pipe and temperatures were estimated for the individual exhaust between 90°C to 350°C for the 2013 data set. This system and calibration have been used and reported on in previous measurements of HDV in California.[11]

To convert infrared emission images to an absolute temperature involves knowing the emissivity of the material being imaged. Heavy-duty truck exhaust systems are primarily stainless steel, thus the choice for the laboratory calibration, however small changes in its formulation and finish can result in large (in some cases up to a factor of 10) changes to the steels emissivity.[16] Because of these uncertainties in emissivity we undertook the development of a field calibration of the infrared camera using the camera and a thermocouple on real HDVs. Appendix B details the temperature

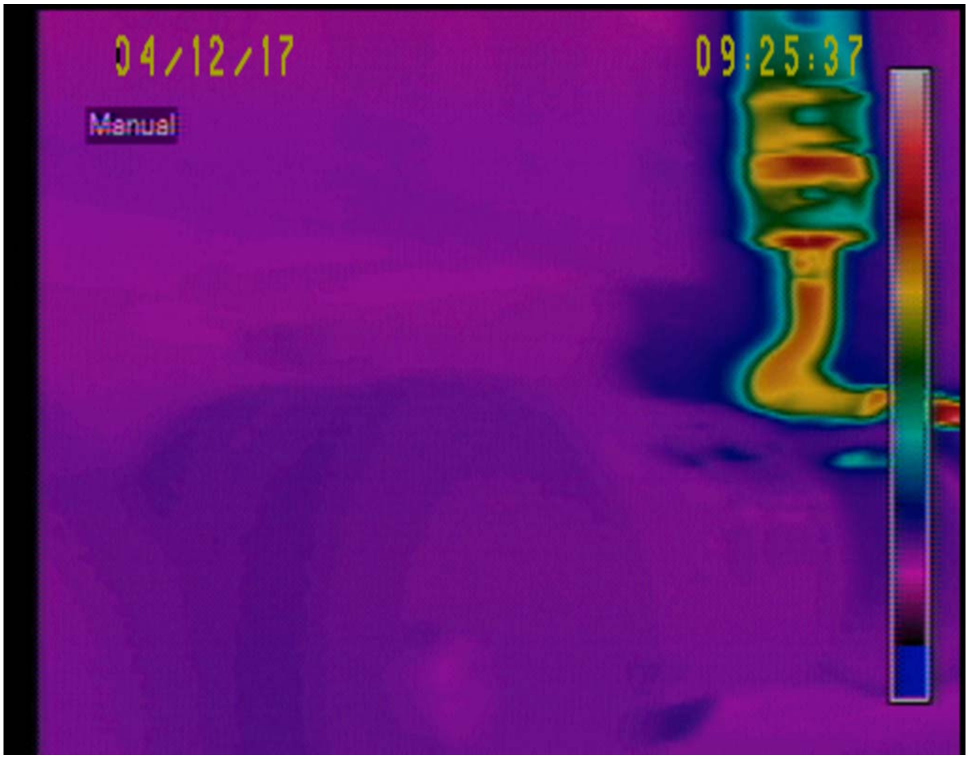

Figure 4. Thermographic image of the exhaust pipe taken at the Cottonwood location of a truck leaving the scales. The relative scale ranges from approximately ~50°C for blue to ~160°C for bright red.

measurements on 226 HDV which resulted in a significant reduction in the temperature scale range than was originally used.

A second, consumer grade, digital camera (Canon SX100) was used to collect images of the driver side of the vehicles measured. DMV vehicle registration information does not provide any information regarding the emission control devices that might be installed on HDVs limiting data analysis to using chassis model year as the defining emissions classification. Since the NO_x emission standard was phased in beginning with 2010 engines and was not fully phased in until 2015, engines many trucks in that age range do not have SCR systems. These pictures are an attempt to locate trucks with visible urea tanks, often with distinguishable blue tank caps visible on the driver's side of the truck as shown in Figure 5. The images were visually inspected and trucks found to have a urea tank were marked as such in the database. The more variable the exit speeds are the more difficult it is to consistently photograph the required region of the truck and therefore the success rate varies by location.

Fuel Specific Measurements and Calibration

OHMS directly measures HDVs fuel specific emissions of CO, THC, NO, NO_x, PM, BC as ratios to CO_2, which yields ratios that are often constant for a given exhaust plume. Unlike our optical measurement method which measures for only one second, restricting driving to only a single mode, the tent is long enough to allow the possibility of multiple operating modes and introduces

Figure 5. Driver side image of a truck leaving the port location with the urea tank clearly visible.

the possibility of measuring differing emission ratios. This means that some of the fuel specific emissions that are reported are averages of those multiple operating modes. Because we are measuring emission ratios the calibration methods employed are similar to those used with our optical measurements.

The CO_2 analyzer is zeroed and spanned at each site with a certified mixture of 3.5% CO_2 in nitrogen (Air Liquide). The CO, HC, NO and total NO_x analyzers are adjusted to have a positive offset when sampling background air to preclude any negative readings. Daily calibrations of CO, HC, NO and the total NO_x analyzers are made with multiple injections of a BAR-97 certified low-range calibration gas (0.5% CO, 6% CO_2, 200ppm propane and 300ppm NO in nitrogen) using a large Delrin syringe and injecting into the gas sampling pump intake tube above the inline fan and averaging the measured CO/CO_2, HC/ CO_2, NO/CO_2 and NO_x/CO_2 ratios and then dividing by the cylinder's certified ratios. The results are used to scale all of the measured vehicle emission ratios.

An additional field calibration was attempted in 2013 to determine the NO_2 conversion efficiency of the catalyst in the total NO_x analyzer. Like the other ratio calibrations, we injected multiple samples of a certified NO_2/CO_2 calibration gas (91 ppm NO_2 in 2.99% CO_2, Air Liquide) and averaged the results for each site. The results were extremely inconsistent from day to day and site to site and resulted in much lower conversion efficiencies than expected (73% at the port and 55% at Cottonwood). These efficiencies greatly increased the proportion of NO_2 in the total NO_x measurements to levels that were inconsistent with literature measurements.[10]

To investigate the reliability of the field NO_2/CO_2 calibrations we setup both the NO and total NO_x analyzers in the lab to test the catalyst conversion efficiency by performing an ozone titration of NO. In this titration we introduce a steady stream of NO to both analyzers and after stabilizing we record both of their concentration measurements. When both readings are stable we turn on an ozone generator and produce enough ozone to titrate approximately half of the NO, by converting it to NO_2 ($NO + O_3 \rightarrow NO_2 + O_2$), and thus lowering the reported concentration from the NO detector by half. When the readings stabilize we again record the reported concentrations from both analyzers. If the reducing agent in the total NO_x detector is 100% effective the output from the total NO_x analyzer will not change during this experiment while the output from the NO analyzer will be reduced by approximately 50%. Figure 6 shows the graphical results of that experiment and, within our ability to measure the reducing agent efficiency it is 100%, as initially expected and as advertised by the instrument vendor. It is possible that our field calibrations suffer from inconsistent NO_2 losses; either via a chemical reaction, or from wall loses in the syringe, or the exhaust handling system. The final results in this report from all the field campaigns have used the laboratory calibration. Preliminary reports from earlier studies we conducted prior to these measurements used the field "calibrations" which we now believe were incorrect.

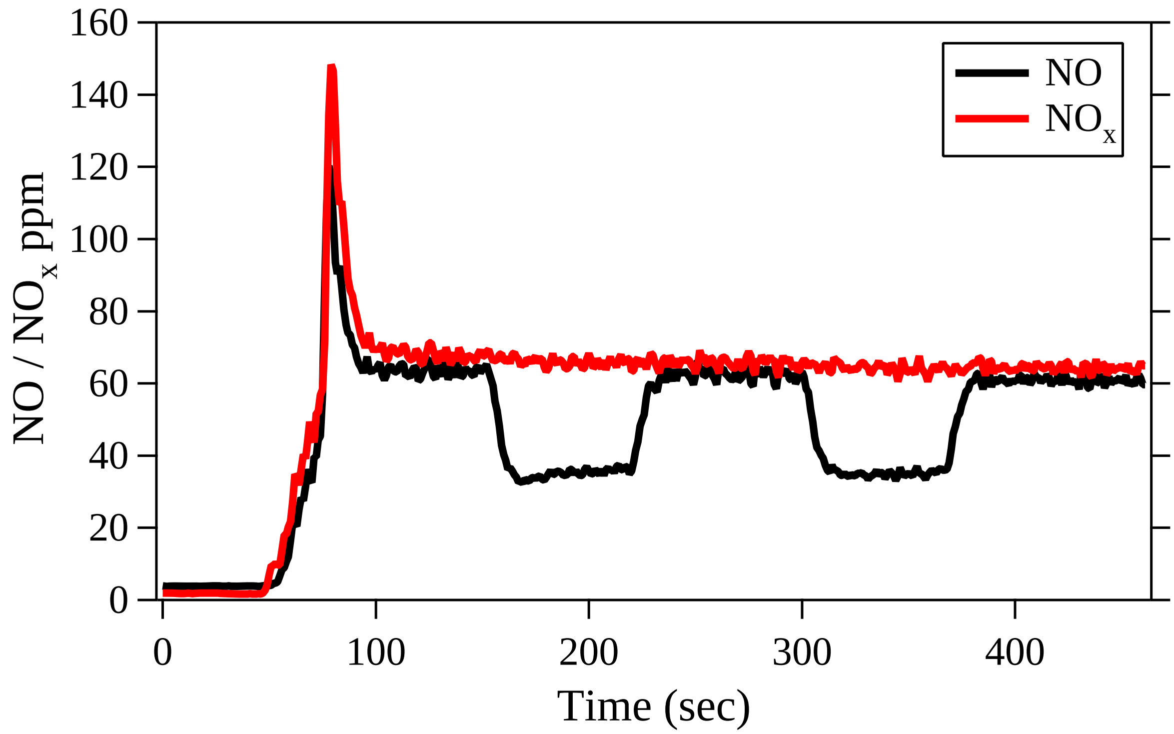

Figure 6. NO (black line) and NO_x (red line) concentrations versus time during an ozone titration of NO. The large peak at the beginning is from opening the NO bottle and after equilibration the ozone generator is turned at a level which titrates about half of the NO in the sampling stream leaving the total NO_x concentration unaffected.

Data collection is initiated when the IR body sensor at the tent exit is blocked, signaling the presence of a vehicle. Digital images are recorded from the plate camera, the IR camera and the SCR camera and emissions voltage data are collected at 1Hz from the five analyzers. The length of the sampling can be tailored to each particular site depending on the frequency of the HDV traffic. For this study we initially collected 20 seconds of emissions data at the Port and 15 seconds of data at the Cottonwood weigh station in 2013. In 2015 and 2017 only 15 seconds of data was collected at both sites. The voltage data are converted into concentrations, either ppm or $\mu g/m^3$ depending on the analyzer, using the instrument response equations. Figures 7 and 8 are the reported second by second emission concentrations for a 2003 Freightliner measured at the Cottonwood weigh station. The raw data as shown have not yet been time aligned, which is readily apparent when comparing the CO_2 trace with the NO_x. The increase in CO_2 emissions seen for this truck is at about the mean ΔCO_2 for all of the trucks measured at the Cottonwood weigh station in 2013.

The data are time aligned using the lags that were predetermined during the setup of the emissions sampling system. The alignment is not always perfect as some of the analyzers have time constants which are slightly more or less than our full one second of sampling. After the data have been time aligned, each emission species is correlated against CO_2 and a least squares line is fit to the data with the slope of that line equal to that species fuel specific emissions ratio.

Figures 9 and 10 show the results of those correlations for the 2003 Freightliner. Note that some of the y-axis species have been offset in order to show them more clearly. The measured pollutant ratios can be reported as the final measurement but we choose to convert them directly into grams of pollutant per kilogram of fuel burned. This is achieved by first converting the ratios to moles of pollutant per mole of carbon in the exhaust with the following equation:

$$\frac{\text{moles pollutant}}{\text{moles C}} = \frac{\text{pollutant}}{CO + CO_2 + HC} = \frac{\left(\frac{\text{pollutant}}{CO_2}\right)}{\left(\frac{CO}{CO_2}\right) + 1 + \left(\frac{HC}{CO_2}\right)} = \frac{Q, Q', Q''}{Q + 1 + Q'}$$

OHMS directly measures the ratios of $Q = \frac{CO}{CO_2}$, $Q' = \frac{HC}{CO_2}$, $Q'' = \frac{NO}{CO_2}$, etc. that are often constant for a given exhaust plume. Moles of pollutant are converted to grams by multiplying by molecular weight, such that if CO is the gas measured in the calibration, then 28gCO/mole is the conversion, and the moles of carbon in the exhaust are converted to kilograms by multiplying the result by 0.014 kg of fuel per mole of carbon in fuel (~860 gCarbon/kg of fuel), assuming the fuel is stoichiometrically CH_2. Grams per brake-horsepower emissions can be estimated from grams per kg of fuel burned by assuming an engine fuel usage rate. In previous work we have estimated a constant fuel usage rate of 0.15 kg/bhp-hr, based on an average assumption of 470g CO2/bhp-hr.[17]

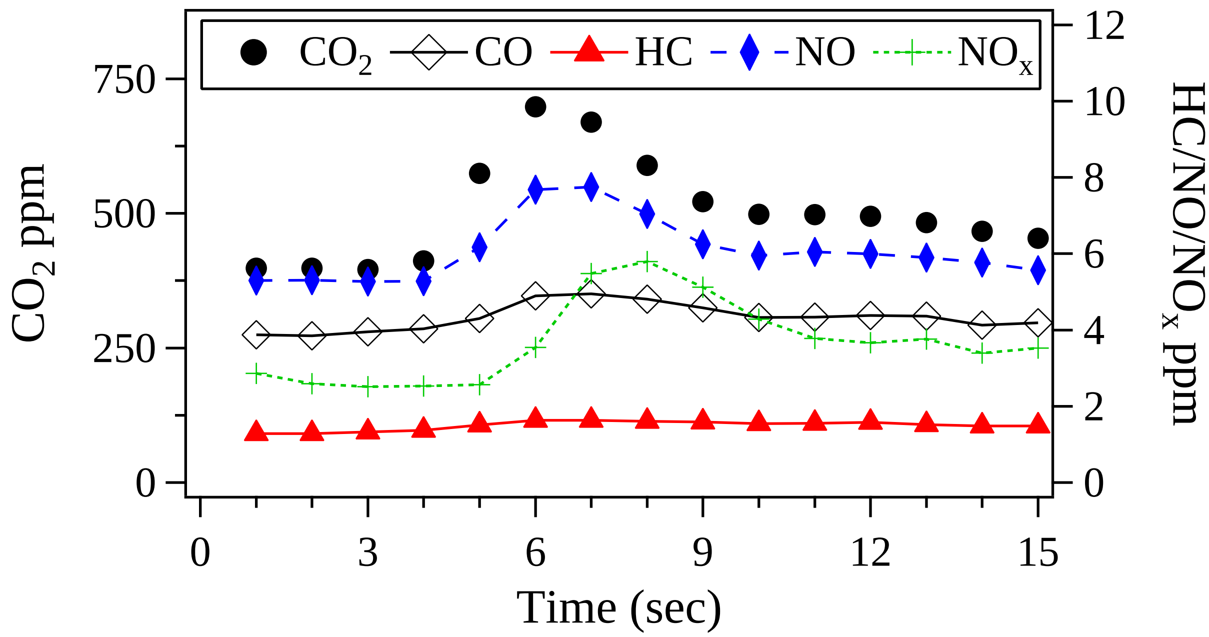

Figure 7. Concentration time series for the gaseous species from a 2003 Freightliner measured at the Cottonwood site. CO_2 data (circles) are plotted on the left axis while the CO (open diamonds), HC (triangles), NO (filled diamonds) and NO_x (pluses) are plotted on the right axis. Data has not been time aligned.

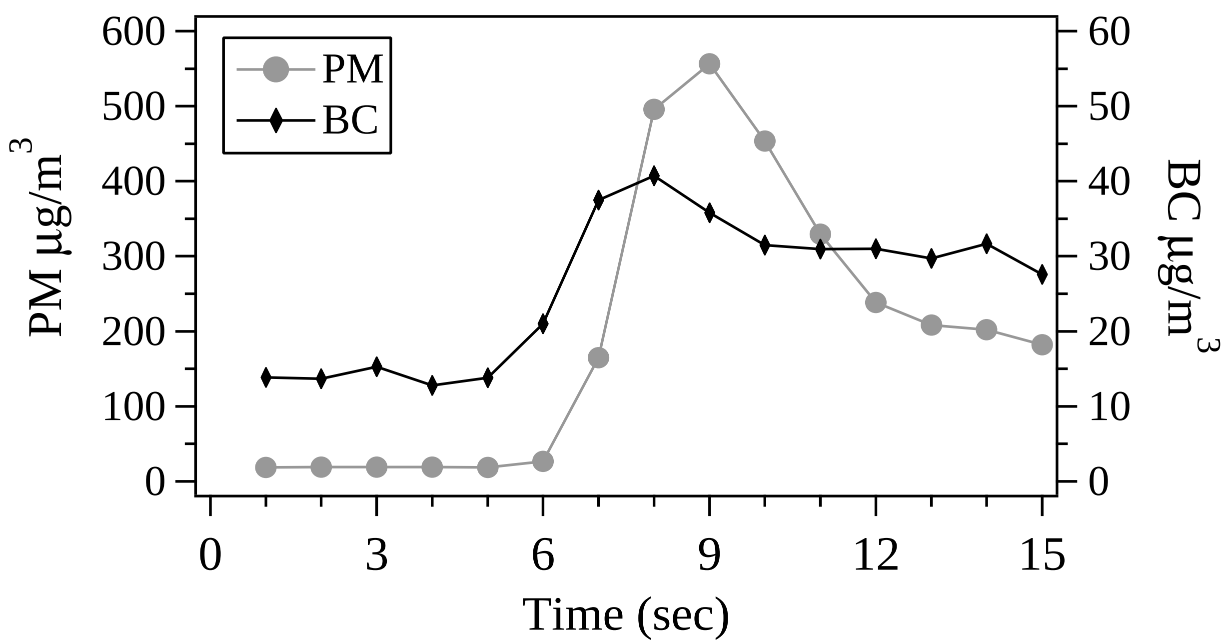

Figure 8. Concentration time series for the particulate emissions from a 2003 Freightliner measured at the Cottonwood scales. Total PM mass (circles) data are plotted on the left axis and the BC mass (diamonds) are plotted on the right axis. Data are not time aligned.

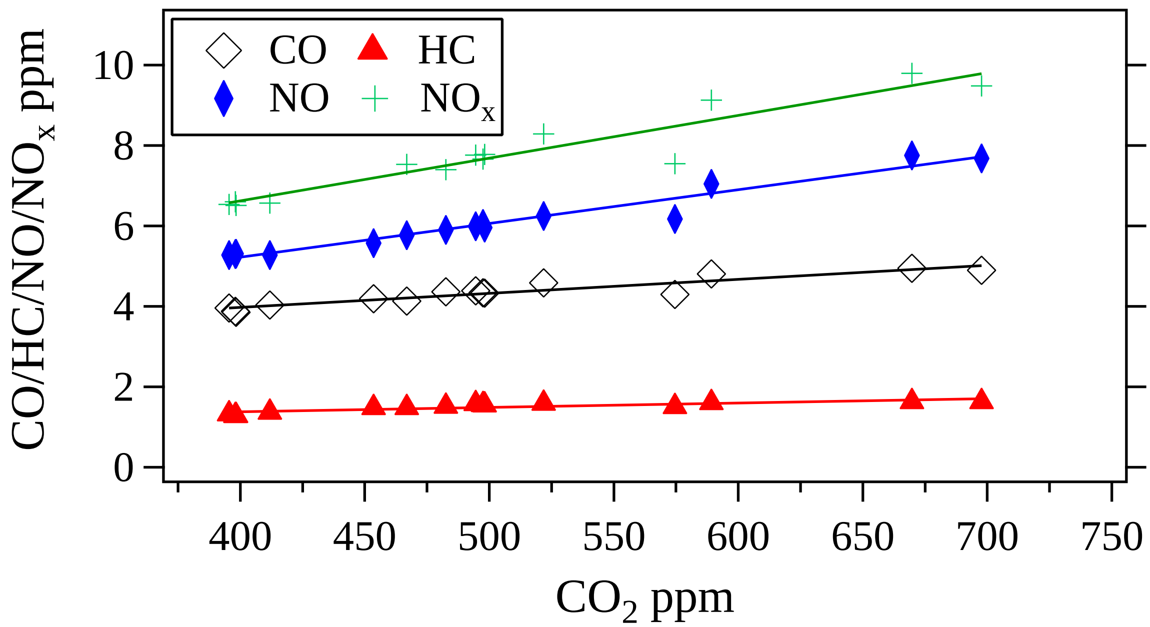

Figure 9. Correlation plots for each of the gaseous species against CO_2 for the 2003 Freightliner measured at the Cottonwood weigh station. The NO_x concentration data have been offset from their true values to clearly show the data points.

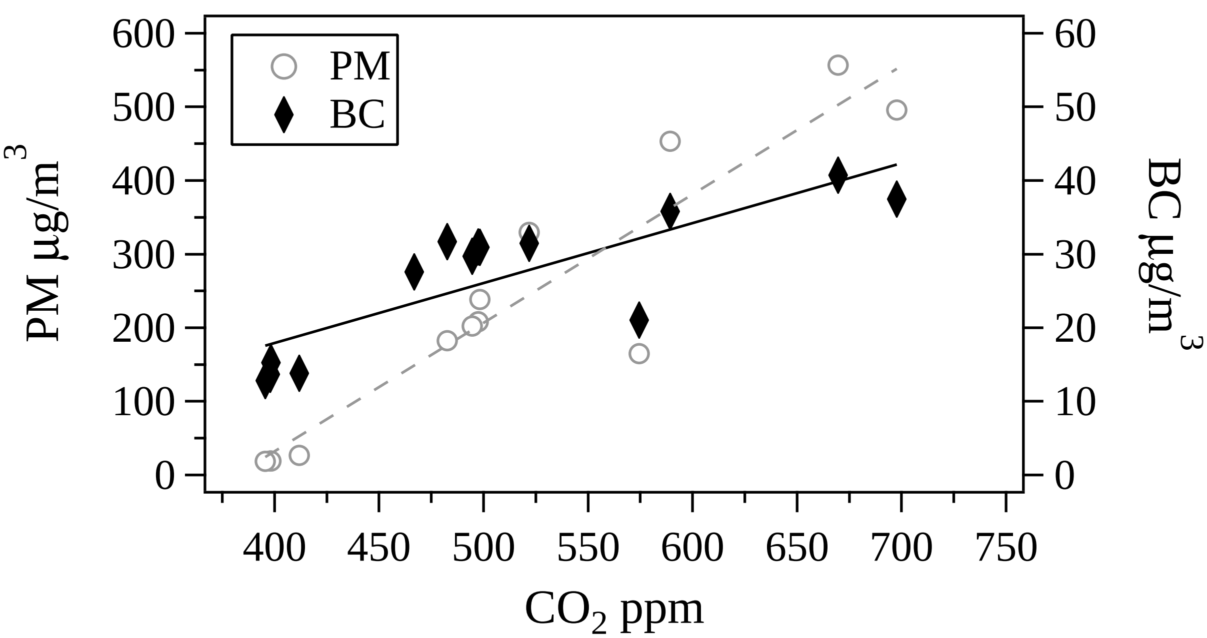

Figure 10. Correlation plots for fuel specific PM (left axis) and BC (right axis) against CO_2 for the 2003 Freightliner measured at the Cottonwood weigh station.

Field Sampling Sites

Emission measurements were collected at two locations in California in the spring of each year, one at the Port of Los Angeles (POLA) and the other at the California Highway Patrol's Cottonwood weigh station. Figure 11 is a map showing the two sites relative location to each other. The POLA site in Wilmington, CA has been used since 2008 for four additional measurement campaigns of HDV conducted by the University of Denver.[10, 11] Measurements are made at the exit gate from TraPac's container berths just west of the intersection of West Water Street and South Fries Avenue. The Cottonwood weigh station is located on North I-5 between Red Bluff and Cottonwood, CA.

Figure 11. Map showing relative locations of the two California sampling sites.

Results and Discussion for the 2013 Measurements Campaign

The Port sampling collection was conducted between Monday April 22 and Friday April 26, 2013 from approximately 8:00 to 17:00 just beyond the blue checkout exit kiosk. Three lanes led to the exit, lane one was used for the OHMS set-up and collection and the remaining two lanes were used by Trapac for overflow and bobtails. The set-up is just west of the intersection of West Water Street and South Fries Avenue approximately 30 feet beyond the blue exit kiosk. A picture of the OHMS set-up at the port is shown in Figure 12. The trucks would come to a halt at the exit kiosk and then accelerate through the OHMS set-up.

The Cottonwood weigh station is located on the northbound side of I-5 in Tehama County. Sampling collection from 8:00 to 17:00 occurred on Monday May 6th to Friday May 10th, 2013. Three lanes pass through the weigh station with the OHMS equipment occupying the east lane (see setup in Figure 1). As drivers exited the highway, variable message signs instructed the trucks to use lane one except during periods of heavy traffic when the overflow was diverted into lanes two and three. After the scales, a flag man at the entrance to the tent would waive the truck through the tent or instruct the driver to bypass the tent and exit via the parking area to the right. Bypassing some trucks was required because the OHMS system could not always maintain a high enough throughput to keep up with the number of trucks.

Figure 12. Photograph at the Port of Los Angeles of the OHMS setup in 2013 used to detect exhaust emissions from heavy-duty diesel trucks. The perforated exhaust sampling and integration tube is again visible on the left side of the tent.

The five days of data collection at the Port resulted in 1278 readable license plates with a valid CO_2 plume detection. The numbers of trucks available for measurements was lower than in past campaigns at this location due to startup and learning issues with the OHMS equipment and by a long port side electrical power outage that shutdown all activity on Friday April 26th. Data were filtered by undetected emissions, unmatched license plates, and invalid CO_2 detection. Appendix C provides a summary of the validity criteria used. As seen in previous campaigns at the port, the vast majority of trucks at this location are California registered vehicles with only 37 vehicles registered outside of the state. Table 1 details the state registration counts, the total number of measurements and the number of unique trucks measured. License plates were match for the California and Oregon registered trucks.

The five days of data collection at the Cottonwood weigh station resulted in 2316 readable license plates with a valid CO_2 plume detection. With the weigh station on a major north-south trade route the number of trucks registered outside of California increased significantly. Table 2 details numbers of trucks observed from the various states and Canada. License plates were matched for California, Oklahoma, Oregon, Washington State and British Columbia Canada.

Table 1. Distribution of Identifiable Port of Los Angles Plates.

State	Readable Plates	Unique Plates	Unique Matched Plates	Total Measurements
Arizona	1	1	0	0
California	1227	920	912	1218
Illinois	2	2	0	0
Indiana	11	11	0	0
New Jersey	13	11	0	0
Ohio	5	5	0	0
Oregon	2	2	2	2
Texas	2	2	0	0
Totals	1263	954	914	1220

Table 3 provides a data summary of all the measurements that were collected at the two sites. The measured mean ratios to CO_2 are reported along with the g/kg of fuel emissions with standard errors of the mean calculated using the daily mean measurements at each site. The Port fleet is much younger than the weigh station fleet as a result of the San Pedro Bay Ports Clean Air Action Plan (CAAP) having been fully implemented.[18, 19] Since the CAAP requires all of the class 7 and class 8 trucks to be DPF equipped the fleet means for PM and BC are significantly lower at the port location. As previously reported, the measured exhaust temperatures at the port are lower than measured at the weigh station due in large part to the stop and go nature of the port driving before our measurement site.[11] Mean NO and NO_x emissions are not however, lower at the port but are similar to the means observed at Cottonwood. The higher NO_x emissions at the port have previously been believed to be a combination of the larger power demand driving mode at the exit (accelerating away from the gate from a complete stop) and lower after-treatment temperatures.[11] The mean vehicle specific power (VSP) estimates for the two sites has been calculated using the equation developed by Jimenez.[20]

IR thermographs of external exhaust pipes were captured on as many trucks as possible at each of the locations. We had some technical difficulties at Cottonwood on the last two days of measurements that produced images which were unreadable and they had to be excluded from the analysis. Figure 13 is a bar chart showing the IR estimated exhaust temperature distributions for each site. Keep in mind these are the temperatures observed on the external exhaust pipes which are not necessarily adjacent to the exhaust after-treatment equipment. This analysis has been restricted to diesel fuel trucks only, and excluded the LNG trucks at the Port. The temperature difference between the Port and Cottonwood is approximately 12º C which is about 11º C less difference than observed during our last Port and Peralta weigh station measurements.[11] The temperatures observed in the Port trucks are consistent with their lower operating activity and are about 10º C warmer than previous measurements. The temperatures observed at Cottonwood are similar to those measured at Peralta in 2012 (105 ± 5ºC).

Table 2. Distribution of Identifiable License Plates at the Cottonwood Weigh Station.

State / Country	Readable Plates	Unique Plates	Unique Matched Plates	Total Measurements
Alabama	1	1	0	0
Arkansas	14	12	0	0
Arizona	2	0	0	0
California	1143	0	1002	1122
Connecticut	13	0	0	0
Florida	1	1	0	0
Georgia	8	0	0	0
Iowa	7	0	0	0
Idaho	6	0	0	0
Illinois	18	0	0	0
Indiana	25	0	0	0
Louisiana	184	0	0	0
Michigan	13	0	0	0
Minnesota	6	0	0	0
Mississippi	5	0	0	0
Missouri	3	0	0	0
Montana	1	1	0	0
Nebraska	8	0	0	0
New Jersey	2	0	0	0
New Mexico	27	0	0	0
Nevada	1	1	0	0
North Dakota	10	0	0	0
Ohio	5	0	0	0
Oklahoma	26	0	25	25
Oregon	451	0	437	437
Pennsylvania	9	0	0	0
South Dakota	6	0	0	0
Tennessee	14	0	0	0
Texas	2	0	0	0
Utah	1	1	0	0
Washington	201	0	189	196
Wisconsin	5	0	0	0
Canada	98	0	86	86
Totals	2316	17	1739	1866

Table 3. OHMS 2013 Data Summary.

Study Site	Port of Los Angeles	Cottonwood Weigh Station
Mean CO/CO_2 (g/kg of fuel ± SEM)	0.0012 (2.3 ± 0.4)	0.0026 (5.1 ± 0.2)
Median gCO/kg	0.74	3.0
Mean HC/CO_2 (g/kg of fuel ± SEM)	0.0002 (0.20 ± 0.03)	0.00025 (0.25 ± 0.04)
Median gHC/kg	0.086	0.11
Mean NO/CO_2 (g/kg of fuel ± SEM)[a]	0.0058 (12.4 ± 0.3)	0.005 (10.6 ± 0.4)
Median gNO/kg[a]	11.2	10.1
Mean gNO_x/CO_2 (g/kg of fuel ± SEM)[b]	0.0063 (20.7 ± 0.8)	0.0062 (20.3 ± 0.7)
Median gNO_x/kg[b]	19.5	19.3
Mean NO_2/CO_2 (g/kg of fuel ± SEM)	0.00069 (2.3 ± 0.3)	0.0011 (3.5 ± 0.1)
Median gNO_2/kg	1.1	3.1
Mean Mass NO_2/NO_x	0.11	0.17
Mean gPM/kg ± SEM	0.031 ± 0.007	0.65 ± 0.11
Median gPM/kg	0.003	0.21
Mean gBC/kg ± SEM	0.020 ± 0.003	0.23 ± 0.03
Median gBC/kg	0.002	0.074
Mean PN/kg ± SEM	$1.5 \times 10^{14} \pm 2.5 \times 10^{13}$	$2.1 \times 10^{15} \pm 6.0 \times 10^{13}$
Median PN/kg	2.8×10^{12}	5.8×10^{14}
Mean Model Year	2009.1	2005.6
Mean IR Estimated Exhaust Temperature (°C) ± SEM	86 ± 1	98 ± 5
Mean Entrance Speed (mph)	4.8	9.8
Mean Exit Speed (mph)	5.8	10.5
Mean Entrance Accel (mph/s)	0.24	0.68
Mean Exit Accel (mph/s)	0.34	0.55
Mean VSP (kw/tonne)[c]	0.73 / 1.1	2.4 / 2.2
Slope (degrees)	0°	(-0.5)°

[a]grams of NO

[b]grams of NO_2

[c]calculated using equation from Jimenez et al., 1999.

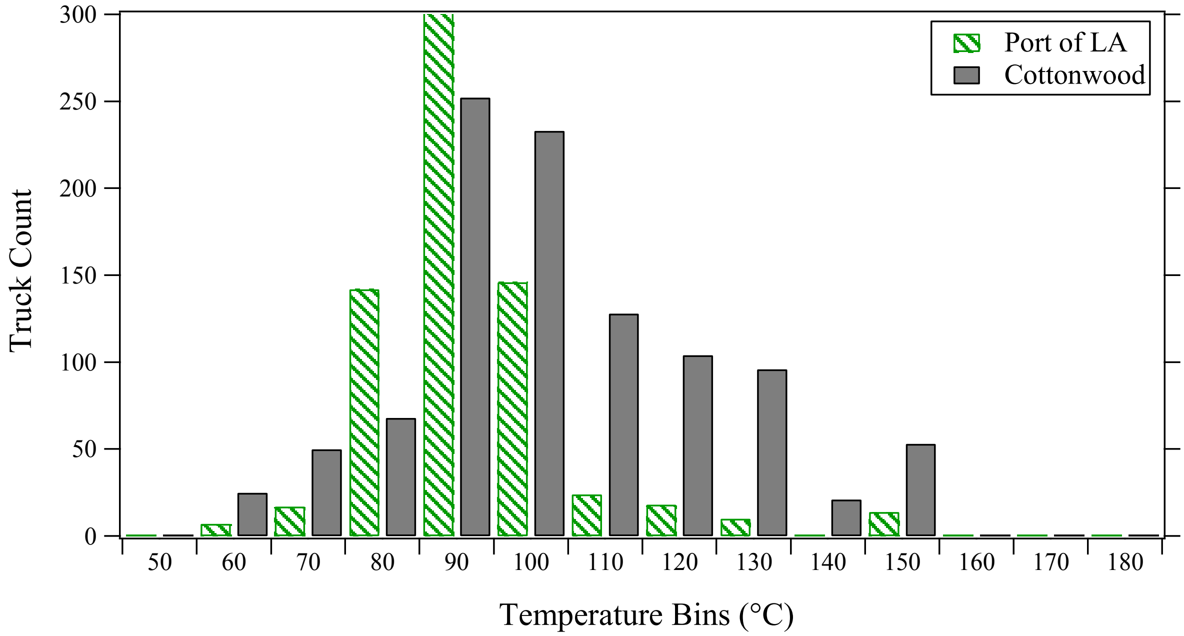

Figure 13. Distribution of infrared estimated exhaust temperatures for HDV at the two measurement locations in 2013. These data use the 2015 field calibration of the infrared camera (see Appendix B).

Figures 14 and 15 are bar charts showing the emission trends for NO, NO_2 and total NO_x emissions by chassis model year at our two sampling locations. In these plots the grams of NO are plotted as grams of NO_2 and the uncertainties are standard errors of the means determined using the daily means at each site for the total. As mentioned in the discussion of the fleet means the NO_x emissions at the Port are higher than would be expected based totally on the age and certification standards of the engines in-use. The Port NO_x emissions are more comparable to models about five years older that we observed at the weigh station and the newest models do not show the increasing NO_x reductions. As briefly mention before this is not a new observation as previous emission comparisons with a weigh station in the Anaheim Hills showed similar results.[11]

Figures 16 and 17 compare the mean gNO_x/kg of fuel emissions by chassis model year for the OHMS measurements and our last year (2012) of optical measurements in the South Coast Air Basin. The comparison at the Port are from the identical sampling location while the most significant differences in the weigh station comparison is that at Peralta (EB SR-91, Anaheim Hills) the station exit is slightly uphill (1.6º). Keep in mind that the similar chassis model years are older in the OHMS measurements. The error bars are plotted as standard errors of the mean determined from the daily means.

At the Port where we have a direct comparison between the two methods, the means and emission trends by model year are very similar. At the weigh stations the comparison show a few more differences with the FEAT optical measurements at the Peralta weigh station having lower mean gNO_x/kg of fuel emissions beginning with the 2004 chassis models. However, the trends are remarkably similar between the two weigh stations and both show significant reductions in mean NO_x emissions with the 2008 and 2011 chassis model years. The NO_x reductions observed starting

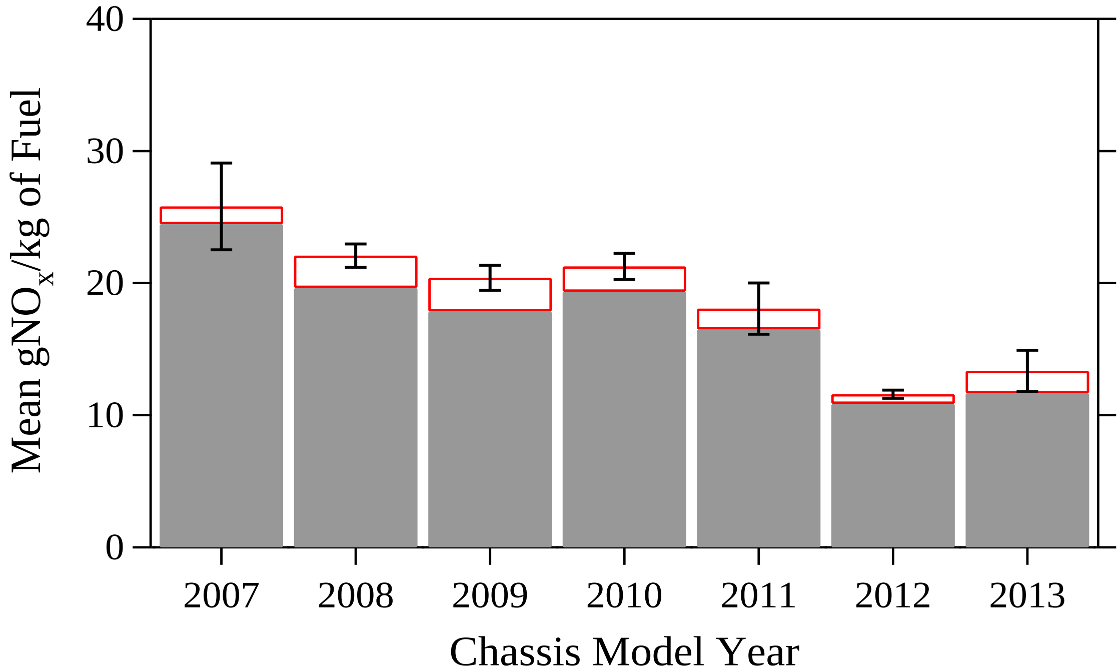

Figure 14. Mean gNO$_x$/kg of fuel versus chassis model year for the Port of Los Angeles location. Grams of NO are reported as grams of NO_2 and the standard errors of the mean are for the total and were calculated using the daily means.

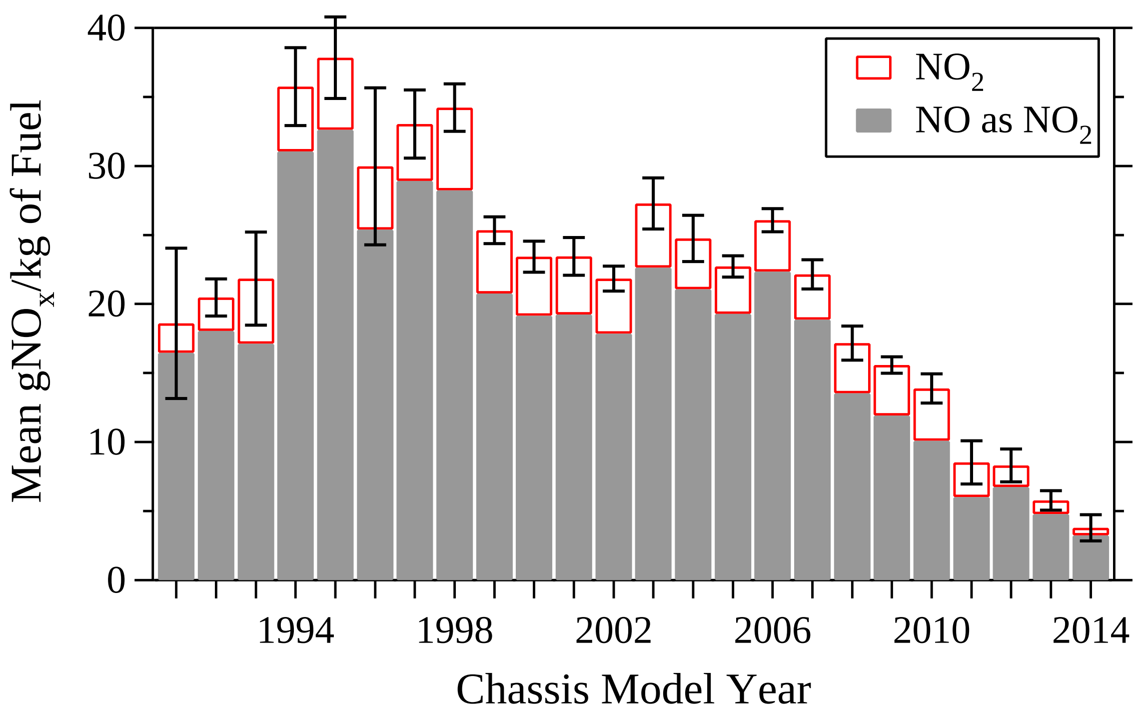

Figure 15. Mean gNO$_x$/kg of fuel versus chassis model year for the Cottonwood weigh station site. Grams of NO are reported as grams of NO_2 and the standard errors of the mean are for the total and were calculated using the daily means.

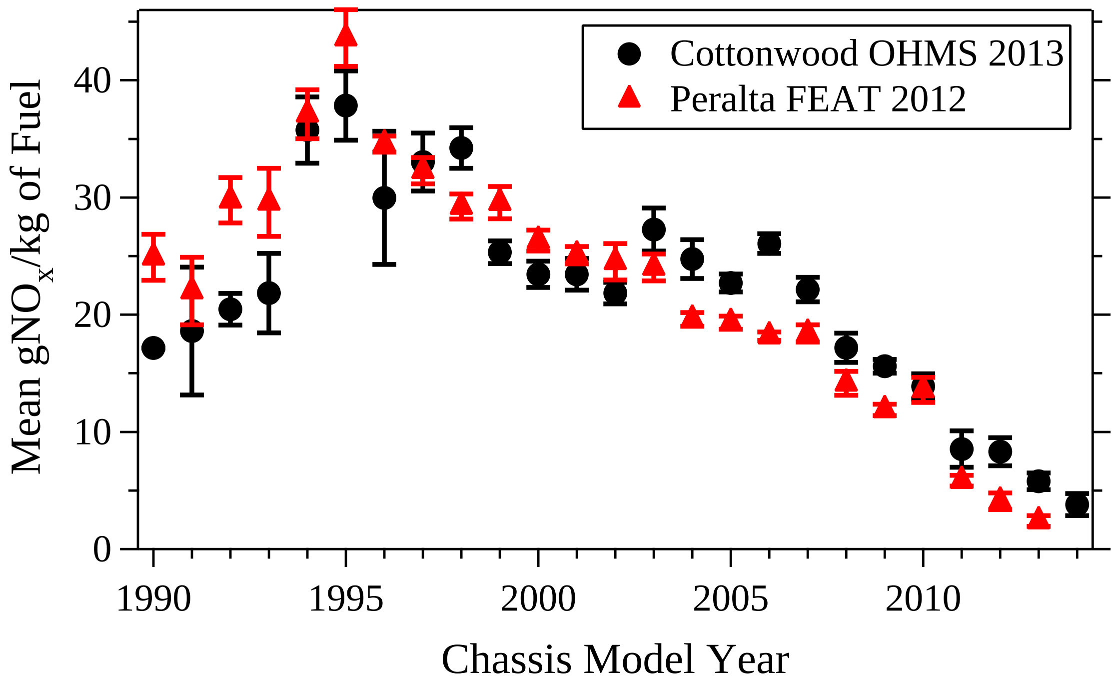

Figure 16. A weigh station comparison of mean gNO$_x$/kg of fuel emissions versus chassis model year for the OHMS results at Cottonwood and the 2012 FEAT optical measurements from Peralta. Uncertainties are standard errors of the means calculated from the daily means.

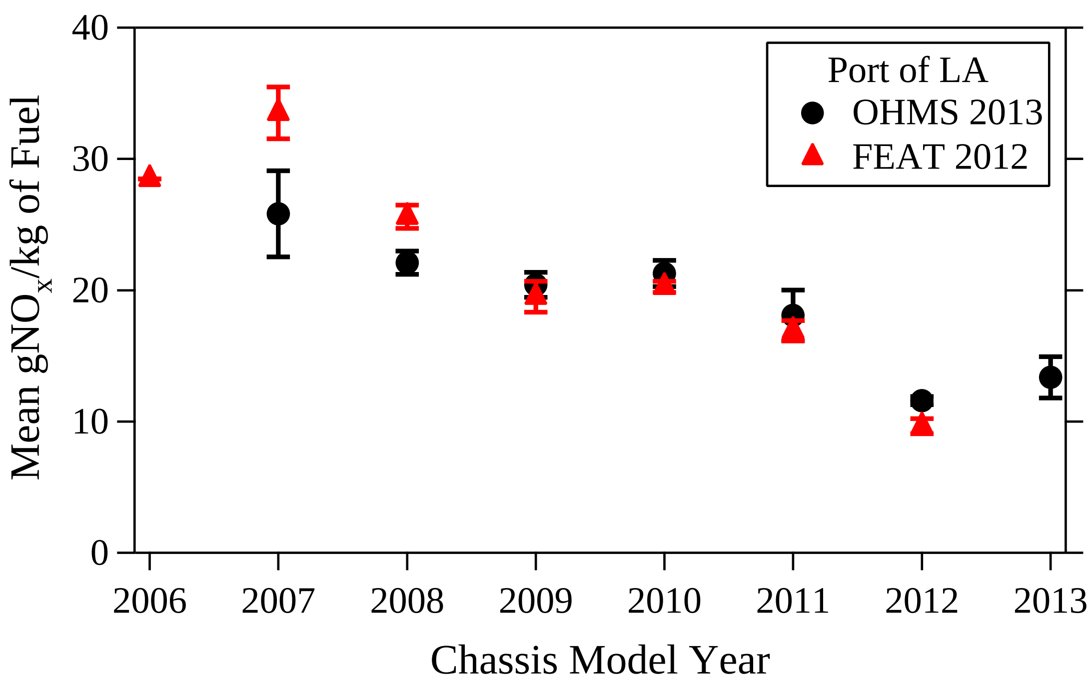

Figure 17. Mean gNO$_x$/kg of fuel emissions versus chassis model year comparison between the OHMS results and the 2012 FEAT optical measurements. Uncertainties are standard errors of the means calculated from the daily means.

with the 2011 chassis model year trucks accompanies the introduction of SCR systems to meet the Federal 2010 NO_x standard. With the phase in of engines meeting the Federal 0.2 g/bhp-hr NO_x standard we see the fuel specific NO_x emissions decreasing rapidly with each new model year. At Cottonwood the newest 2014 models have gNO_x/kg means of 3.8 g/kg which is a little less than 3 times the new engine certification level of approximately of 1.33 g/kg of fuel assuming that 0.15 kg of fuel is consumed per brake horsepower hour.

There are additional differences between the two weigh station fleets than just the differences in grade. The Cottonwood fleet on average is about 1 year newer than the Peralta fleet when measured and is made up of a smaller fraction of California registered vehicles (60% versus 94%). The mean speeds and accelerations at Cottonwood are both slightly lower than at Peralta (the tent and flagman at Cottonwood likely influence this). Traffic at Peralta includes many HDV that are strictly for local use only. These include refuse, construction (gravel haulers) and delivery trucks while predictably at Cottonwood the vehicles are dominated by long haul vehicles.

The Federal and California emission regulations that have targeted major reduction in PM emissions have been met with the introduction of DPFs. The filters physically trap the particles requiring a mechanism to oxidize the trapped particles to keep the filter from plugging. One early approach used was to install an oxidation catalyst upstream of the filter or catalyze the filter itself to convert engine-out NO emissions to NO_2. NO_2 is then capable of oxidizing the trapped particles to regenerate the filter at lower temperatures than is possible with other species. However, if the production of NO_2 is not controlled well it can lead to an increase in NO_2 tailpipe emissions, and the unintended consequence of increased ozone in urban areas.[21, 22] European experiences, with increasing prevalence of DPFs, have shown a correlation with increases in urban NO_2 emissions.[23, 24] California has codified this concern by passing rules that limit any increases in NO_2 emissions from the uncontrolled engine baseline emissions for retrofit DPF devices.[25]

Figures 18 and 19 compare the mean mass ratio of NO_2/NO_x versus chassis model year at the two OHMS location with the previous optical FEAT measurements. The uncertainties plotted are the standard errors of the mean determined from the distribution of the daily means. One of the first noticeable differences is that the measurement errors are much larger for the OHMS measurements at both locations. OHMS measures NO_2 as the difference between the two readings on the NO and total NO_x analyzers. It is common knowledge that differences between two numbers of similar magnitudes result in a number with a much larger uncertainty and that certainly seems to be the outcome in this case. While the ratios versus chassis model year are statistically identical at the Port location the Cottonwood ratios are much larger than what was previously observed at the Peralta weigh station. However, both measurements show the increases in NO_2 emissions starting with the 2008 chassis model year that coincided with the introduction of catalyzed DPFs and the subsequent decrease with each successive new model year. The reduced ratios in the newest model year are continuing evidence of manufacturers changing to active regeneration of DPFs. The NO_2/NO_x ratio for the 2008 and newer chassis are larger at Cottonwood than at the Port which is another outcome of the lower operating temperatures and reduced catalytic activity of the Port trucks.

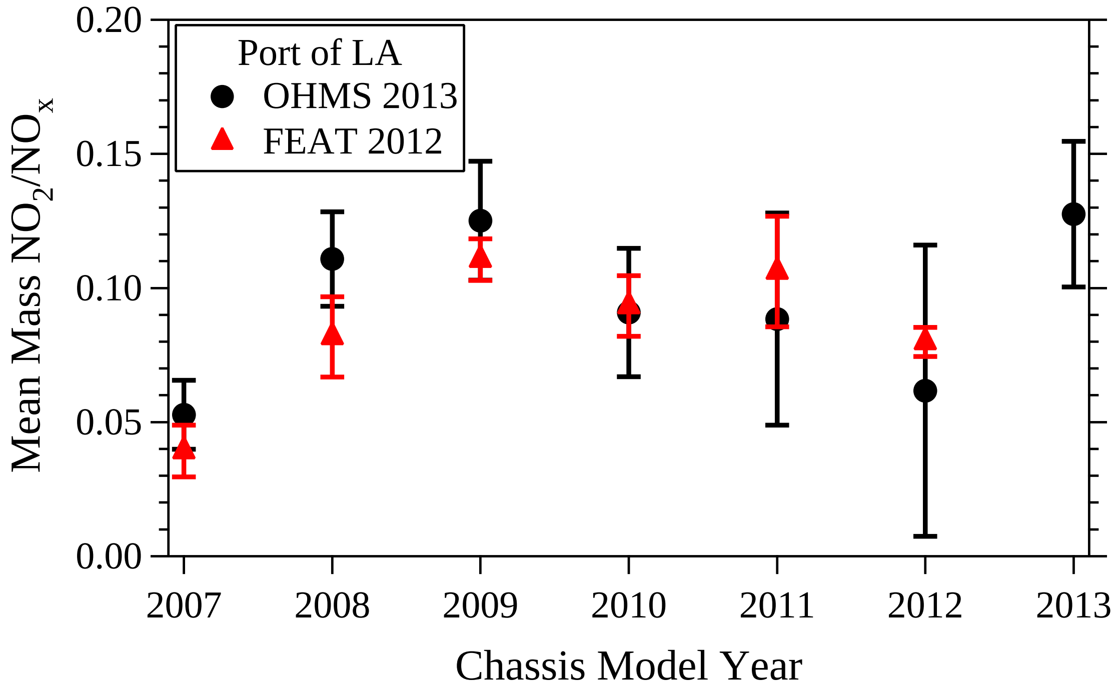

Figure 18. Mass NO_2/NO_x ratio versus chassis model year comparison plot for the OHMS 2013 and FEAT 2012 measurements at the Port of Los Angeles location. The uncertainties plotted are standard errors of the mean calculated from the daily means.

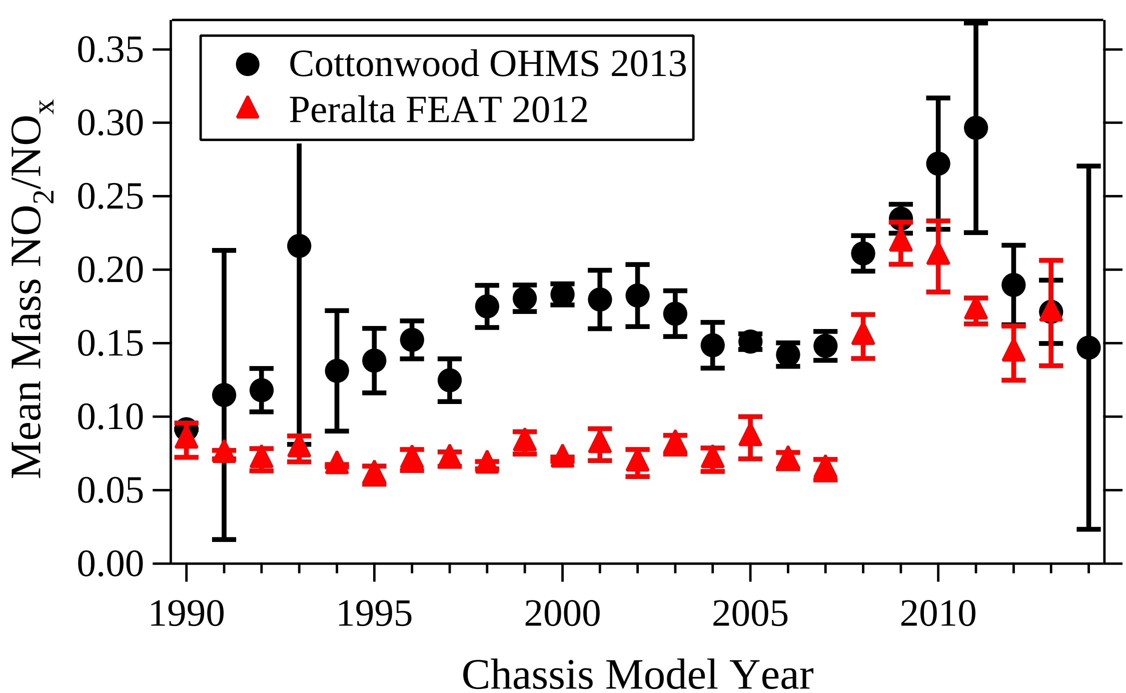

Figure 19. Mass NO_2/NO_x ratio versus chassis model year comparison plot for the Cottonwood OHMS 2013 and FEAT 2012 Peralta weigh station measurements. The uncertainties plotted are standard errors of the mean calculated from the daily means.

Figures 20 and 21 graphs the gCO/kg emissions versus chassis model year and compares the means between the last two data sets collected at the Port and the two weigh stations. The FEAT measurements are obviously less sensitive and have more noise than the OHMS measurements. Data from both of the weigh station shows the substantial reductions in CO that were experienced when catalyzed DPF systems were added to the fleet with the 2008 chassis's. At the Port the higher FEAT gCO/kg means are higher than the OHMS measurements in part because they include a larger number of measurements on the natural gas powered trucks at the Port which emit substantially more CO and HC than their diesel counterparts.

Figures 22 and 23 plots the gHC/kg emissions versus chassis model year comparison for the last two data sets collected at the Port location and the two weigh station sites. As with the CO measurements the OHMS data show significantly less noise than the optical measurements. As with the CO emissions the gHC/kg emissions at the Port are strongly influenced by the higher methane emissions from the natural gas powered trucks which make up 16% of the 2012 fleet and only 3% of the OHMS 2013 fleet. There are also methane influences in the data collected at the Cottonwood weigh station as a result of measurements on a number of cattle transport trucks which will be discussed later.

Particle Measurements

One of the prime motivators for the OHMS system was the desire for a method that could provide direct measurements of vehicle particle emissions that was sensitive enough to resolve differences on an individual vehicle basis. Our optical method is an IR opacity measurement which attempts to correlate the reduction of light transmitted through the exhaust plume against CO_2 at the IR wavelength of 3.9μm. The technique is not very sensitive, especially for particles that are not black, and suffers from very poor signal to noise limits requiring a large number of measurements. However, it has proven capable of measuring the large fleet average changes in HDV smoke emissions at the Port as the fleet changed from an unfiltered diesel fleet to one entirely equipped with DPFs.[11] To study DPF deterioration rates though we needed a method that would allow for the use of analyzers that are significantly more sensitive. Both of the particulate analyzers used in California in 2013 have very good signal to noise levels (see Figure 8). On one level OHMS has achieved success as to date this is the largest data set collected on individually identified HDV for PM and BC emission.

Figures 24 and 25 are mean g/kg of fuel emissions for PM and BC plotted against chassis model year for the Port and Cottonwood locations. The errors plotted are standard errors of the mean calculated from the daily means. The range of mean particulate emissions is larger at Cottonwood because of the age of the fleet. The majority of the Cottonwood fleet (61%) was older than 2008 models when newly manufactured trucks were equipped with DPFs. It is of course possible that some of the older California registered trucks have been retrofitted with a DPF but that has not been determined at this time. If we only compare 2008 and newer HDV models between the Port and Cottonwood the mean gPM/kg of fuel values are 0.03 and 0.17 gPM/kg of fuel respectively. The factor of 5.7 differences in the means is largely accounted for by one extreme 2009 outlier, a

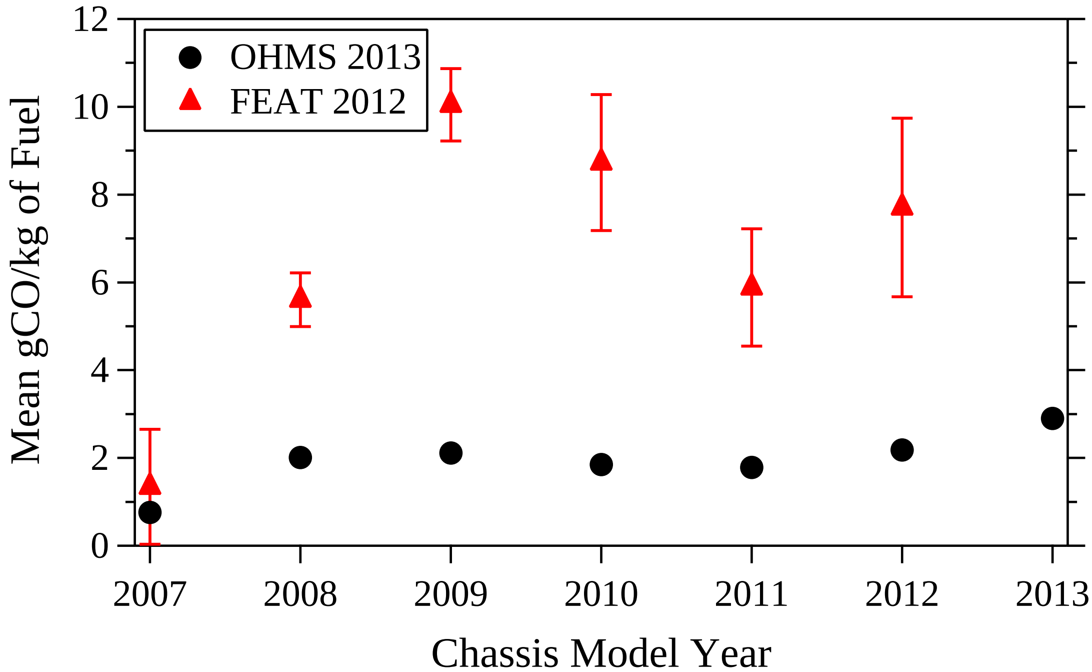

Figure 20. Mean gCO/kg of fuel emissions versus chassis model year comparison between the OHMS results and the 2012 FEAT optical measurements. Uncertainties are standard errors of the means calculated from the daily means.

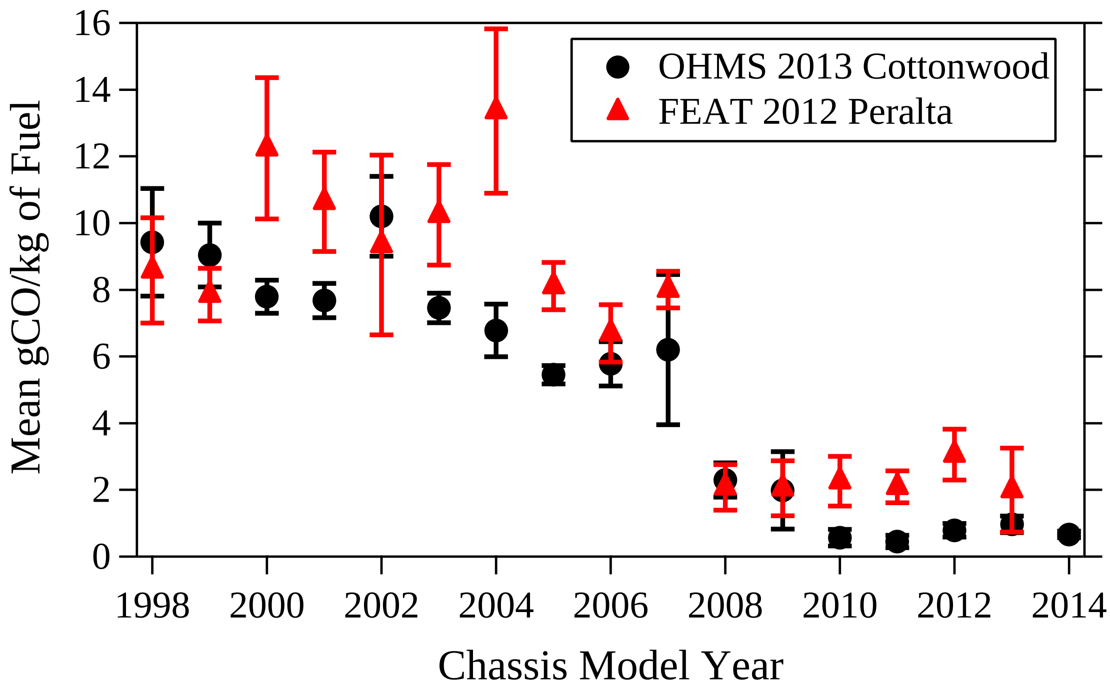

Figure 21. Comparison of mean gCO/kg of fuel emissions versus chassis model year for the OHMS results at Cottonwood and the 2012 FEAT optical measurements from Peralta. Uncertainties are standard errors of the means calculated from the daily means.

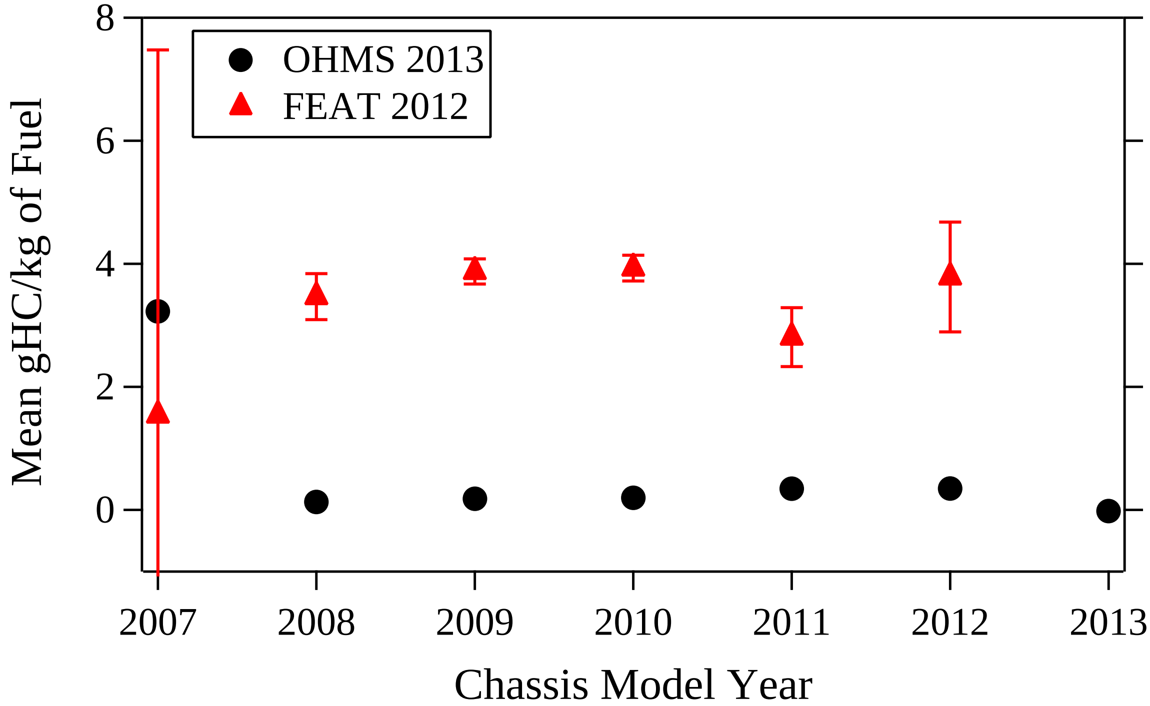

Figure 22. Mean gHC/kg of fuel emissions versus chassis model year comparison between the OHMS results and the 2012 FEAT optical measurements. Error bars are standard errors of the means calculated from the daily means.

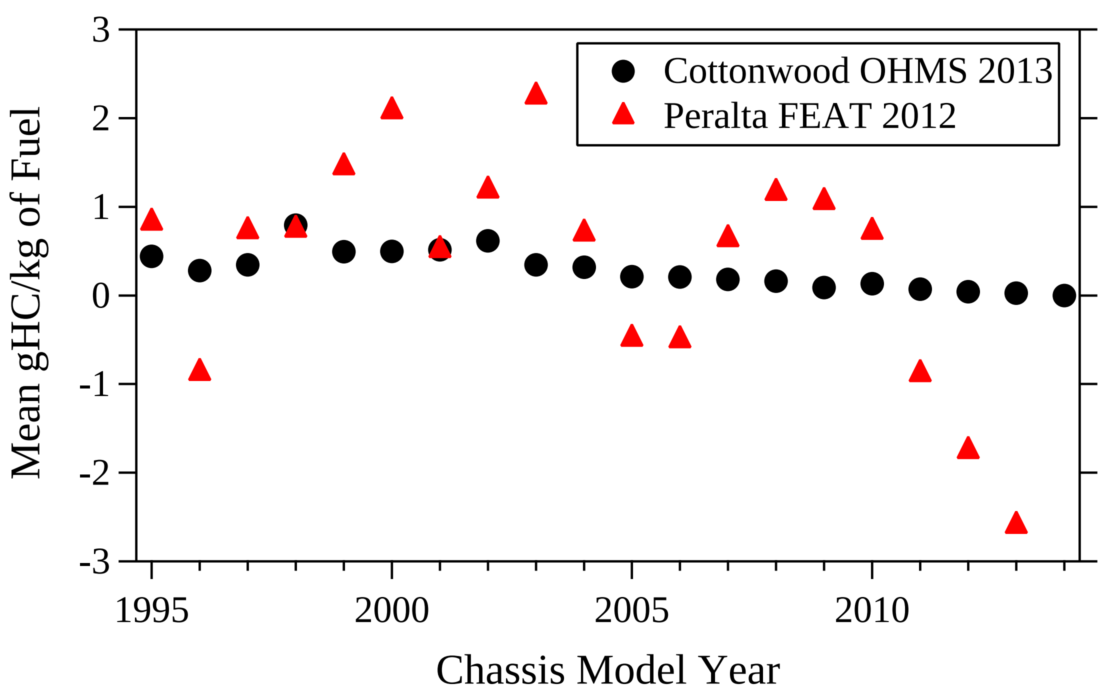

Figure 23. Comparison of mean gHC/kg of fuel emissions versus chassis model year for the OHMS results at Cottonwood and the 2012 FEAT optical measurements from Peralta.

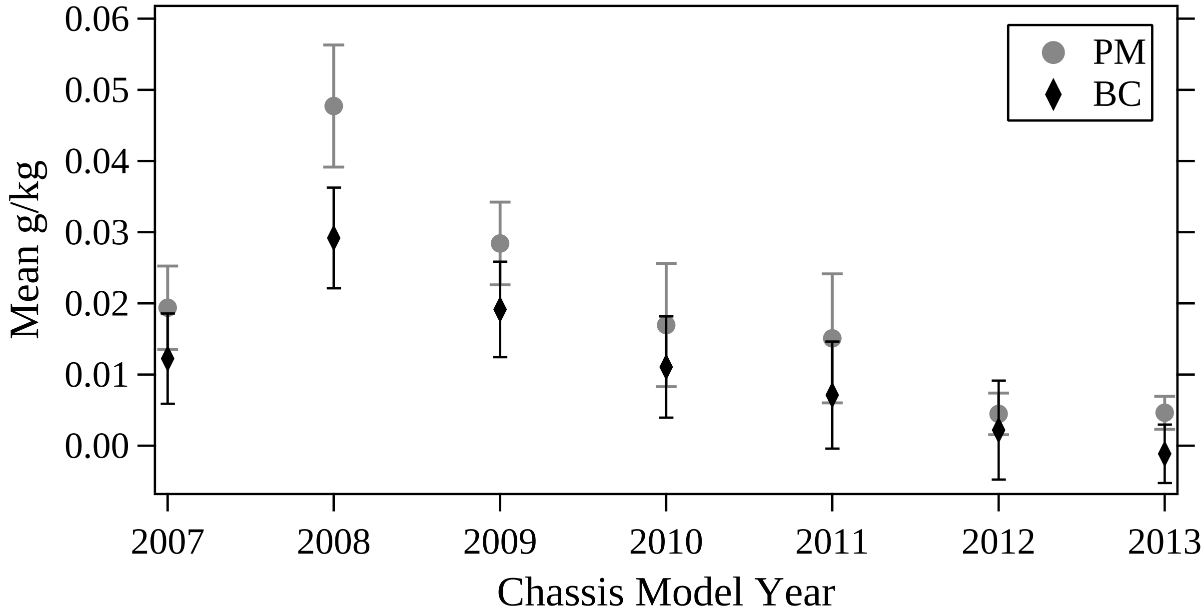

Figure 24. Mean gPM and gBC/kg of fuel versus chassis model year from the Port of Los Angeles. Uncertainties plotted are standard errors of the mean calculated from the daily means.

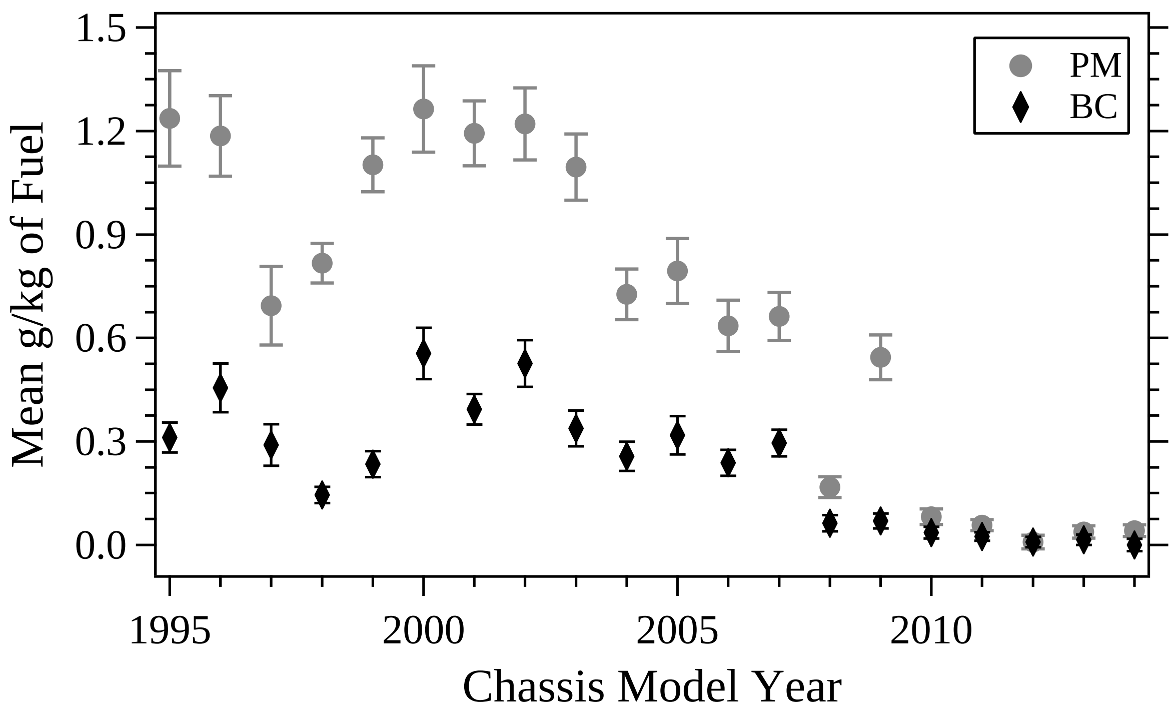

Figure 25. Mean gPM and gBC/kg of fuel versus chassis model year from the Cottonwood weigh station. Uncertainties plotted are standard errors of the mean calculated from the daily means.

white smoker that will be discussed in more detail later, which if excluded from the Cottonwood average reduces the mean to 0.07 gPM/kg of fuel.

If we again assume that 0.15 kg of fuel is consumed per brake horsepower hour for an average truck we can covert the Federal PM 0.01g/bhp-hr standard into 0.07 gPM/kg of fuel to compare against the measurements. The majority of the 2008 and newer trucks at both locations are meeting this level with the Port mean a factor of two below this value. The low PM and BC means for the 2007 model year trucks at the Port are from ten measurements of which 7 are natural gas powered vehicles (dual fuel compression ignition engines). The Cottonwood data has enough older model year trucks to see the significant reductions in both total PM and BC achieved with the addition of DPFs. There is a 75% reduction in PM between 2004-2007 (0.7 gPM/kg) models versus 2008 and newer models (0.17 g/kg) and an 86% reduction in BC (0.28 vs 0.04 gBC/kg).

Figures 26 and 27 are box and whisker plots of the PM (shaded) and BC (open) particulate measurements at the Port and Cottonwood weigh station plotted against chassis model year. The box is defined as the 25th, 50th and 75th percentiles, the whiskers extend from the 10th to the 90th percentiles and the circles are the remaining individual measurements. The filled square is the mean value for each chassis model year or model year grouping. Split y-axes are used to cover the range of values while preserving the detailed distribution of the majority of the lower emitting vehicles. Within similar technology groups we have aggregated some model years to provide enough measurements. The negative readings reported provide an indicator for the noise level of the technique and a level above which an individual measurement's significance can be judged.

Because of the limited number of model years in operation at the port we can expand the range of the y-axis to see the details of the inter-quartile range for each of the model year groupings. The range shows few significant differences for the 2010 and newer trucks but the inter-quartile range gradually increases in size for both the 2009 and 2008 models while the extent of the outliers is similar. We can speculate that this is the result of deterioration but until we have additional data sets, that is all it can be. This pattern is very similar to the measurements at the Cottonwood weigh station as well, with the one exception for the high emitting 2009 model.

The gPM/kg of fuel graph (Figure 27) for the Cottonwood measurements shows that the highest emitting vehicle, a 2009 model, was measured above 70g PM/kg of fuel. This truck was emitting copious quantities of white smoke, which was corroborated by the BC instrument as not having any significant BC emissions. Except for this truck there are no other measurements that exceed ~20g PM/kg of fuel. The Dekati DMM has an internal particle size cutoff at 1.2µm which likely helps to establish this ceiling without there being an extreme level of smaller particles as seems to be the case with the 2009 truck. A second case where this may apply involves a 2000 model year truck with higher BC emissions (>24g/kg) than total PM emissions (13.5g/kg). This truck's PM measurement still is easily in the top 1% of all of the PM measurements and one possible explanation for its lower PM measurement is the fact that the PAX instrument does not have a particle size limit. Diesel particulate emissions generally do not even approach the 1.2µm size limit in the Dekati instrument but there have been suggestions that soot accumulating on cylinder walls

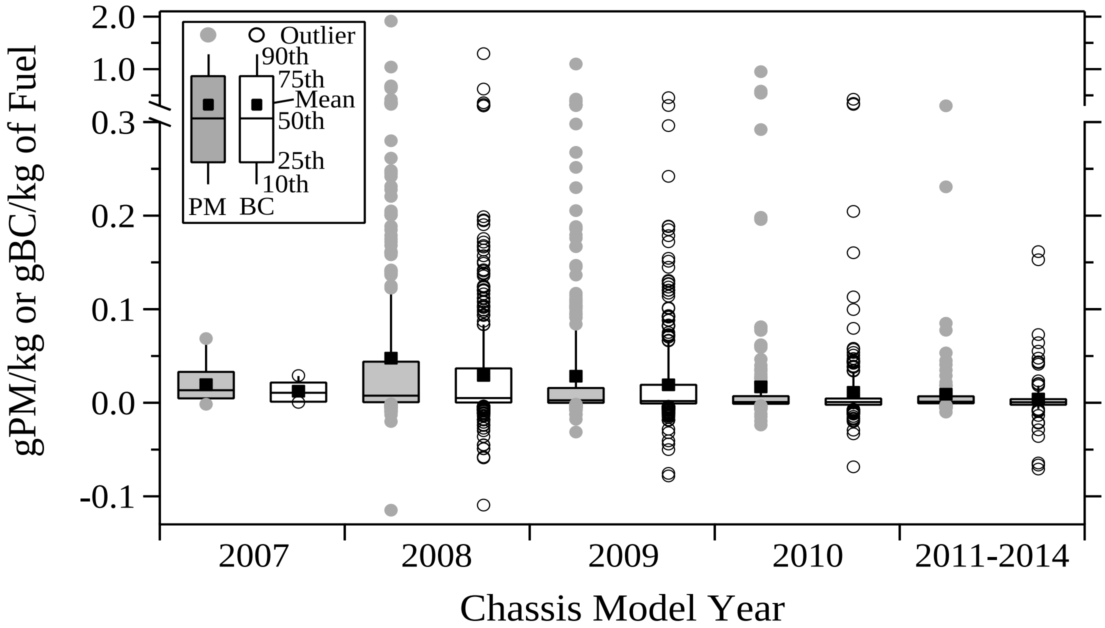

Figure 26. A box and whisker plot of fuel specific PM (shaded) and BC (open) emissions versus chassis model year from the Port of Los Angeles. The box is defined as the 25th, 50th and 75th percentiles, the whiskers extend from the 10th to the 90th percentiles, the circles lie beyond these percentiles and the filled square is the mean.

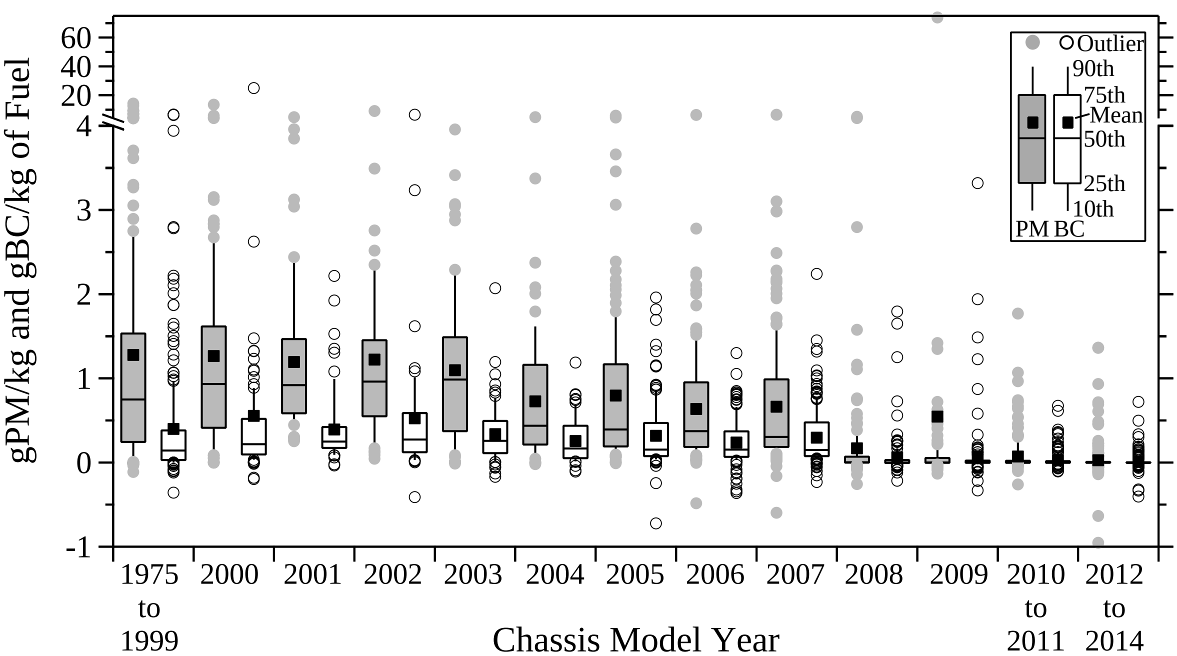

Figure 27. A box and whisker plot of fuel specific PM (shaded) and BC (open) emissions versus chassis model year of measurements from the Cottonwood scales. The box is defined as the 25th, 50th and 75th percentiles, the whiskers extend from the 10th to the 90th percentiles, the circles lie beyond these percentiles and the filled square is the mean.

can be dislodged in larger aggregates of material that could possibly explain this result.[26] As in Figure 25 the introduction of DPFs are clearly evident in the drastic collapse of the inter-quartile range beginning with the 2008 trucks, though a few 2008 and 2009 trucks have PM and BC measurements that are at levels similar to non-DPF vehicles.

Table 4 lists literature values for HDV fleet PM and BC emissions that have been recently reported for on-road fleets and laboratory chassis dynamometer studies for comparison with the OHMS results.[13, 26-28] The values are listed in roughly chronological order with the oldest listed first; however the laboratory measurements have been restricted to specific model year vehicles which are not subject to on-road fleet composition changes. The model years given are for chassis model years except for the first study by Kahlek et al. which reports the engine year. Uncertainties reported are 95% confidence intervals provided by Dallmann et al. and are standard errors of the mean determined from the daily means for the OHMS results. In general the on-road measurements are higher than the laboratory measurements. The Port of Oakland and Caldecott tunnel fleet measurements are three years older than the OHMS measurements and with the decreasing trend in PM and BC emissions those values would be expected to be lower if measured today. They also report an upper limit range of 10g BC/kg of fuel for the Port of Oakland fleet emissions distribution which would be expected to have been contributed by pre-DPF equipped trucks and is very similar to the upper limit observed at Cottonwood. BC emissions are consistently low for all of the reported values for the newest model year trucks and both the PM and BC measurements for these vehicles are orders of magnitude lower than pre-DPF equipped vehicles.

While the digital camera was less than successful for identifying urea tanks on the trucks at the Cottonwood weigh station the pictures did prove useful for identifying trucks hauling cattle transport trailers. We were able to positively identify 90 trucks with cattle trailers though the remaining vehicles may still have cattle trailers among them that we were not able to visually label. Figure 28 graphs the gHC/kg emissions by chassis model year groupings comparing the trucks transporting cattle with those we think are not. The chassis model year groupings generally arrange to match the NO_x certification standards. In all but one of the groupings the HC emissions are increased by the presence of the cattle trailer and significantly so for two of the groups. If the gHC/kg emissions are rank ordered and the 99th percentile is inspected you will find than 7 out of the 18 trucks were identified as transporting cattle trailers and if the fleet mean is calculated by excluding the cattle trailers it decreases 12% from 0.25 to 0.22 gHC/kg. Undoubtedly the additional HC emissions are methane gas from the cattle and manure in the trailers.

Since it is possible for emissions other than from the vehicles exhaust pipe to be captured by OHMS we also used the digital images to find trailers with active refrigeration units (TRU). Many trailers have an LED display on the driver's side of the truck (visible in his rear view mirror) that is green when the refrigeration unit is active. The light does not indicate that the TRU's engine is running only that the trailer box temperature is being regulated. We were able to identify 53 trailers that had active TRU's as identified by the green lights. When comparing the gNO_x/kg of fuel and the gPM/kg of fuel emissions by model year the trucks with active TRU's have larger uncertainties

Table 4. Particulate Emission Measurement Comparisons with Reported Literature Values.

Location (Measurement Year)	Reference	Model Year Grouping	Mean gPM/kg	Mean gBC/kg	Mean gEC/kg
Laboratory	Khalek et al.	2007[a]	0.0007		0.0001
Caldecott Tunnel (2010)	Dallmann et al.	N.A.		0.58 ± 0.09	
Port of Oakland (2010)	Dallmann et al.	N.A.		0.49 ± 0.08	
Laboratory	May et al.	2010	0.007		0.0007
Laboratory	May et al.	2007	0.135		0.0008
Laboratory	May et al.	pre-2008	0.513		0.183
Port of LA (2013)	This Work	2011 & newer	0.009 ± 0.004	0.004 ± 0.006	
Port of LA (2013)	This Work	2008-2010	0.034 ± 0.007	0.022 ± 0.003	
Cottonwood Scales (2013)	This Work	2011 & newer	0.03 ± 0.01	0.013 ± 0.005	
Cottonwood Scales (2013)	This Work	2008-2010	0.3 ± 0.2	0.059 ± 0.009	
Cottonwood Scales (2013)	This Work	pre-2008	0.96 ± 0.12	0.36 ± 0.04	

[a]Engine model year

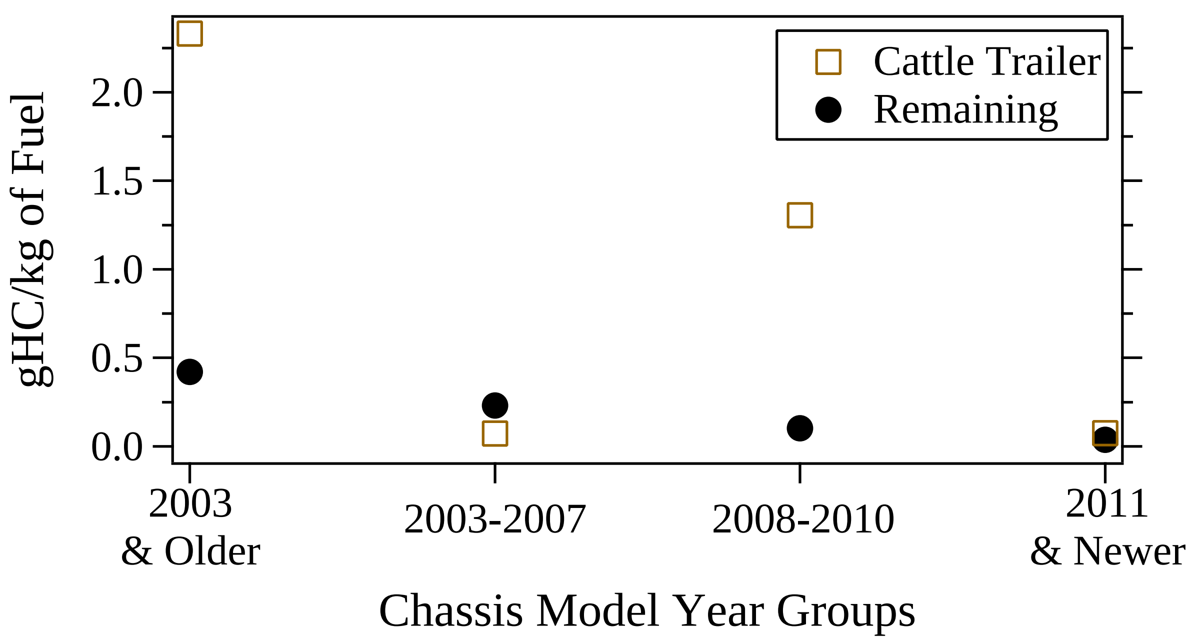

Figure 28. Mean gHC/kg of fuel emissions versus chassis model year groups for HDV positively identified as transporting a cattle trailer and the remaining HDV.

but no pattern immerges suggesting that the refrigeration units had any significant effect on the NO_x measurements.

Results and Discussion for the 2015 Measurements Campaign

The University of Denver continued the HDV emissions research in California at our Port of Los Angeles and Cottonwood weigh station sites in 2015 with a total of eight days of sampling. Sampling took place at the Port of Los Angeles between Monday, March 23 and Friday, March 27. The measurements were made from approximately 8:00 to 17:00, with 1457 total successful measurements made during the week. The location of the sample collection was moved slightly from the 2013 measurements due to the Port of Los Angeles reconstructing their entrance and exit into the port. In 2015 there were two new automated exit lanes and OHMS was setup on the eastern most lane. The majority of the HDV passed through the lane that OHMS was set-up over, but the other lane was used for overflow when the exit became congested and for bobtails. The new exits were more automated than in the past and while many of the HDV did stop before exiting, thus encouraging acceleration under the OHMS tent, not all of the HDV were required to as in the past. This combined with the OHMS tent having to be situated about 15 feet further away from the exit gate than in 2013 allowed for an increase in average vehicle speeds. Figure 29 is a photograph of the OHMS system installed at the new exit from the Trapac facility. On average the speeds at the new exit were higher in 2015, with similar entrance accelerations. The exit accelerations for the 2015 measurements had to be disregarded due to an unfound error in the data collection program.

Figure 29. Photograph at the new Trapac Port of Los Angeles exit with the OHMS setup used to detect exhaust emissions from heavy-duty trucks in the foreground. The blue roofed canopies at the rear of the tent is one of the new exit check points.

Sampling was conducted at the Cottonwood weigh station on I-5 near Redding CA from Wednesday, April 8th to Friday, April 10th. High winds prohibited measurements from being made on Monday and Tuesday of that week, April 6th and 7th. During the three days of work we collected emission measurements on a total of 694 HDV.

The licenses for both locations were read for the HDV with CO_2 emissions levels that exceeded our minimum plume criteria. The OHMS validity criterion are detailed in Appendix C. At the Port, out of state plates were matched against the drayage truck registry for make and model year and a few additional trucks from Colorado, Georgia, Illinois, New Jersey, Ohio, Texas and Utah were included. At Cottonwood, license plates were matched against state records for California, Oregon and Washington, and vehicle plates from British Columbia were compared to 2013 records and 3 trucks were found to be the same. Vehicles with valid CO_2 emissions and a matched license plate have their emissions measurement reviewed one final time to exclude any measurements that indicate the presence of more than one vehicle. If the presence of a second vehicle plume is found the vehicle is eliminated from the final data set. Tables 5 and 6 give the distribution of plates successfully read and matched at the Port of Los Angeles and the Cottonwood weigh station. Similar to 2013 data, the Port had more repeat HDV but the number of repeats did increase at Cottonwood due to the CARB opacity inspections.

Table 5. Distribution of Identifiable Port of Los Angles Plates in 2015.

State	Readable Plates	Unique Plates	Unique Matched Plates	Total Measurements
California	1523	947	904	1429
Colorado	1	1	1	1
Georgia	1	1	1	1
Illinois	1	1	1	1
Indiana	26	23	0	0
New Jersey	3	1	1	2
Ohio	11	11	9	9
Texas	28	13	7	12
Utah	1	1	1	1
Totals	1595	999	914	1456

A detailed summary for both sites of measurements made in 2015 is provided in Table 7. The measured mean ratios to CO_2 are reported along with the g/kg of fuel values for all gaseous, particulate and number emissions. In addition to the exhaust species measured the mean model year, infrared temperatures, speed and accelerations and VSP are included. The uncertainties reported are standard errors of the mean (SEM) determined using the daily mean measurements at each site. The accelerations reported by the second speed unit (exit location) at the Port are not reported because of a software error that invalidated those measurements. In 2015 the fleet measured at our Port location still remains younger than the fleet measured at Cottonwood (mean model year of 2009.3 compared to 2008.1). However, the Cottonwood fleet is getting younger (~

Table 6. Distribution of Identifiable License Plates in 2015 at the Cottonwood Weigh Station.

State / Country	Readable Plates	Unique Plates	Unique Matched Plates	Total Measurements
Arizona	6	4	0	0
California	469	414	404	459
Colorado	1	1	0	0
Florida	1	1	0	0
Georgia	2	2	0	0
Iowa	3	3	0	0
Idaho	3	2	0	0
Illinois	13	11	0	0
Indiana	56	54	0	0
Kentucky	2	2	0	0
Louisiana	4	4	0	0
Minnesota	5	5	0	0
Missouri	2	2	0	0
Montana	2	2	0	0
Nebraska	1	1	0	0
Nevada	1	1	0	0
North Carolina	6	5	0	0
Ohio	4	3	0	0
Oklahoma	4	4	0	0
Oregon	153	141	137	148
Tennessee	4	4	0	0
Texas	7	7	0	0
Washington	84	75	75	84
Wisconsin	3	3	0	0
Canada	43	41	3	3
Totals	879	792	619	694

0.5 model years younger since 2013) while the Port fleet is getting older (~ 1.8 model years older since 2013). Accompanying the age changes in the two fleets are changes in the measured emissions as well. At the Port particulate emissions are on the increase from previously very low values while large reductions in particulate emissions occurred at the weigh station.

IR images captured at each location allowed for analysis of external exhaust pipe temperatures. Pictures that had a clear IR image of an elevated exhaust pipe were assigned a temperature based on the field calibration described in Appendix B. The histograms for these temperatures at both locations in 2015 are shown in Figure 30. At the Port, average exhaust pipe temperatures were 91º C with only 0.7% of the HDV above 120º C and at the Cottonwood weigh station, the average was 105º C and 6% of the IR readings above 120º C. SCR systems have a temperature dependence, and usually require operating temperatures above 200º C to 250º C, depending on the catalyst type.

Table 7. OHMS 2015 Data Summary and Comparison.

Study Site	Port of Los Angeles	Cottonwood Weigh Station
Mean CO/CO_2 (g/kg of fuel ± SEM)	0.0016 3.0 ± 0.4	0.0015 3.0 ± 0.2
Median gCO/kg	0.27	0.65
Mean HC/CO_2 (g/kg of fuel ± SEM)	0.00039 1.2 ± 0.4	0.00020 0.66 ± 0.05
Median gHC/kg	0.20	0.27
Mean NO/CO_2 (g/kg of fuel ± SEM)[a]	0.0060 12.8 ± 0.5	0.0056 11.9 ± 0.2
Median gNO/kg[a]	11.1	10.8
Mean gNO_x/CO_2 (g/kg of fuel ± SEM)[b]	0.0066 21.6 ± 2.1	0.0068 22.1 ± 0.7
Median gNO_x/kg[b]	19.5	19.6
Mean NO_2/CO_2 (g/kg of fuel ± SEM)	0.00071 2.3 ± 1.0	0.0012 4.1 ± 0.5
Median gNO_2/kg	1.3	3.4
Mean Mass NO_2/NO_x	0.11	0.18
Mean gPM/kg ± SEM	0.11 ± 0.01	0.22 ± 0.04
Median gPM/kg	0.0042	0.002
Mean gBC/kg ± SEM	0.08 ± 0.01	0.08 ± 0.002
Median gBC/kg	0.0039	0.011
Mean PN/kg ± SEM	$2.8 \times 10^{14} \pm 2.8 \times 10^{13}$	$1.7 \times 10^{15} \pm 1.4 \times 10^{13}$
Median PN/kg	7.6×10^{12}	1.2×10^{13}
Mean Model Year	2009.3	2008.1
Mean IR Estimated Exhaust Temperature (ºC) ± SEM	91 ± 2	105 ± 1
Mean Entrance Speed (mph)	7.0	9.0
Mean Exit Speed (mph)	7.8	9.3
Mean Entrance Accel (mph/s)	0.2	0.38
Mean Exit Accel (mph/s)	N/A	0.32
Mean VSP (kw/tonne)[c]	1.17 / 0.28	1.8 / 1.7
Slope (degrees)	0º	-0.5º

[a]grams of NO

[b]grams of NO_2

[c]calculated using equation from Jimenez et al., 1999.

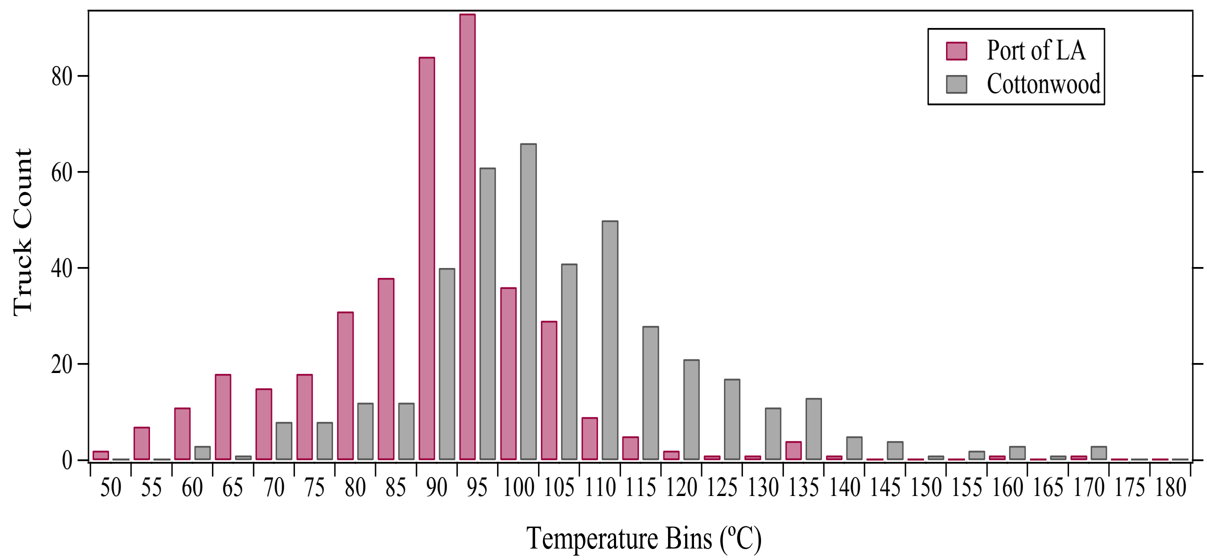

Figure 30. Infrared temperature distributions for the two locations in 2015.

The exhaust pipe temperatures at each location for the two measurement years are compared in Figures 31 and 32 using the new field calibration for the IR images. The Port location, Figure 33, had an average temperature in 2013 of 87 ºC but in 2015 had a slightly warmer average exhaust pipe temperature of 91 ºC. At Cottonwood (see Figure 32) the average exhaust pipe temperature increased from 98 ºC in 2013 to 105 ºC in 2015. Although the average temperature is only slightly higher at Cottonwood, it is important to note that Cottonwood had a higher percentage of trucks with exhaust pipe temperatures above 120 ºC degrees than at the Port in both 2013 (17% vs 3%) and 2015 (20% compared to 3%).

Shown in Figure 33 are the mean fuel specific emissions for CO, HC, NO, NO_2 and NO_x and in Figure 34 fuel specific emission means of PM, BC and PN data for the 2013 and 2015 measurements at both locations. The uncertainties plotted are standard errors of the mean calculated from the daily means of each emission. The increasing age of the fleet at the Port has been accompanied by an increase in CO, HC, PM, BC and PN from 2013 with negligible changes in NO, NO_2 and NO_x. The younger fleet at Cottonwood showed large reductions in CO, PM, BC and PN from 2013 to 2015 while HC, NO, NO_2 and NO_x showed slight increases or statistically insignificant changes.

To gauge the link between the significant particle emission reductions and decreasing fleet age observed at Cottonwood in 2015 we performed an age adjusted comparison of the PM and BC emissions. To perform this calculation the number of measurements made for each model year in 2013 was multiplied by the mean emissions by model year in 2015 to give a sum of 2015 emissions with the same age of the 2013 fleet. This sum was then divided by the number of measurements made in 2013 to produce the 2015 fleets age adjusted mean with the 2013 fleets age. Emissions measured in 2013 for gPM/kg of fuel and gBC/kg of fuel were 0.65 and 0.23 respectively. The age adjusted mean of the 2015 Cottonwood fleet was 0.40 gPM/kg of fuel and 0.14 gBC/kg of fuel compared with the actual emissions measured were 0.20 gPM/kg of fuel and 0.08gBC/kg of fuel.

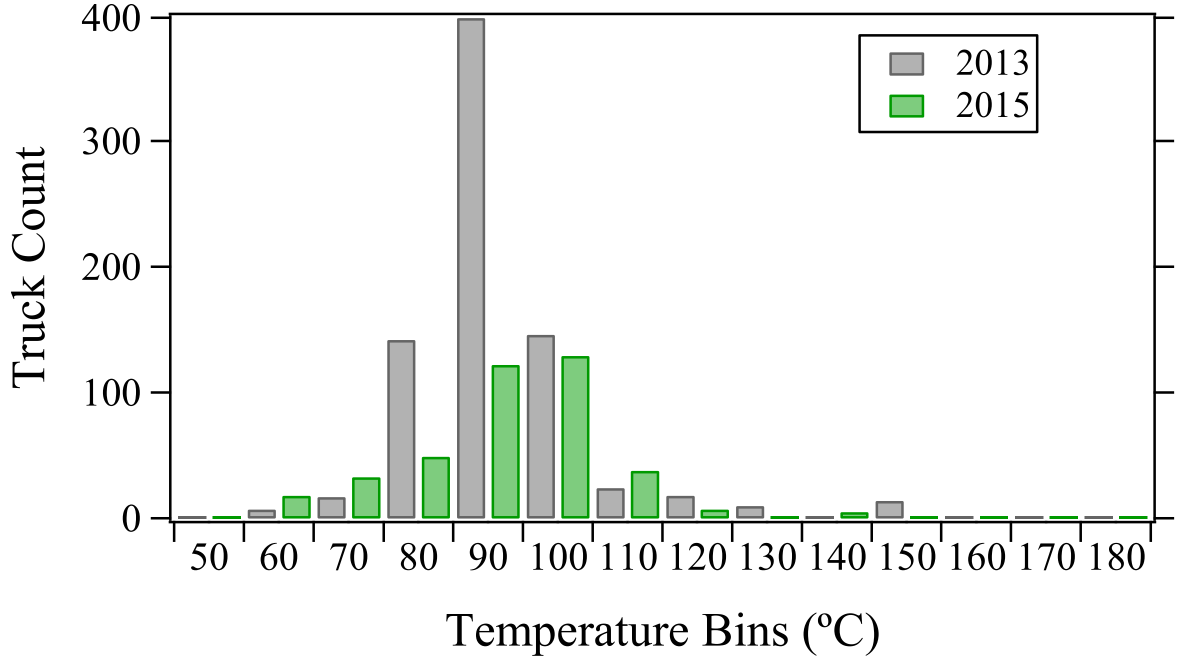

Figure 31. Infrared temperature distribution comparison at the Port of Los Angeles for both measurement years.

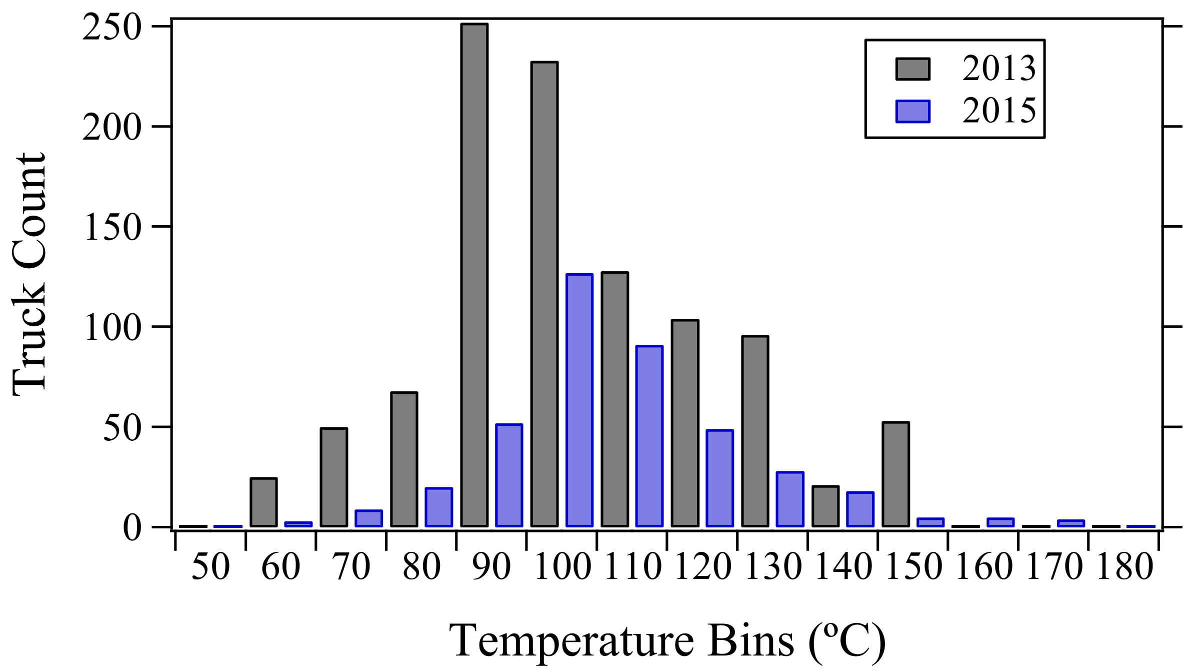

Figure 32. Infrared temperature distribution comparison at the Cottonwood weigh station for both measurement years.

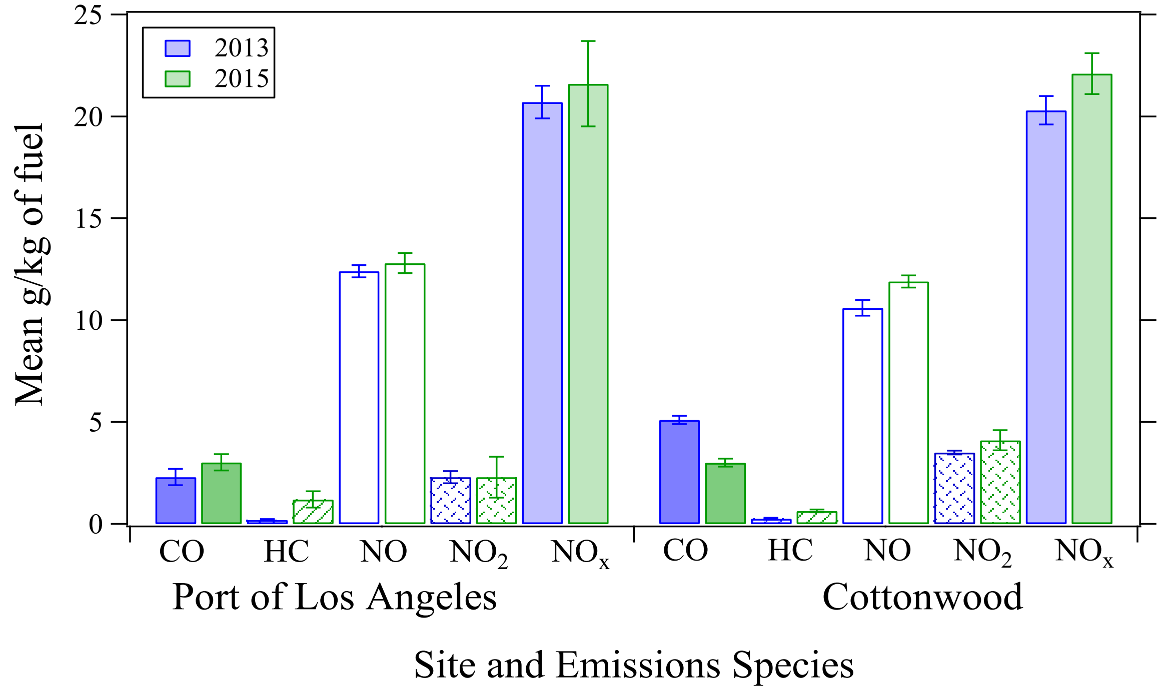

Figure 33. Fuel specific emissions for CO, HC, NO, NO_2 and NO_x for both measurement years at both locations. The uncertainties plotted are standard errors of the mean calculated from the daily means.

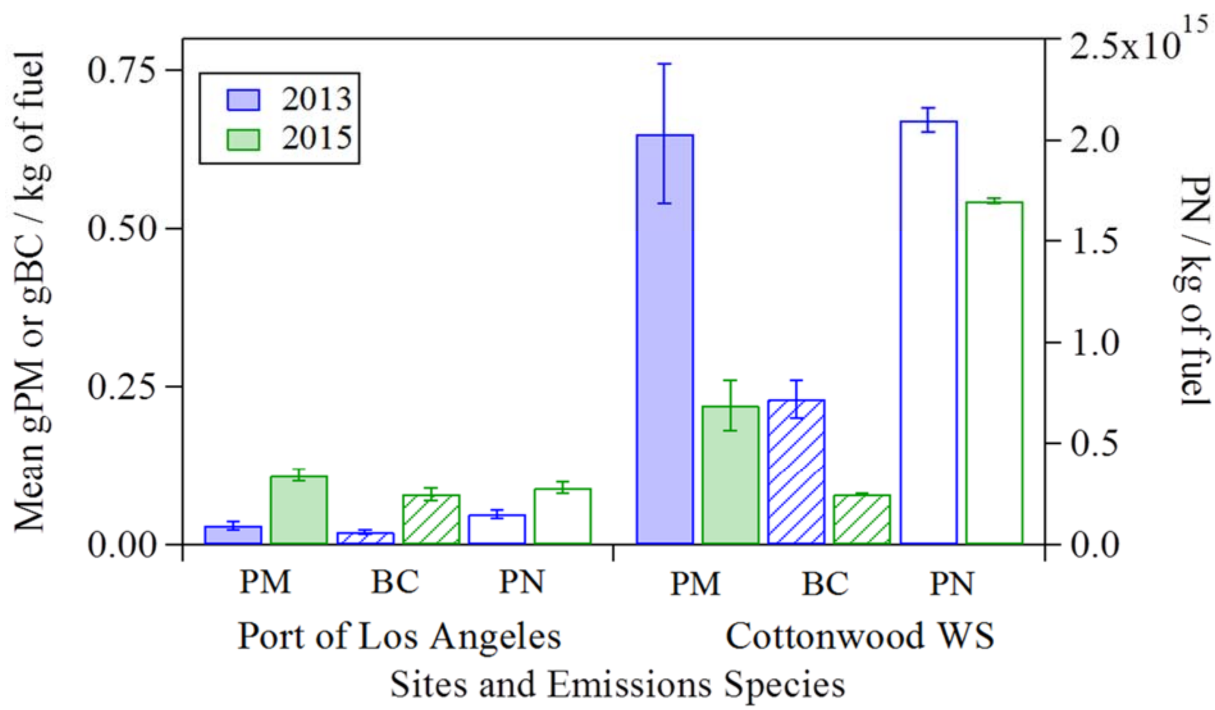

Figure 34. Fuel specific emissions of PM and BC (left axis) and PN (right axis). Data for both locations and for both measurement years are shown. The uncertainties plotted are standard errors of the mean calculated from the daily means.

This simple comparison estimates that the younger fleet age seen in 2015 at the Cottonwood weigh station is likely responsible for 55% of the PM reductions observed and about 60% of the gBC/kg of fuel emission changes. This is a significant portion of the observed differences though the age change does not account for the entire reduction at Cottonwood, other contributing factors will be discussed later.

Figures 35 and 36 compare the gCO/kg of fuel by model year for the 2013 and 2015 Port of Los Angeles and Cottonwood weigh station measurements. The uncertainties plotted are the standard errors of the mean computed from daily means. Overall gCO/kg of fuel means changed little at the Port of Los Angeles between 2013 and 2015 and that is reflected in Figure 35. The large uncertainty associated with model year 2012 is attributed to three high emitting HDV that run off of compressed natural gas (CNG) measured in 2015. These vehicle engines are designed to operate at stoichiometry but at our Port exits they are more often observed to be operating on the rich side of stoichiometry resulting in elevated CO and HC emissions. At Cottonwood gCO/kg of fuel emissions decreased (5.1 ± 0.2 versus 3.0 ± 0.2) along with PM and BC between 2013 and 2015. Figure 36 shows that many of the 2015 chassis model year means are lower than the 2013 measurements. However, the uncertainties increase for the smaller number of measurements by model year making many of the differences only statistically significant for the fleet means.

HC emissions increased at both locations between 2013 and 2015 but only the increases at Cottonwood were statistically significant. At the Port mean HC emissions are generally dictated by the number of natural gas powered trucks that we successfully measure. In 2013 only 2.6% of the HC measurements were from natural gas vehicles while in 2015 that percentage increased to 4.1%. Figure 37 displays gHC/kg of fuel emissions by chassis model year for the Port of Los Angeles. Only increases in chassis model years 2009 and 2012 were statistically significant in 2015. Again the large increases in the 2012 model year vehicles is due to methane emissions from a few CNG vehicles. In 2015 diesel vehicles averaged 0.7 gHC/kg of fuel while the CNG vehicles averaged 13.2 gHC/kg of fuel. At Cottonwood, shown in Figure 38, gHC/kg of fuel emission increased for all but the newest model years in 2015. The larger errors associated with the older trucks at Cottonwood are due to the small number of measurements in 2015.

Mean fuel specific emissions of NO, NO_2 and total NO_x by chassis model year are displayed in Figures 39 and 40 for each site and each measurement year. The uncertainties plotted are the standard errors of the mean for the total NO_x emissions and were determined from the daily means for each model year. Grams of NO are plotted as grams of NO_2 to allow for total NO_x to equal the sum of NO plus NO_2. NO_x emissions at the new port exit showed little change from those previously measured in 2013 (20.7 ± 0.8 versus 21.6 ± 2.1 gNO_x/kg of fuel). At Cottonwood fuel specific NO_x emissions showed fleet mean increases of approximately 10% in 2015 (20.3 ± 0.7 to 22.1 ± 0.7). However, these increases are fairly consistent across just about all of the chassis model years.

Figures 41 and 43 compare the differences in the mean mass ratio of NO_2 and NO_x for all model years at the Port of Los Angeles and Cottonwood. This ratio does not significantly change at the

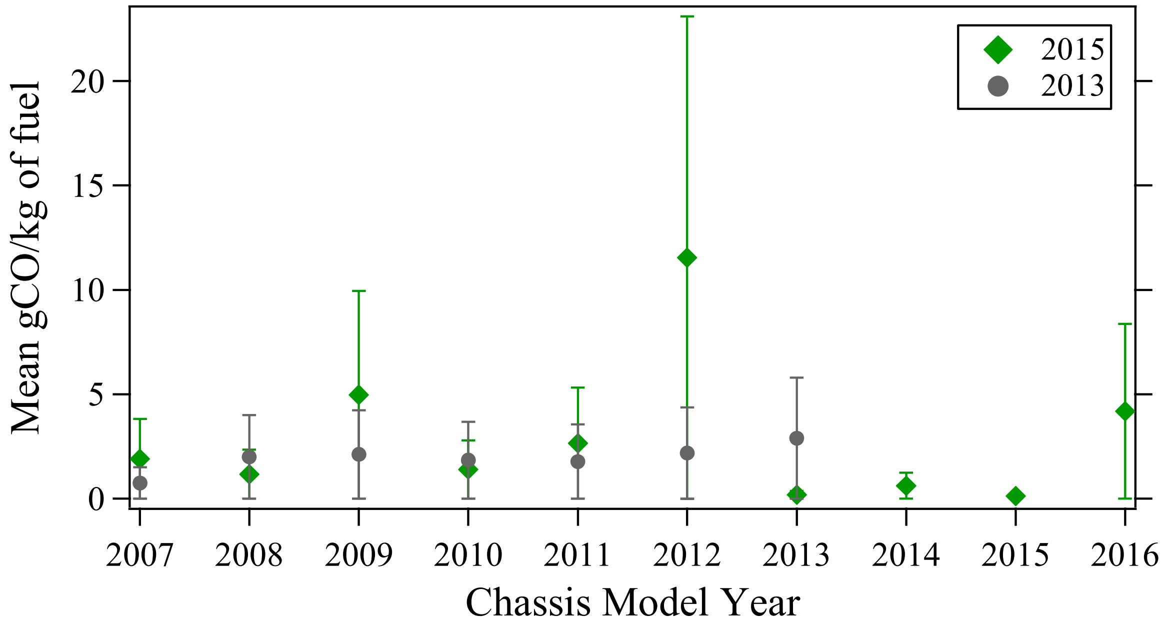

Figure 35. The Port of Los Angeles mean gCO/kg of fuel by chassis model year for 2013 (circles) and 2015 (diamonds) measurements. The uncertainties are the standard errors of the mean calculated from the daily means for each model year. Three 2012 CNG HDV measurements are included in the 2015 results increasing the mean and uncertainty.

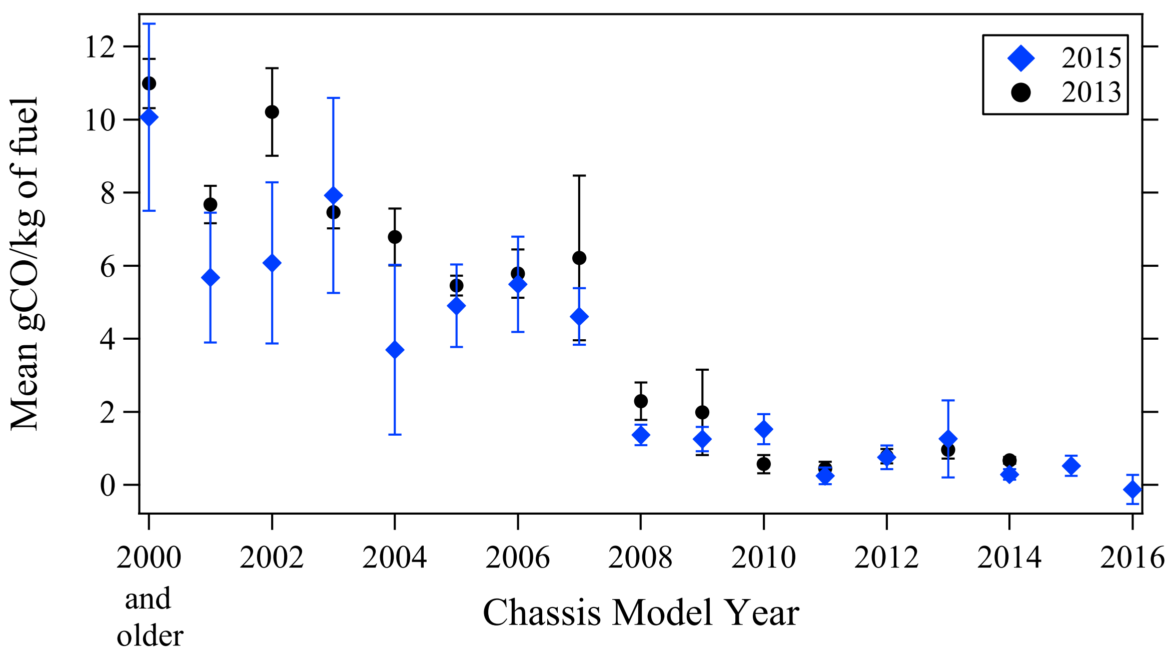

Figure 36. The Cottonwood weigh station mean gCO/kg of fuel by chassis model year for 2013 (circles) and 2015 (diamonds) measurements. The uncertainties are the standard errors of the mean calculated from the daily means for each model year.

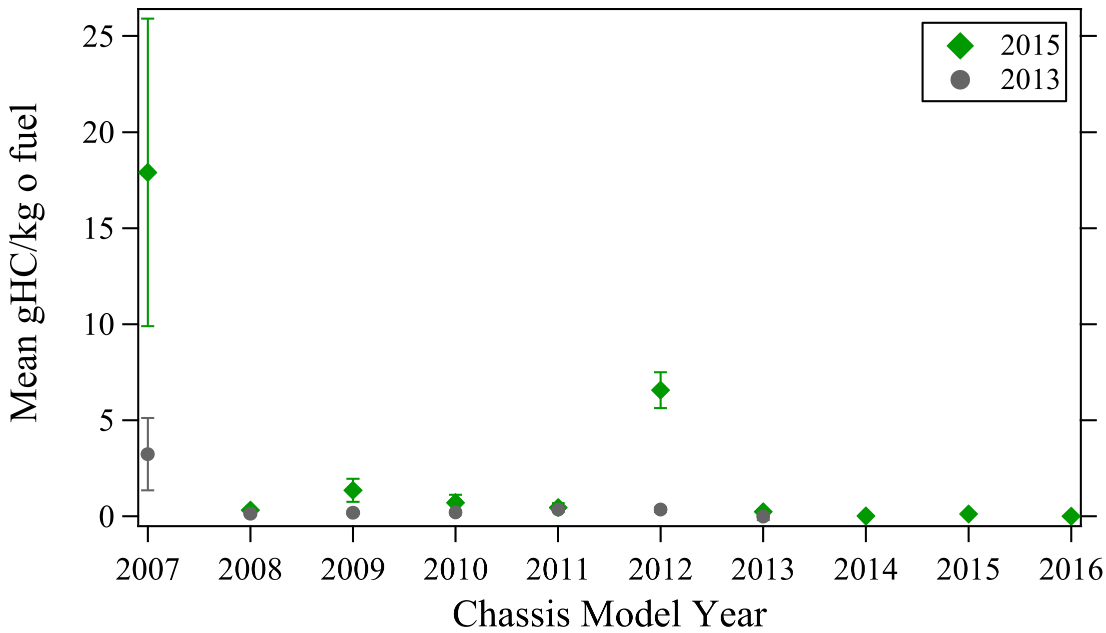

Figure 37. The Port of Los Angeles mean gHC/kg of fuel by chassis model year for 2013 (circles) and 2015 (diamonds) measurements. The uncertainties are the standard errors of the mean calculated from the daily means for each model year. Three 2012 CNG HDV measurements are included in the 2015 results increasing the mean and uncertainty.

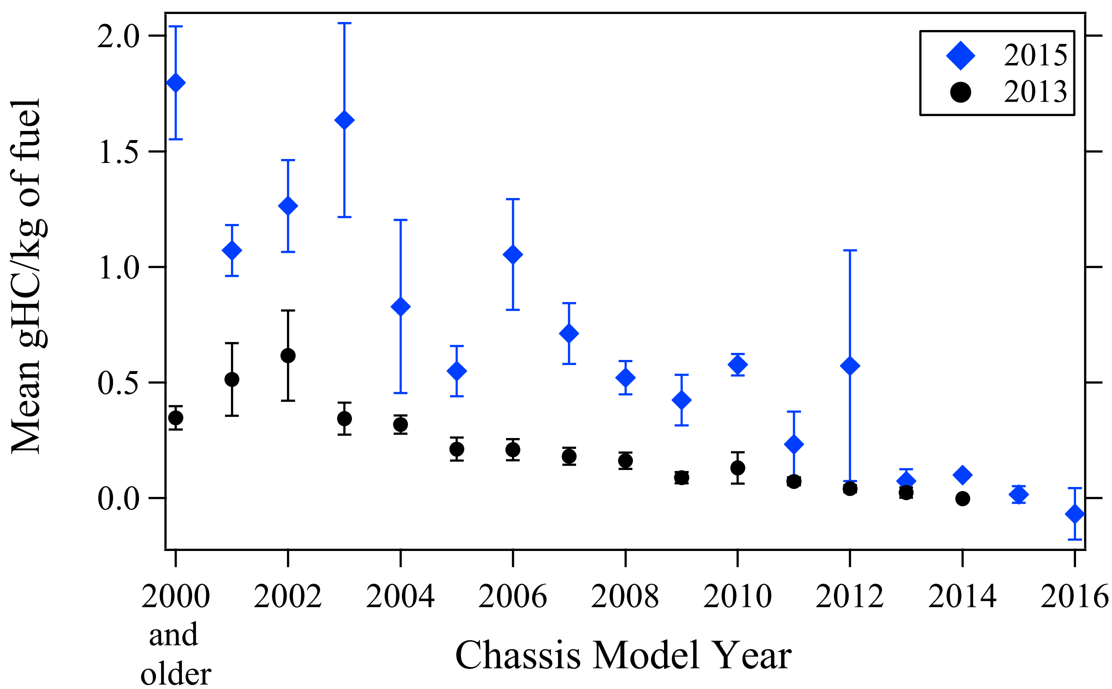

Figure 38. The Cottonwood weigh station mean gHC/kg of fuel by chassis model year for 2013 (circles) and 2015 (diamonds) measurements. The uncertainties are the standard errors of the mean calculated from the daily means for each model year.

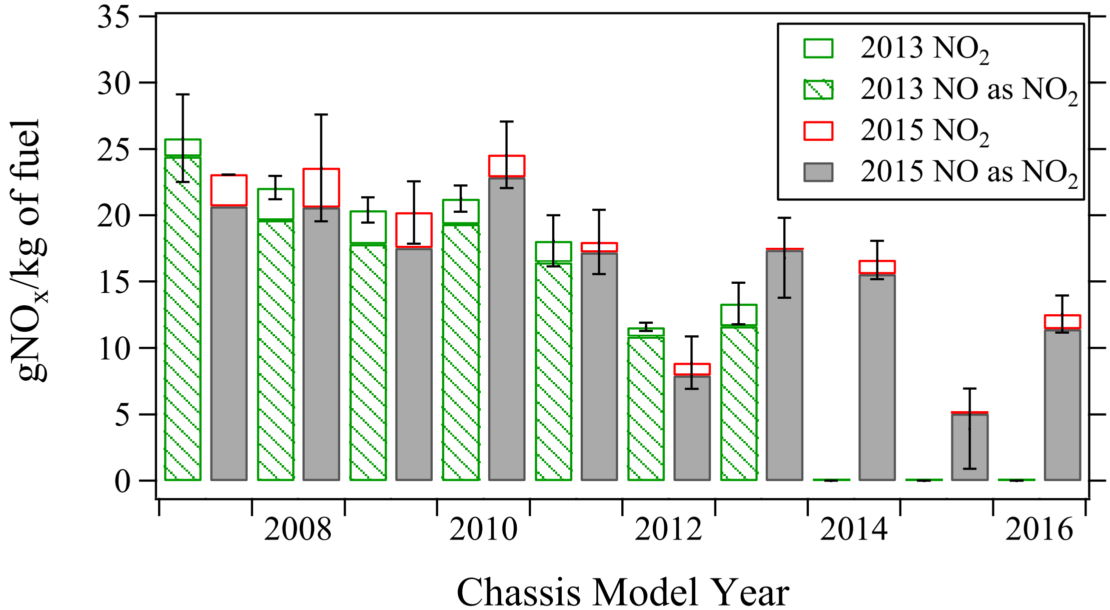

Figure 39. Port of Los Angeles total gNO_x/kg of fuel emissions by chassis model year measured in 2013 and 2015 showing the individual contributions of NO (hatched or filled) and NO_2 (open bar). NO emissions have been converted into NO_2 equivalents so that the height of each bar is total gNO_x/kg of fuel emissions. Uncertainties plotted are standard errors of the mean calculated from each model year's daily means.

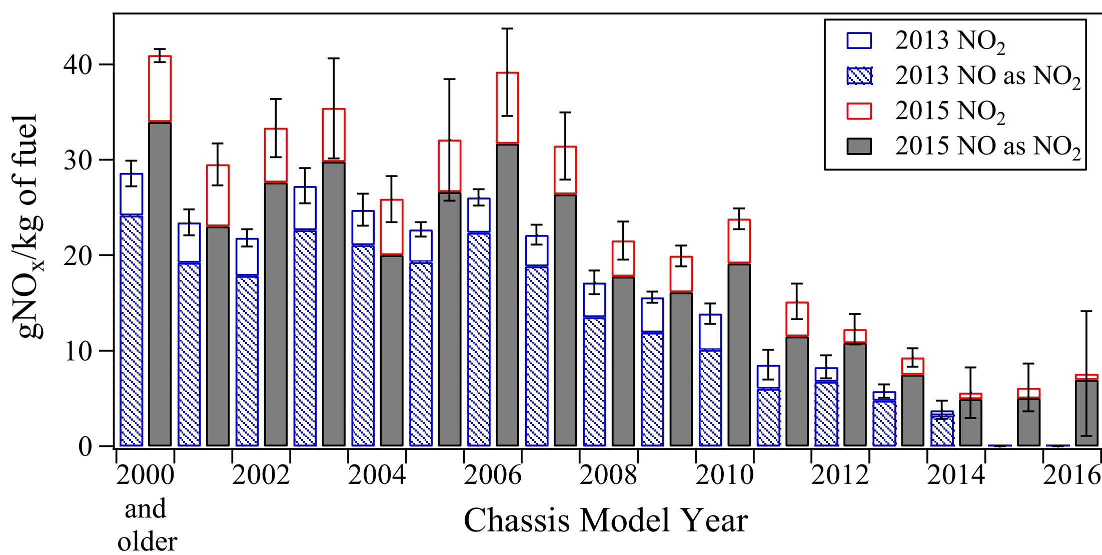

Figure 40. Cottonwood total gNO_x/kg of fuel emissions by chassis model year measured in 2013 and 2015 showing individual contributions of NO (hatched or filled) and NO_2 (open bar). NO emissions have been converted into NO_2 equivalents, making the height of each bar the total gNO_x/kg of fuel emissions. Uncertainties plotted are standard errors of the mean calculated from each model year's daily means.

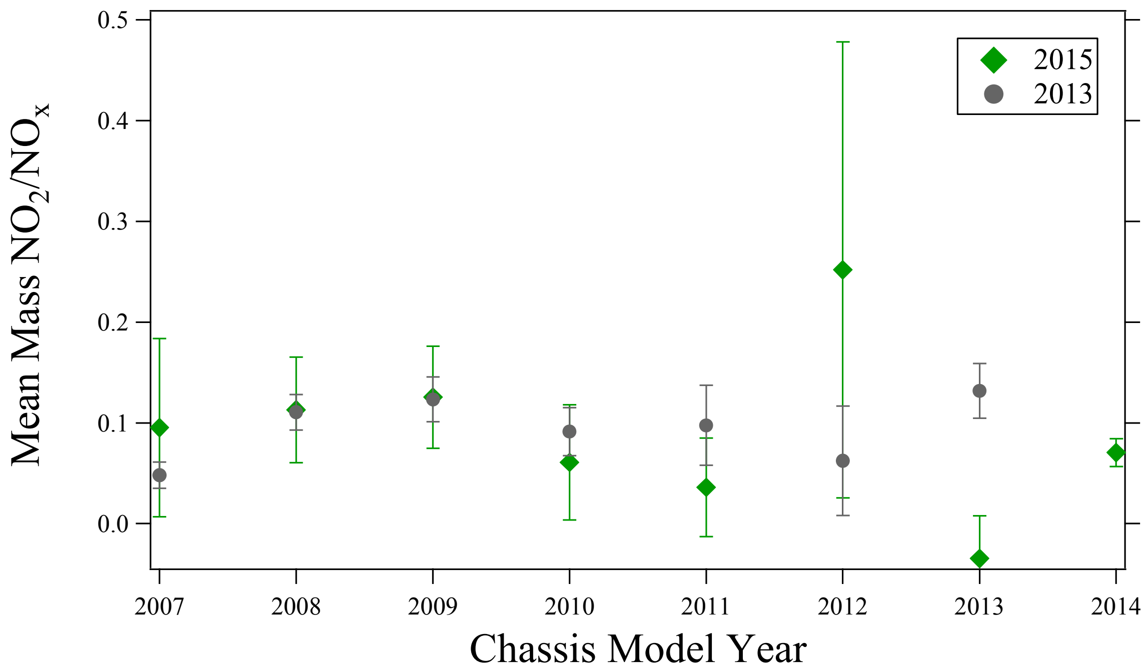

Figure 41. Mean mass NO_2/NO_x at the Port of Los Angeles versus chassis model year for data from 2013 (circles) and 2015 (diamonds). The uncertainties plotted are standard errors of the mean calculated from the daily means for each model year.

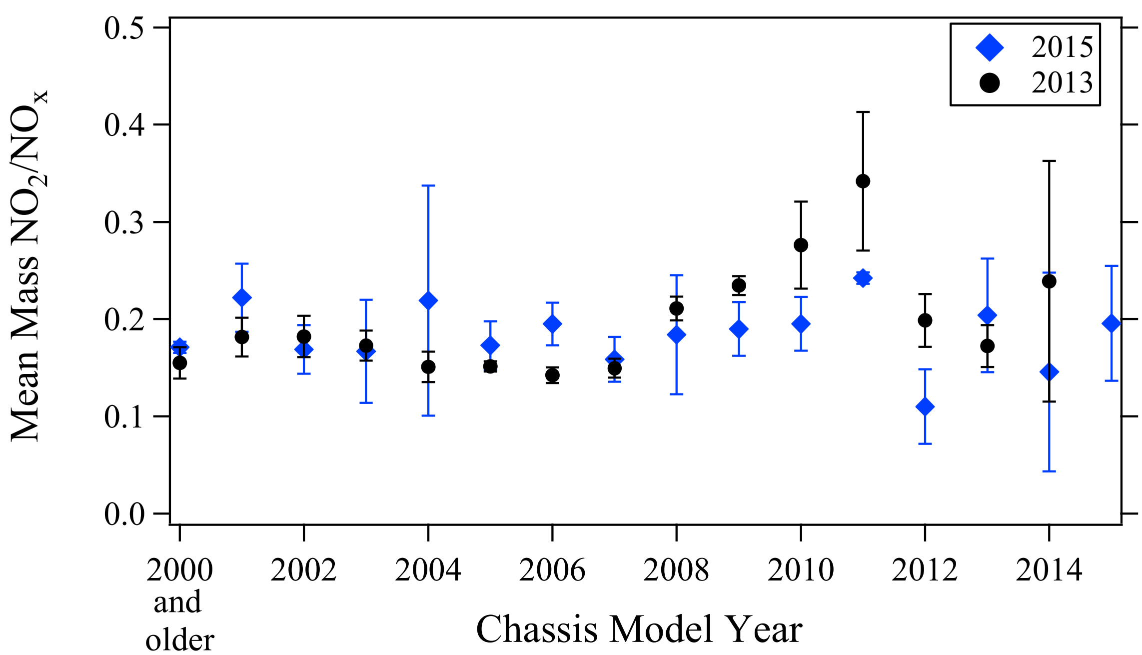

Figure 42. Mean mass NO_2/NO_x at the Cottonwood weigh station versus chassis model year for data from 2013 (circles) and 2015 (diamonds). The uncertainties plotted are standard errors of the mean calculated from the daily means for each model year.

Port except for model year 2013, where it has decreased as those HDV have aged. This means that the total NO_x is comprised of more NO in 2015 than in 2013. At both of our measurements sites we continue to see reductions in the NO_2/NO_x ratios as the HDV age which is consistent with previously published results.[10]

Particle Measurements

Fuel specific PM emissions versus chassis model year are compared from the 2013 and 2015 measurement campaigns in in Figures 43, showing the Port results, and 44, displaying the Cottonwood weigh station data. The uncertainties plotted are the standard error of the means calculated from the daily means. As previously discussed the fuel specific PM, BC and PN emissions are moving in opposite directions at our two sampling locations. The Port of Los Angeles was required to replace all HDV with 2007 compliant engines or newer HDV in 2010 as part of the San Pedro Clean Port initiative. This resulted in a very rapid fleet makeover during a very short period of time with the result being that the Port truck fleet had very low particle emissions which we observed in our 2013 measurements. Fast forward to 2015 and the 2008 and 2009 chassis model year vehicles, the most abundant HDV at our Port location, are now 5 to 6 years old. Figure 45 shows that chassis model years 2008 – 2010 all show increases in gPM/kg of fuel emissions with the 2008 and 2009 models having the largest increases. Mean gPM/kg of fuel emissions are still quite low, 0.11 ± 0.01 which is half of the mean observed at the Cottonwood weigh station, but this is almost a factor of 4 increase from the mean observed in 2013.

The Cottonwood weigh station site saw reductions in particle emissions in 2015 of almost a factor of 3 (0.65 ± 0.11 to 0.22 ± 0.04). About half of this reduction is likely the result of the Cottonwood fleet getting 0.5 model years newer as new model years continue to show very low particle emissions. Unlike at the Port the 2008 and 2009 chassis model year vehicles showed gPM/kg of fuel emission reductions in 2015 (see Figure 44), however, the differences observed in the 2009 models are greatly exaggerated by a single high emitter measured in 2013 (73.8 gPM/kg of fuel). What is also apparent in Figure 44 is that chassis model years older than 2008, though much fewer in number, appear to have lower PM emissions than observed in 2013.

The pattern observed for PM emissions is repeated for BC emissions as one would expect since the majority of PM emissions will likely be some form of soot. Figures 45 and 46 graph the fuel specific BC emissions versus chassis model year for the Port and Cottonwood weigh station respectively. The uncertainties plotted are the standard error of the means calculated from the daily means. At our Port locations we again see mean gBC/kg of fuel emissions increase by a factor of 4 from the 2013 measurements (0.02 ± 0.003 to 0.08 ± 0.01) with the 2008 to 2010 chassis model years all showing significant increases in BC emissions. At Cottonwood we again have an almost factor of 3 reduction in mean gBC/kg of fuel emissions with slight reductions in the 2008 and 2009 chassis model year vehicles. We also see improvements in BC emissions in HDV older than 2008 models.

The Port of Los Angeles and Cottonwood weigh station fuel specific PN emissions versus chassis model year are displayed in Figures 47 and 48 respectively. The uncertainties plotted are the

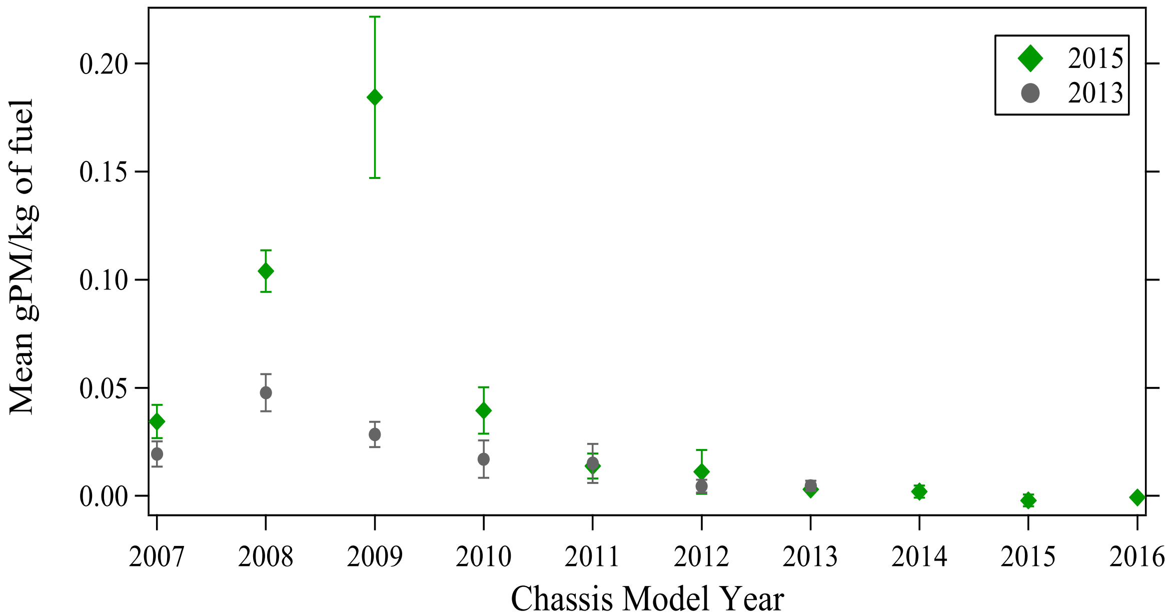

Figure 43. Port of Los Angeles mean gPM/kg of fuel versus chassis model year for data from 2013 (circles) and 2015 (diamonds). The uncertainties plotted are standard errors of the mean calculated from the daily means for each model year.

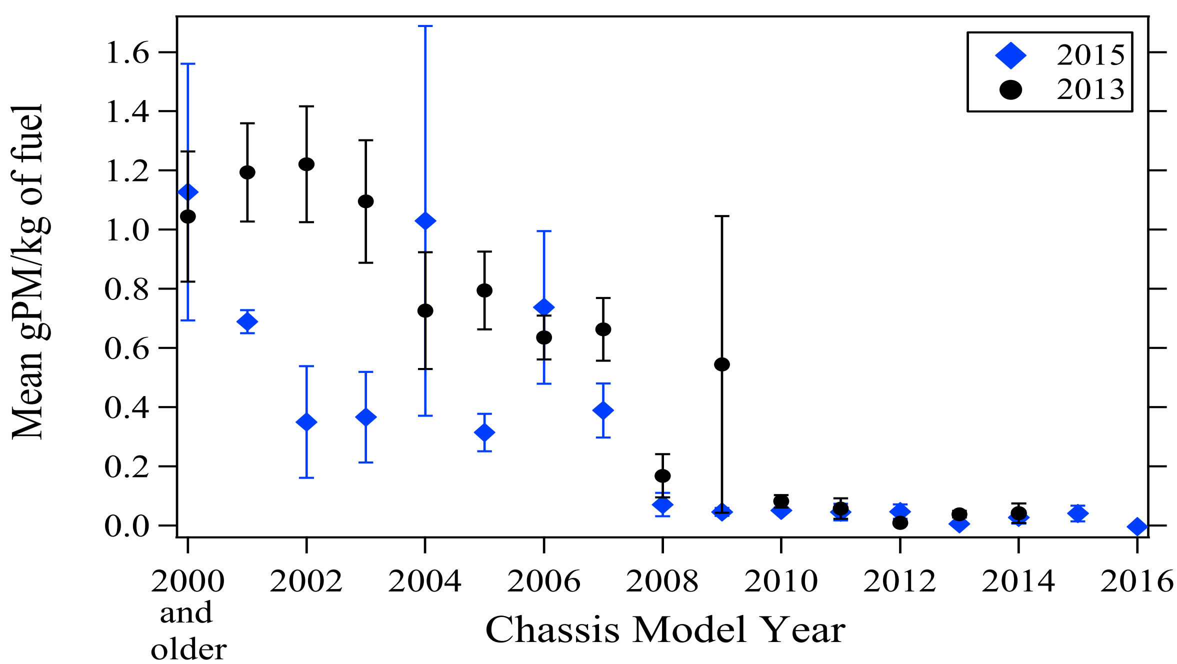

Figure 44. Cottonwood weigh station mean gPM/kg of fuel versus chassis model year for data from 2013 (circles) and 2015 (diamonds). The uncertainties plotted are standard errors of the mean calculated from the daily means for each model year.

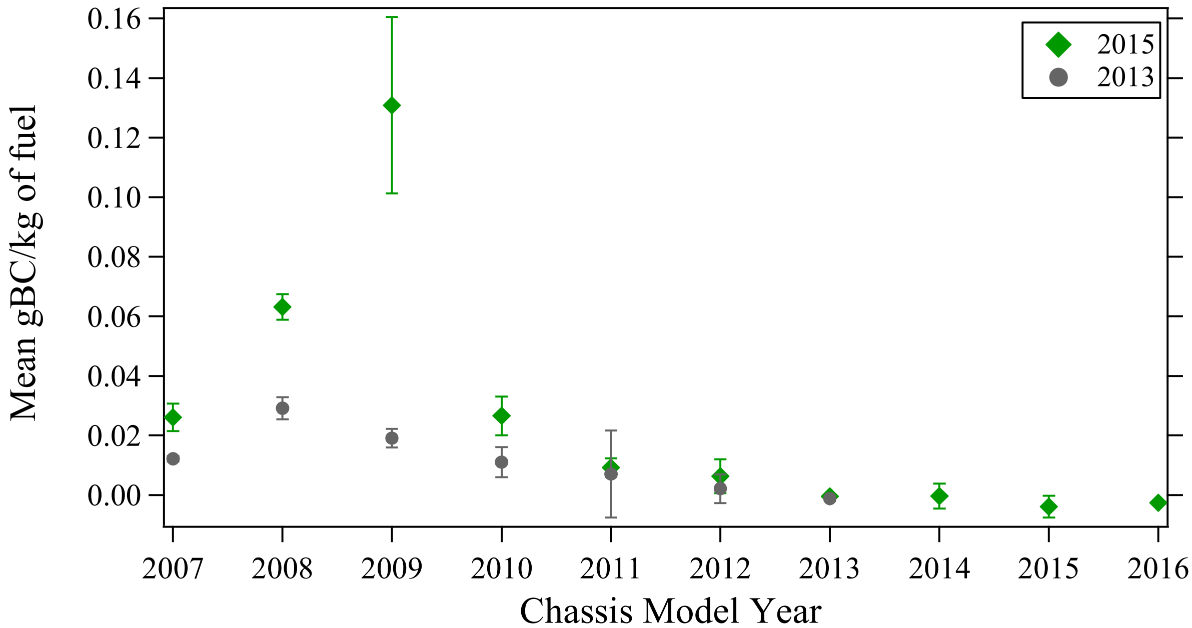

Figure 45. Port of Los Angeles mean gBC/kg of fuel versus chassis model year for data from 2013 (circles) and 2015 (diamonds). The uncertainties plotted are standard errors of the mean calculated from the daily means for each model year.

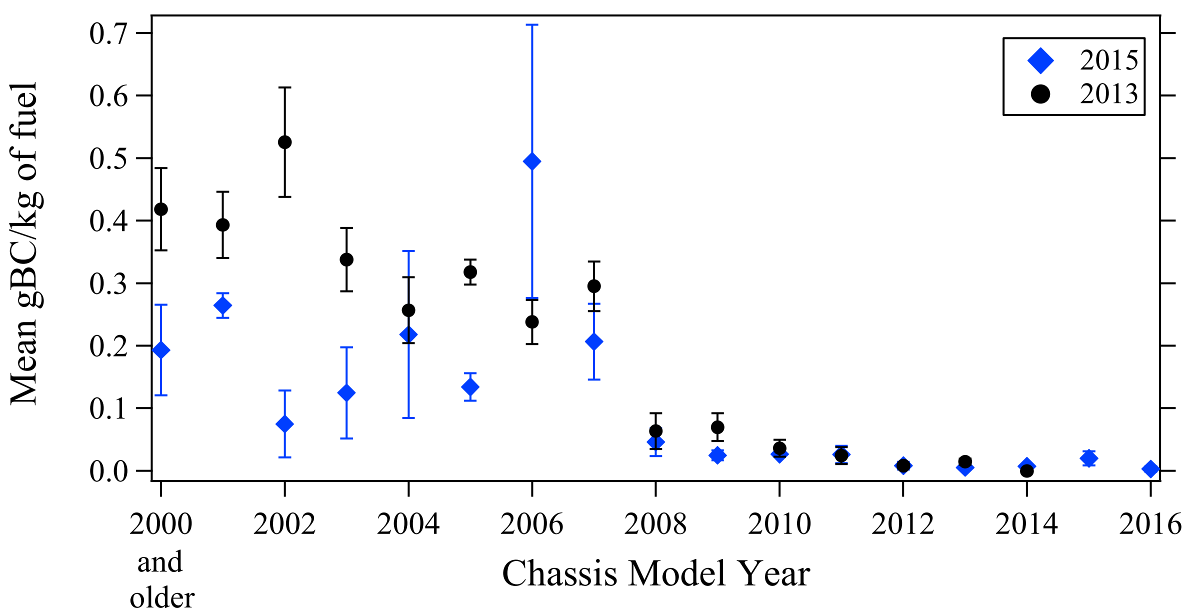

Figure 46. Cottonwood weigh station mean gBC/kg of fuel versus chassis model year for data from 2013 (circles) and 2015 (diamonds). The uncertainties plotted are standard errors of the mean calculated from the daily means for each model year.

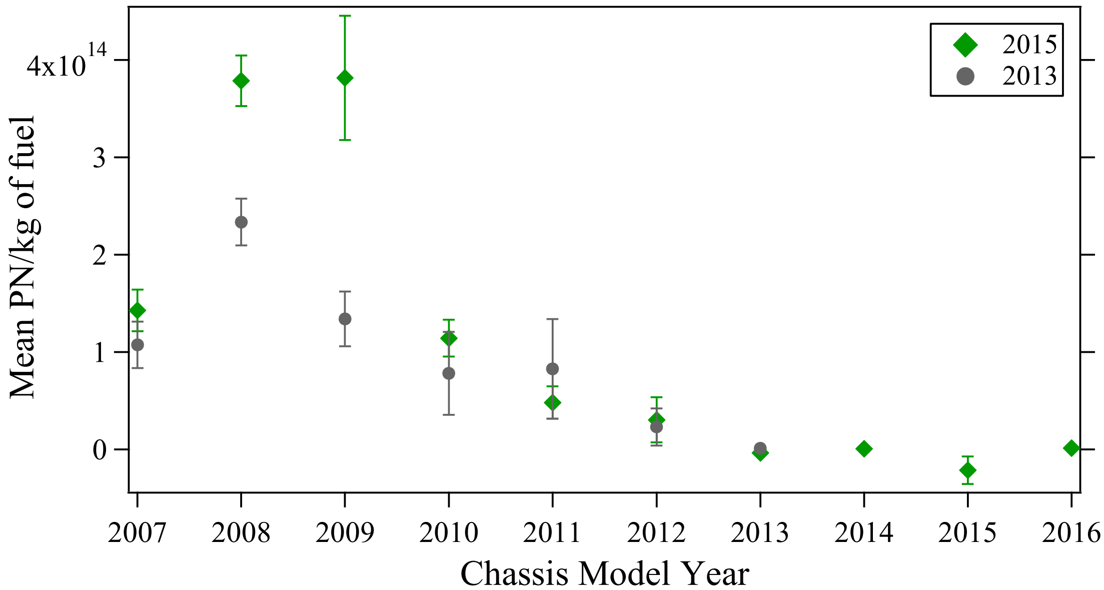

Figure 47. Port of Los Angeles mean PN/kg of fuel versus chassis model year for data from 2013 (circles) and 2015 (diamonds). The uncertainties plotted are standard errors of the mean calculated from the daily means for each model year.

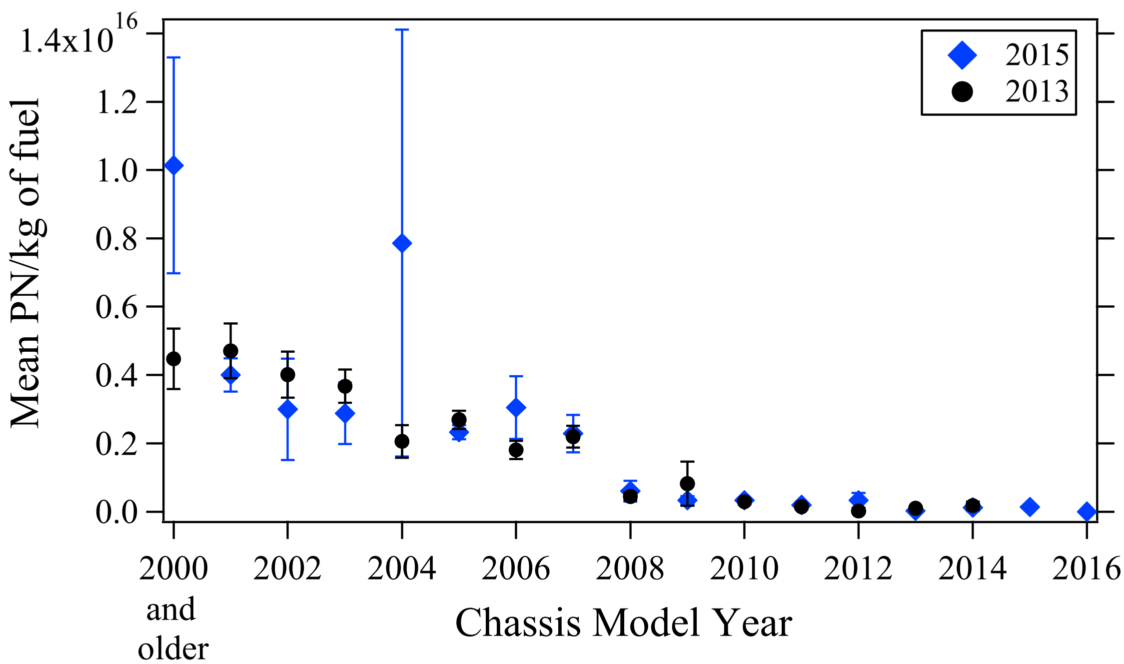

Figure 48. Cottonwood weigh station mean PN/kg of fuel versus chassis model year for data from 2013 (circles) and 2015 (diamonds). The uncertainties plotted are standard errors of the mean calculated from the daily means for each model year.

standard error of the means calculated from the daily means. Again, corresponding with PM and BC trends at the Port, there are significant increases in PN/kg of fuel emissions for model year 2008 and 2009. Cottonwood PN trends are also similar to the PM and BC measurements, as there is a drop in PN with the implementation of DPF systems, but we do not see any increase in PN emissions for the 2008 and 2009 chassis model years that are increasing at the Port.

Changes in mean emissions can result because of a few additional high emitters or due to increased emissions across the entire fleet. To better understand what is changing in the fleet emissions Figures 49, 51 and 53 are box and whisker plots of fuel specific PM, BC and PN emissions for the Port of Los Angeles, and Figures 50, 52 and 54 are similar plots for the Cottonwood weigh station. These figures show all valid readings for the corresponding pollutant using a split y-axis to magnify the interquartile ranges. The mean for each model year is symbolized by a filled square. The bottom whisker signifies HDV measurements that are in the 10th percentile; the box represents the 25th, 50th and 75th percentile, and the top whisker is the 90th percentile. Vehicle measurements outside of the 10th to the 90th percentiles are plotted with colored diamonds or circles.

At the Port location the increases in mean fuel specific PM, BC and PN emissions for the 2008 and 2009 chassis model year vehicles can be seen in Figures 49, 51 and 53 to be a result of emission increases that involve a large number of trucks. Both model years show large increases in the size of the box, whiskers and the number of points beyond the 90th percentile. The increased mean for the 2010 chassis model year appear to be more the result of increases in the 90th percentiles and above as the size of the interquartile range is similar to the size seen in the 2013 data. There are few if any differences in 2011 and newer models.

At Cottonwood particle emissions are decreasing overall and that can be seen in the decreasing size of the interquartile range for the 2015 data for the 2007 and older chassis model years in Figures 50, 52 and 54. Means also decreased for the 2008 chassis model and those reductions appear to be driven by reductions in the number of measurements beyond the 90th percentile. Table 8 shows the percent of HDV above the 2013 90th percentile for both locations. There is a large reduction in the 2009 model year mean gPM/kg of fuel emissions despite the fact that there are slight increases in the percentage of measurements that exceed the 2013 90th percentile. This is due to the fact that in the 2013 measurements the 2009 models included one vehicle with extremely high PM emissions, more than 70 gPM/kg of fuel emissions.

To highlight the changes that have occurred in the shape of the emissions distribution at our two measurement locations Figures 55 (Port) and 56 (Cottonwood) are percentile-percentile plots comparing the 2015 measurements with the 2013 measurements for PM and BC. Each point represents increases in 2.5 percentile increments, the percentile value for the first percentile in 2015 versus the first percentile recorded in 2013 and so on, with a total of 40 points for each figure. The diagonal line represents a 1:1 relationship which is where the points would fall if the two emission distributions were identical. At the Port (Figure 55) the percentiles deviate from the 1:1 line starting with the 45th percentile for PM and the 75th percentile for BC. At Cottonwood (Figure 56) the points leave the 1:1 line starting with the 50th percentile for PM and at the 30th percentile

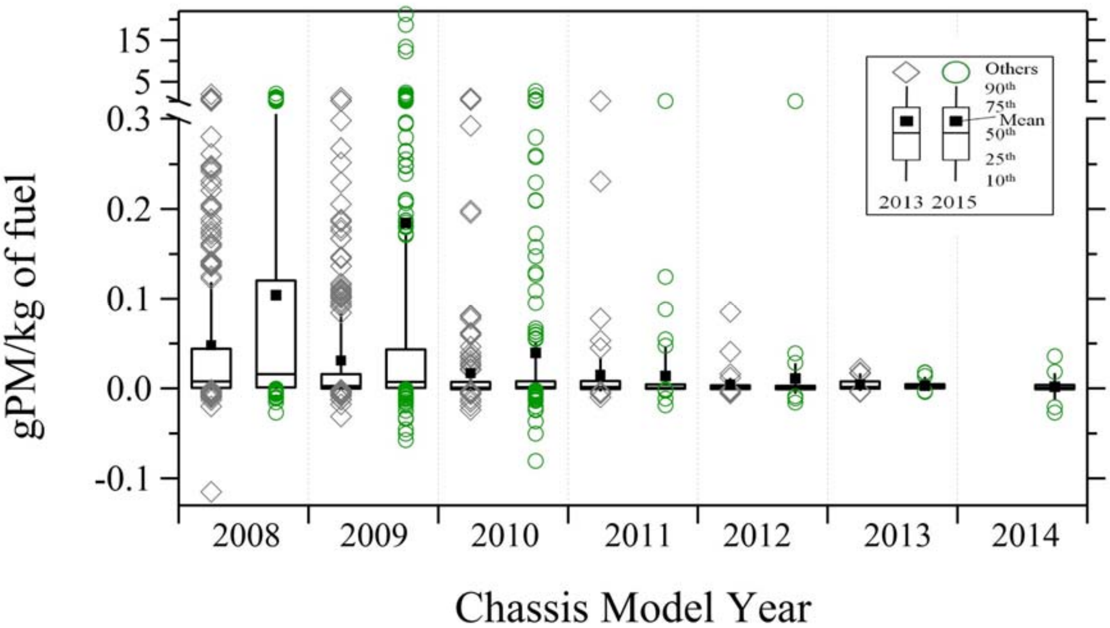

Figure 49. Box and whisker plot for the Port of Los Angeles gPM/kg of fuel emissions by chassis model year for the 2013 (diamonds) and 2015 (circles) data. The box represents the 25th, 50th and 75th percentiles, the vertical lines span the 10th and 90th percentiles and the points are individual measurements that fall outside these percentiles. The filled square is the mean.

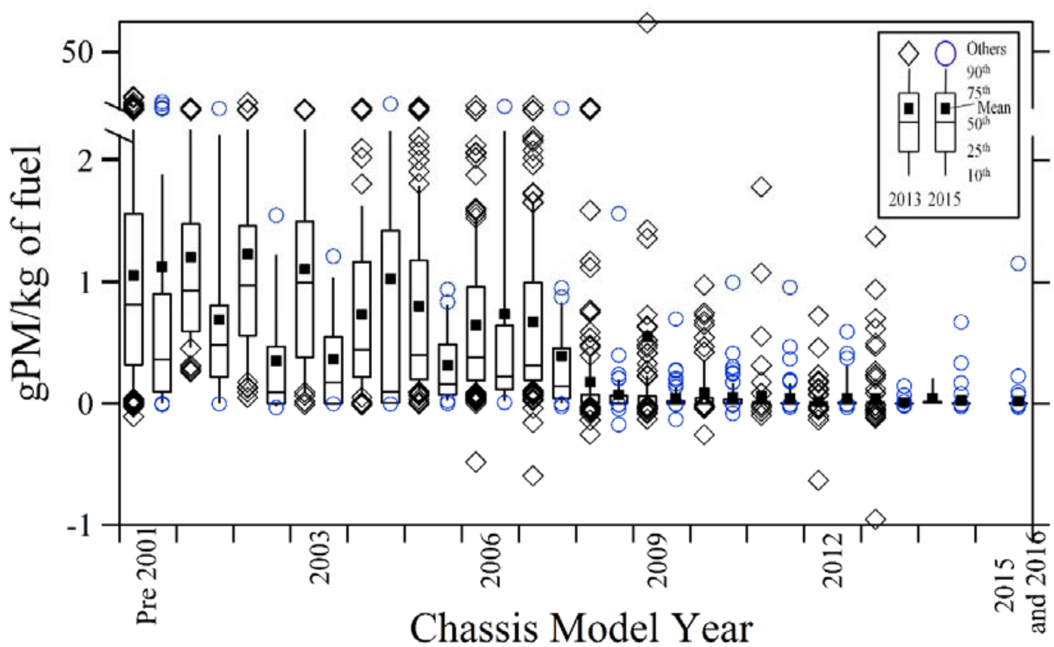

Figure 50. Box and whisker plot for the Cottonwood scales gPM/kg of fuel emissions by chassis model year for the 2013 (diamonds) and 2015 (circles) data. The box represents the 25th, 50th and 75th percentiles, the whiskers span the 10th and 90th percentiles and the points are individual measurements that fall outside these percentiles. The filled square is the mean.

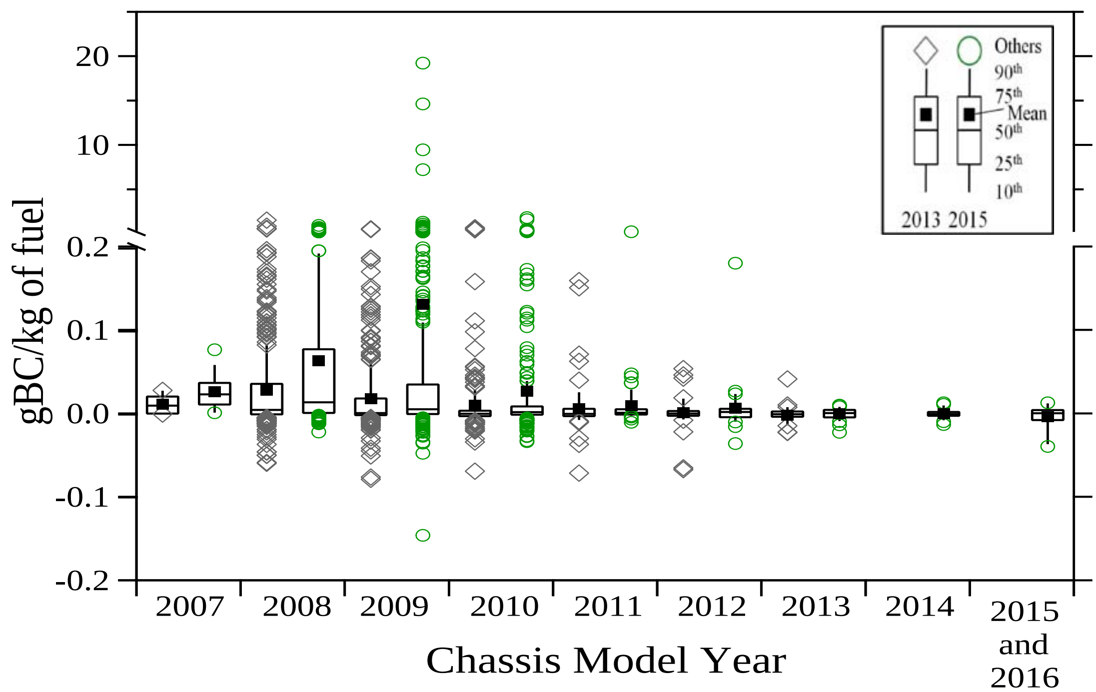

Figure 51. Box and whisker plot for the Port of Los Angeles gBC/kg of fuel emissions by chassis model year for the 2013 (diamonds) and 2015 (circles) data. The box represents the 25th, 50th and 75th percentiles, the whiskers span the 10th and 90th percentiles and the points are individual measurements that lie outside these percentiles. The filled square is the mean.

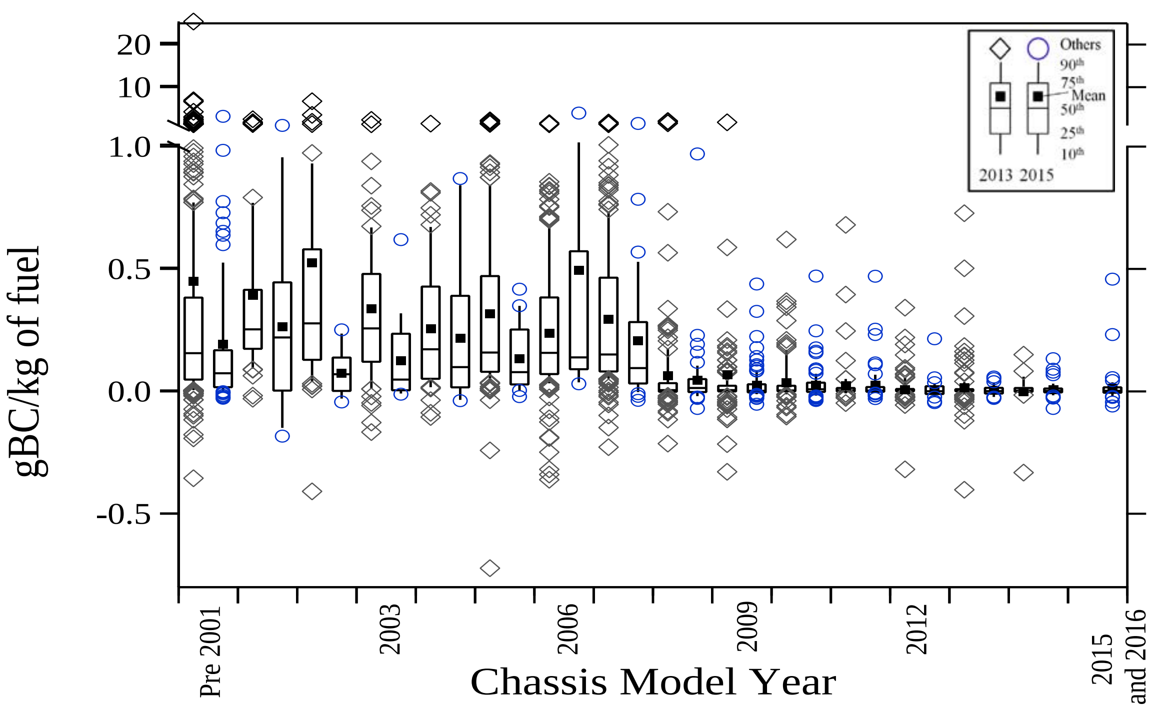

Figure 52. Box and whisker plot for the Cottonwood weigh station gBC/kg of fuel emissions by chassis model year for the 2013 (diamonds) and 2015 (circles) data. The box represents the 25th, 50th and 75th percentiles, the whiskers span the 10th and 90th percentiles and the individual points are plotted that fall beyond those percentiles. The filled square is the mean.

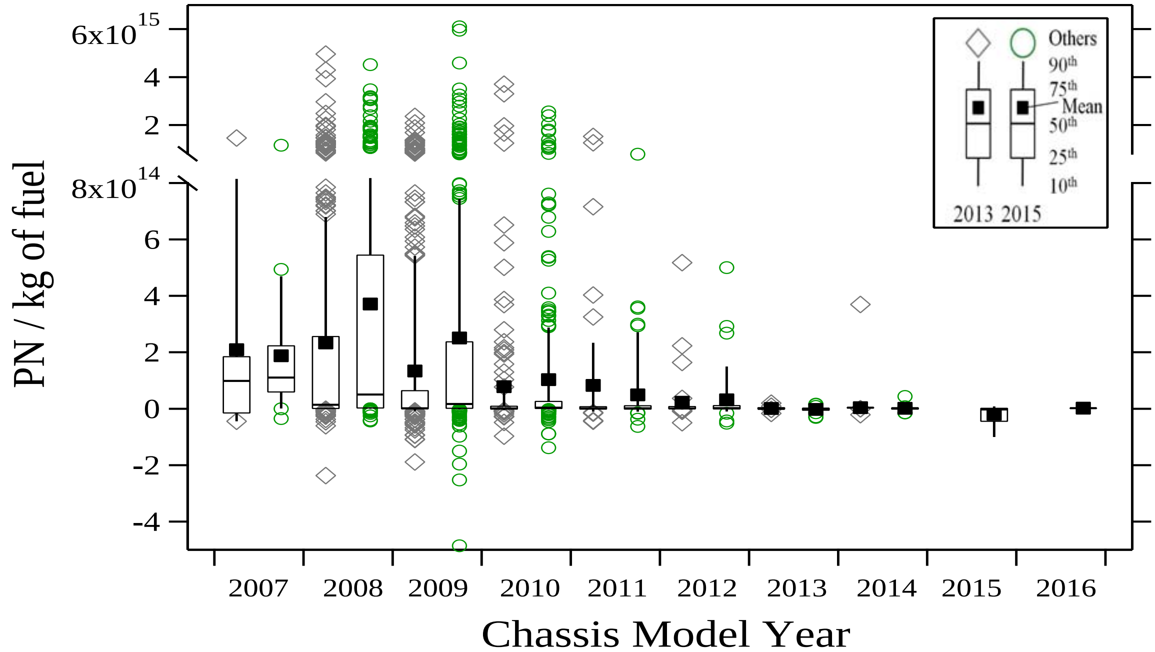

Figure 53. Box and whisker plot for the Port of Los Angeles PN/kg of fuel emissions by chassis model year for the 2013 (diamonds) and 2015 (circles) data. The box represents the 25th, 50th and 75th percentiles, the whiskers span the 10th and 90th percentiles and the individual points are plotted that fall beyond those percentiles. The filled square is the mean.

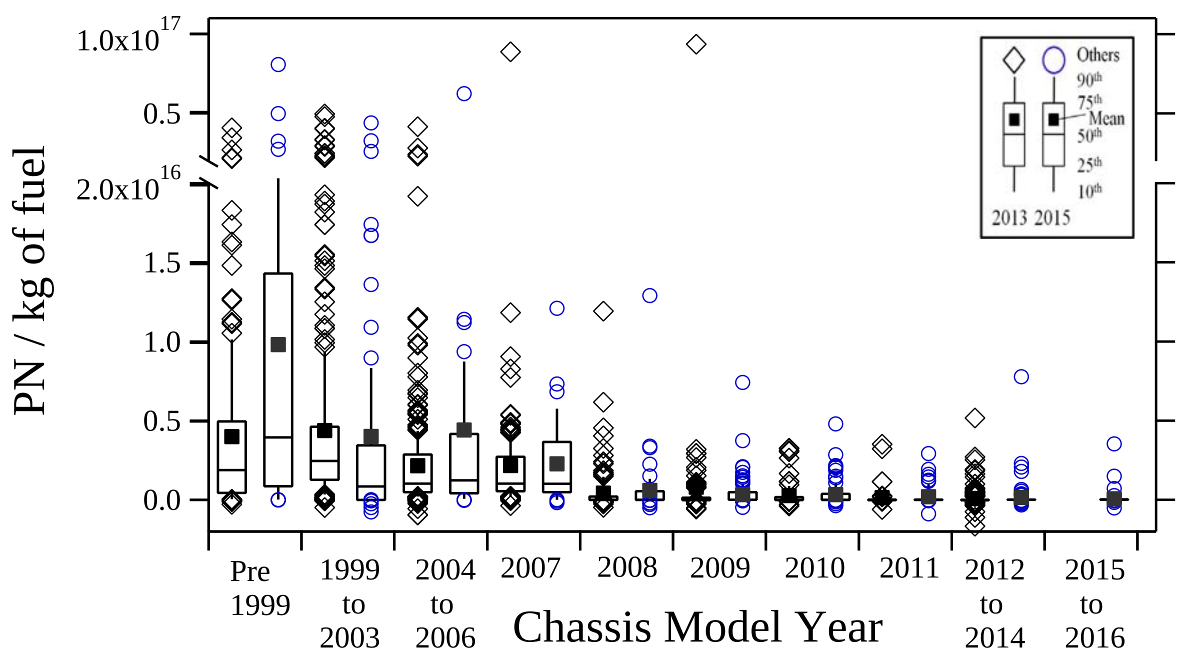

Figure 54. Box and whisker plot for the Cottonwood weigh station PN/kg of fuel emissions by chassis model year for the 2013 (diamonds) and 2015 (circles) data. The box represents the 25th, 50th and 75th percentiles, the whiskers span the 10th and 90th percentiles and the individual points are plotted that fall beyond those percentiles. The filled square is the mean.

Table 8. Percent of HDV above the 2013 90th Percentile.

Model Year	Emissions	Port of Los Angeles			Cottonwood Weigh Station		
		2013 90th Percentile	2013	2015	2013 90th Percentile	2013	2015
2008	gPM/kg	0.12	3.6%	6.5%	0.4	0.6%	0.1%
	gBC/kg	0.08	3.8%	6.1%	0.17	0.7%	0.4%
	PN/kg	6.8E+14	3.4%	5.2%	1.5E+15	0.7%	0.7%
2009	gPM/kg	0.08	3.8%	7.7%	0.2	0.9%	1.4%
	gBC/kg	0.07	2.2%	6.4%	0.07	1.1%	1.8%
	PN/kg	5.4E+14	3.1%	6.1%	7.4E+14	0.8%	2.1%
2010	gPM/kg	0.02	1.8%	3.5%	0.3	0.6%	0.2%
	gBC/kg	0.03	1.8%	2.5%	0.17	0.4%	0.4%
	PN/kg	6.4E+13	1.8%	4.1%	8.9E+14	0.4%	1.4%

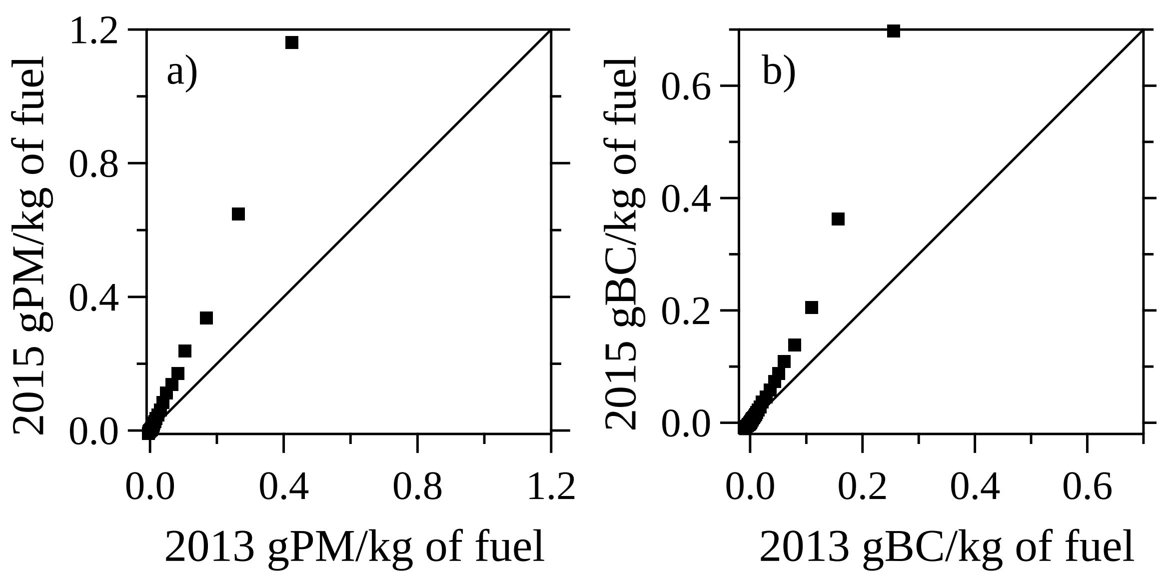

Figure 55. Port of Los Angeles percentile-percentile plots comparing (a) 2015 gPM/kg of fuel emissions versus 2013 gPM/kg of fuel emissions and (b) 2015 gBC/kg of fuel emissions versus 2013 gBC/kg of fuel emissions.

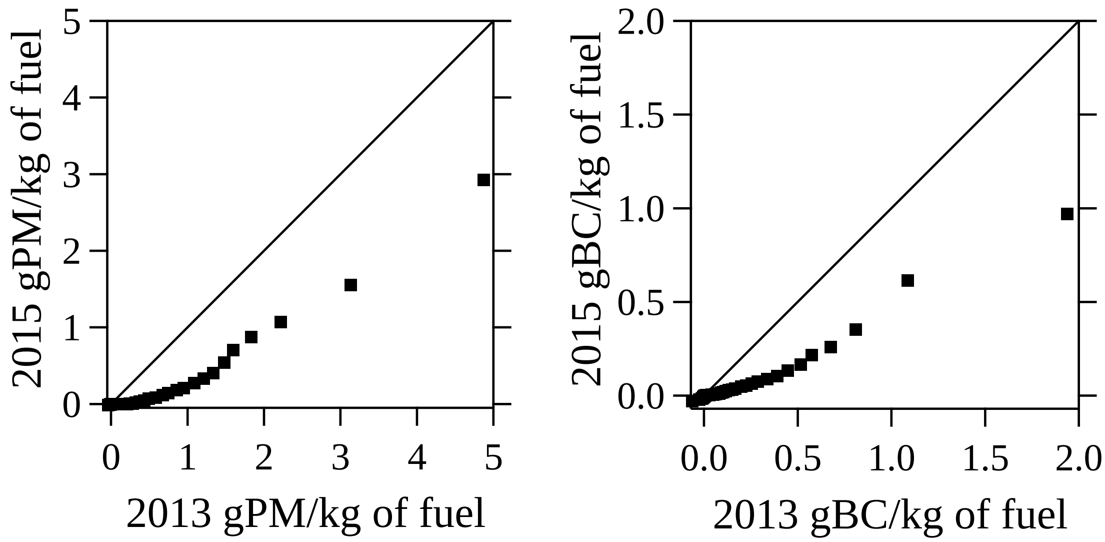

Figure 56. Cottonwood weigh station percentile-percentile plots comparing (a) 2015 gPM/kg of fuel emissions versus 2013 gPM/kg of fuel emissions and (b) 2015 gBC/kg of fuel emissions versus 2013 gBC/kg of fuel emissions.

for BC. The changes in the shape of the emissions distribution are consistent with the changes discussed previously with the Port particle emissions on the increase and fleet changes at Cottonwood leading to decreases. The Port comparison, displayed in Figure 55, shows that fuel specific PM and BC emissions increase with the increasing percentiles in 2015 at a faster rate with the higher percentile measurements in 2015 emitted significantly more PM and BC than they did in 2013. Contrary to that, the 2015 Cottonwood fleet (see Figure 56) experienced a significant decrease in PM and BC compared to 2013 fleet.

As previously discussed about half of the reductions in particle emissions at the Cottonwood site in 2015 is the result of fleet turnover and that newer trucks equipped with DPFs are replacing trucks without filters. The remaining reductions appear to be significant improvements in the particle emissions of chassis model year trucks older than 2008. Using the license plate and vehicle identification numbers we searched the state's drayage truck registry and the TRUCRS database for information as to the retrofit status of our fleet.[29] We found 27 HDV that indicate that they have been retrofitted with a DPF in addition to 29 vehicles that have conducted other upgrades. Figure 59 graphs gPM/kg of fuel by chassis model year for 3 groups of vehicles, retrofitted with a DPF (diamonds), not retrofitted (triangles) and all of the measurements (squares). The uncertainties plotted are standard errors of the mean calculated from the daily means. It is obvious that the majority of the retrofit information we obtained is correct as that group of vehicles show large reductions in PM emissions, the exception being for the 2005 chassis model year.

Repeat and Reoccurring HDV Measurements

Table 9 compares the number of repeat measurements collected for both locations during the first two measurement campaigns. Table 10 only reports the number of times HDVs were seen at

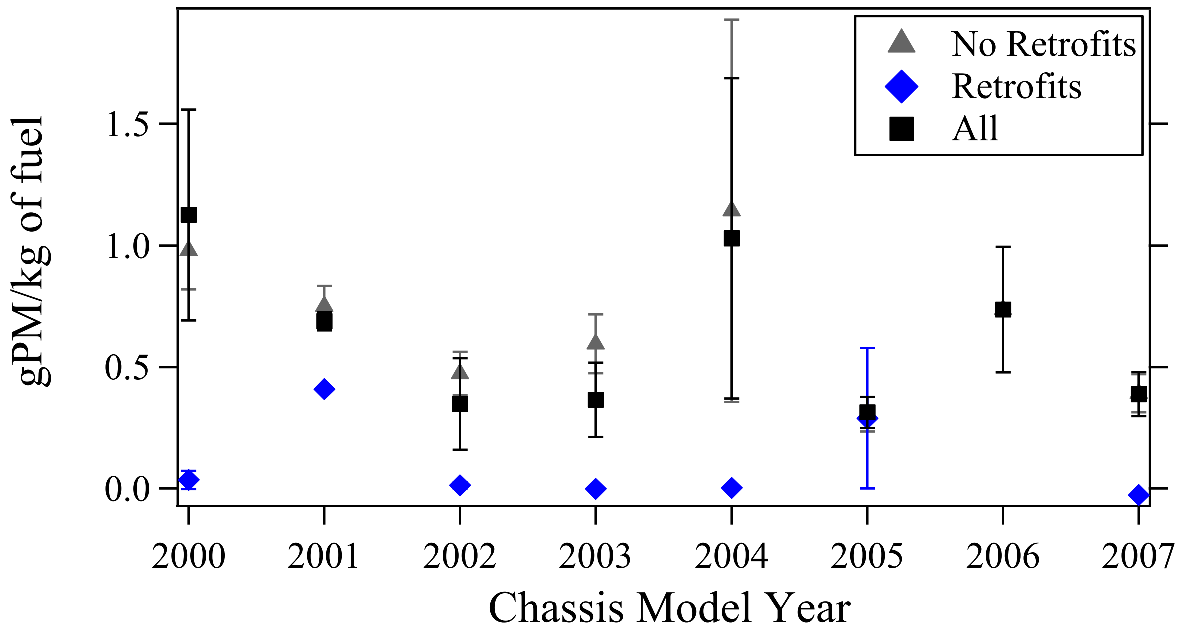

Figure 57. Cottonwood weigh station gPM/kg of fuel emissions versus chassis model year for HDV older than 2008 models. Three vehicle groups are graphed HDV identified as having a retrofitted DPF (diamonds), vehicles with no indication of a retrofit DPF (triangles) and all of the measurements (squares). The uncertainties plotted are standard errors of the mean calculated from the daily means.

Table 9. Number of Repeat Measurements by Site and Year.

Times Measured	Port 2013 Number (%)	Port 2015 Number (%)	Cottonwood 2013 Number (%)	Cottonwood 2015 Number (%)
1	711 (78%)	654 (70.7%)	1578 (92.3%)	557 (88.8%)
2	134 (14.7%)	149 (16.1%)	110 (6.4%)	64 (10.2%)
3	43 (4.7%)	58 (6.3%)	16 (1.0%)	3 (0.5%)
4	14 (1.5%)	27 (2.9%)	5 (0.3%)	0
5	7 (0.8%)	19 (2.1%)	0	0
6	2 (0.2%)	11 (1.2%)	0	3 (0.5%)
7	0	3 (0.3%)	0	0
8	1 (0.1%)	1 (0.1%)	0	0
9	0	0	0	0
10	0	2 (0.2%)	0	0
11	0	0	0	0
12	0	1 (0.1%)	0	0

each location in a given measurement year. There were also HDV that were measured in both years at a site and they will be referred to as reoccurring HDV. Repeat vehicle percentages increased between 2013 and 2015 at the Cottonwood weigh station in large part due to the CARB opacity inspection team which diverted trucks after the OHMS setup which presented the opportunity for a second measurement by the OHMS system.

In 2015 the Port of Los Angeles had 271 vehicles with multiple successful measurements and the Cottonwood weigh station had 70 vehicles. Figures 58 and 59 show the repeat HDV measurements at the Port and at Cottonwood for gPM/kg of fuel in 2015 and Figures 60 and 61 show the repeat HDV measurements in 2015 for gBC/kg of fuel. The trucks are rank ordered by their average PM or BC emissions and then each sequentially plotted along the x-axis with each trucks repeat measurements. Note both axes are split for the Port of Los Angeles data (Figures 58 and 59). As the average emissions increase, so does the variability of the emissions measured. This is not due to variations in the testing method, as the repeatability of the low emitting vehicles is quite good, but a result of variability in the exhaust emissions of the vehicle. This is identical to behavior previously seen from light-duty vehicles.[30]

Particle emissions variability involves an additional factor that is not found in variable exhaust gas emissions. Two steps are required for an elevated particle emission measurement 1) the HDVs engine has to generate particles and 2) those particles have to pass through the filter. If either of these steps is not completed OHMS will report a low measurement reading. This should serve to potentially increase particle measurement variability as not all engine operations generate significant particles. However, even a single high particle emissions measurement requires that the particle filter is not operating as designed. Conversely HDVs with properly working DPFs should never have an elevated particle measurement as the filters are able to trap particles regardless of the driving mode. This can be seen in the low measurement to measurement emissions measurement variability in the large majority of repeat truck measurements in Figures 58 - 61. Analysis in 2013 used a value of 0.21 gPM/kg of fuel or gBC/kg of fuel as a value above which we would consider an emissions violation of the 2007 engines particle certification. At the Port this value is rarely exceeded until after 240 of the 271 repeatedly measured HDV. At Cottonwood it is not generally exceeded until after the 50th of the 69 repeatedly measured HDV. The measurements may stray slightly, but do not show the variability seen with highest emitting vehicles.

Figures 62 and 63 show the reoccurring trucks at the Port of Los Angeles that were measured in both 2013 and 2015 for gPM/kg of fuel and gBC/kg of fuel. Figures 64 and 65 are the same graphs for the reoccurring Cottonwood weigh station fleet. The trucks have been rank ordered by their combined 2013 and 2015 fuel specific emissions mean and then sequentially plotted on the x-axis. At the Port, there were 126 vehicles measured in 2013 and in 2015, and 36 at Cottonwood. High emitting reoccurring HDV show a similar increasing variability with increasing mean emissions pattern as seen with repeat vehicle measurements with the same year. Interestingly, the higher average emitting reoccurring vehicles at the Port generally show an increase in PM and BC

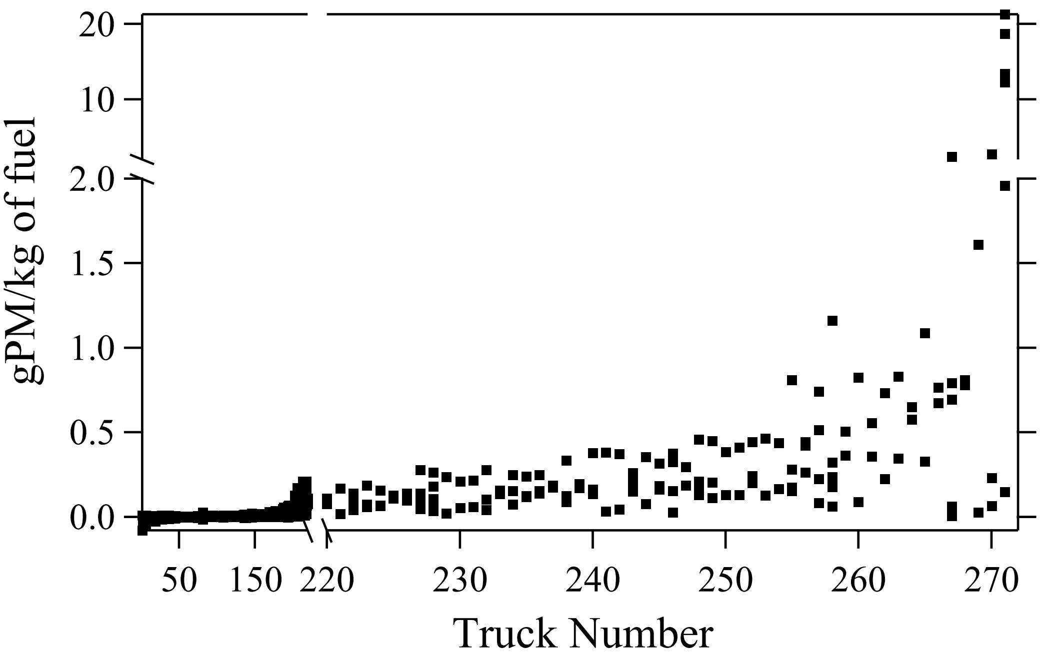

Figure 58. Repeat HDV measurements at the Port of Los Angeles in 2015 for gPM/kg of fuel. Vehicles have been rank ordered by mean gPM/kg of fuel emissions and plotted sequentially on the x-axis. Note that both the x- and y-axis are split.

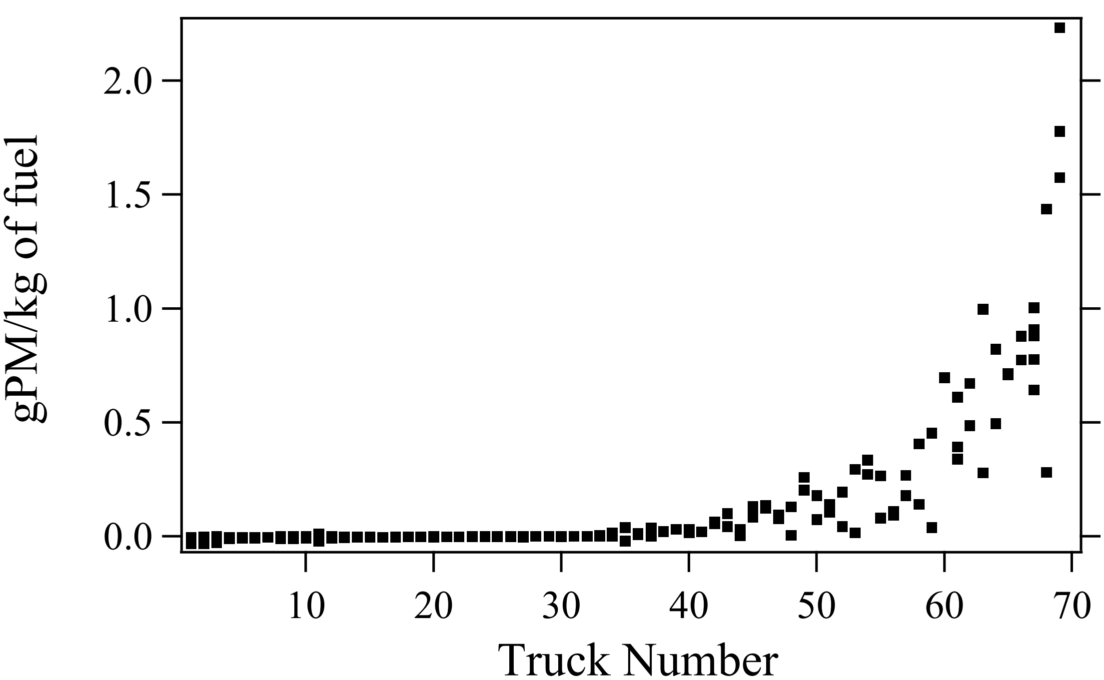

Figure 59. Repeat HDV measurements at the Cottonwood weigh station in 2015 for gPM/kg of fuel. Vehicles have been rank ordered by mean gPM/kg of fuel emissions and plotted sequentially on the x-axis.

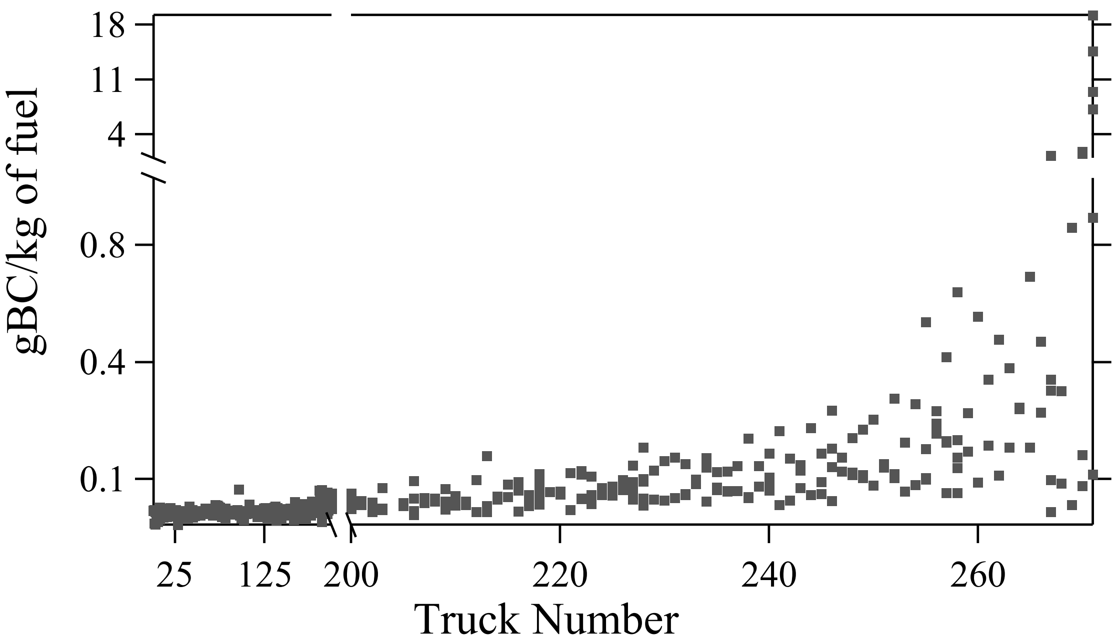

Figure 60. Repeat HDV measurements at the Port of Los Angeles in 2015 for gBC/kg of fuel. Vehicles have been rank ordered by mean gBC/kg of fuel emissions and plotted sequentially on the x-axis. Note that both the x- and y-axis are split.

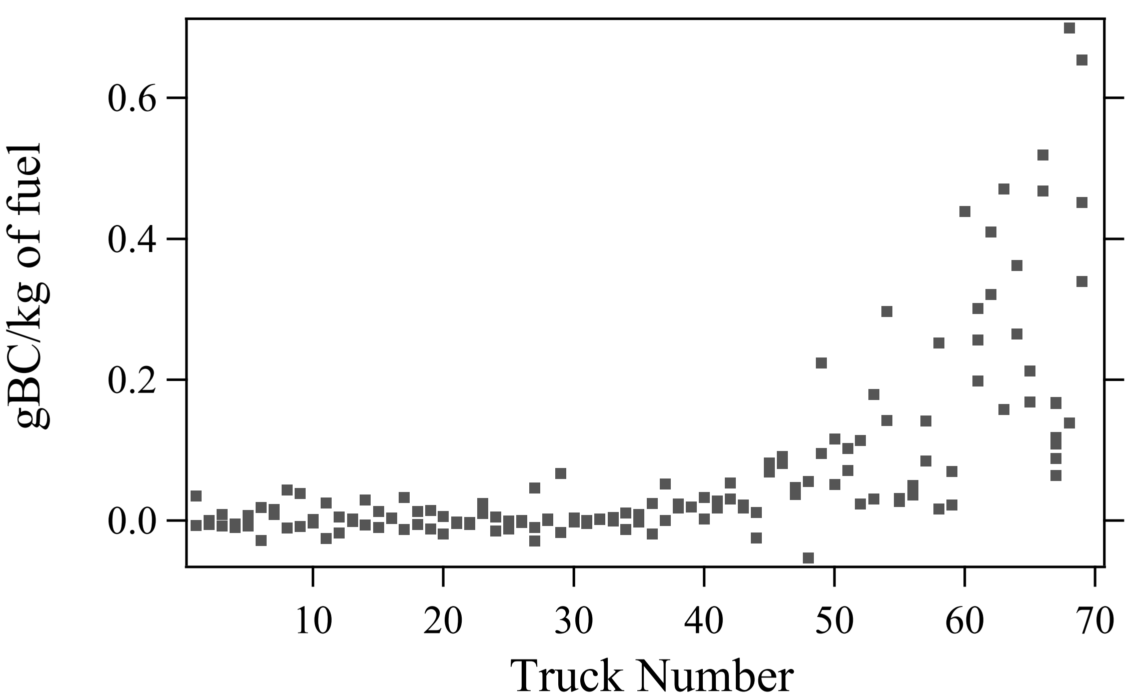

Figure 61. Repeat HDV measurements at the Cottonwood weigh station in 2015 for gBC/kg of fuel. Vehicles have been rank ordered by mean gBC/kg of fuel emissions and plotted sequentially on the x-axis.

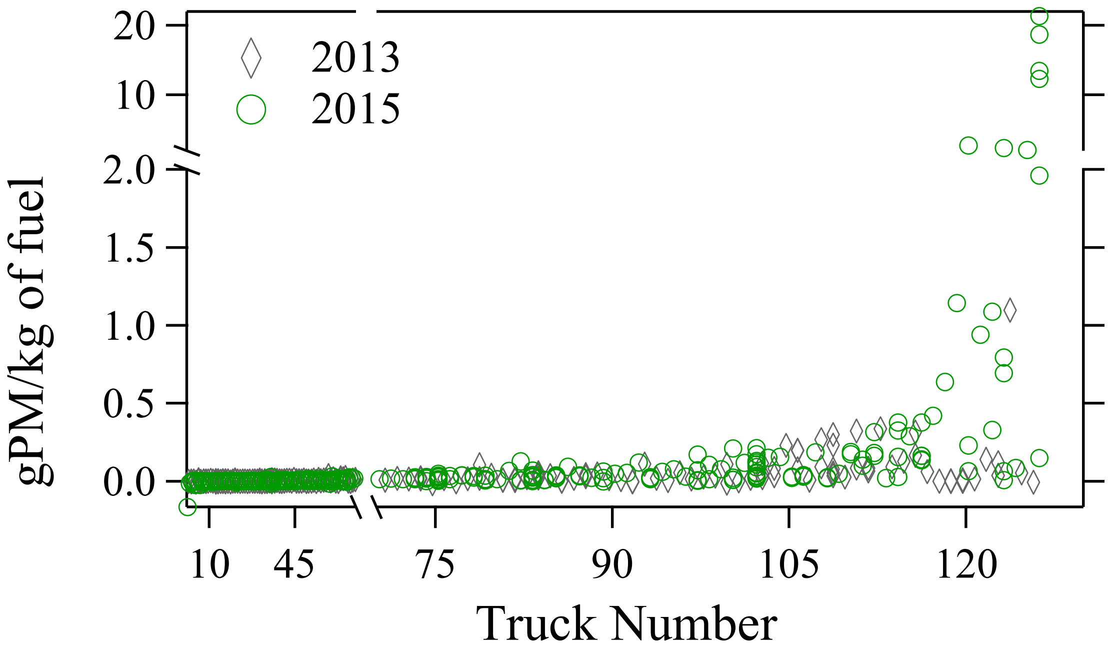

Figure 62. The Port of Los Angeles 127 reoccurring trucks from 2013 (circles) and 2015 (diamonds) for gPM/kg of fuel. Vehicles have been rank ordered by mean gPM/kg of fuel emissions and plotted sequentially on the x-axis. Note that both the x- and y-axis are split.

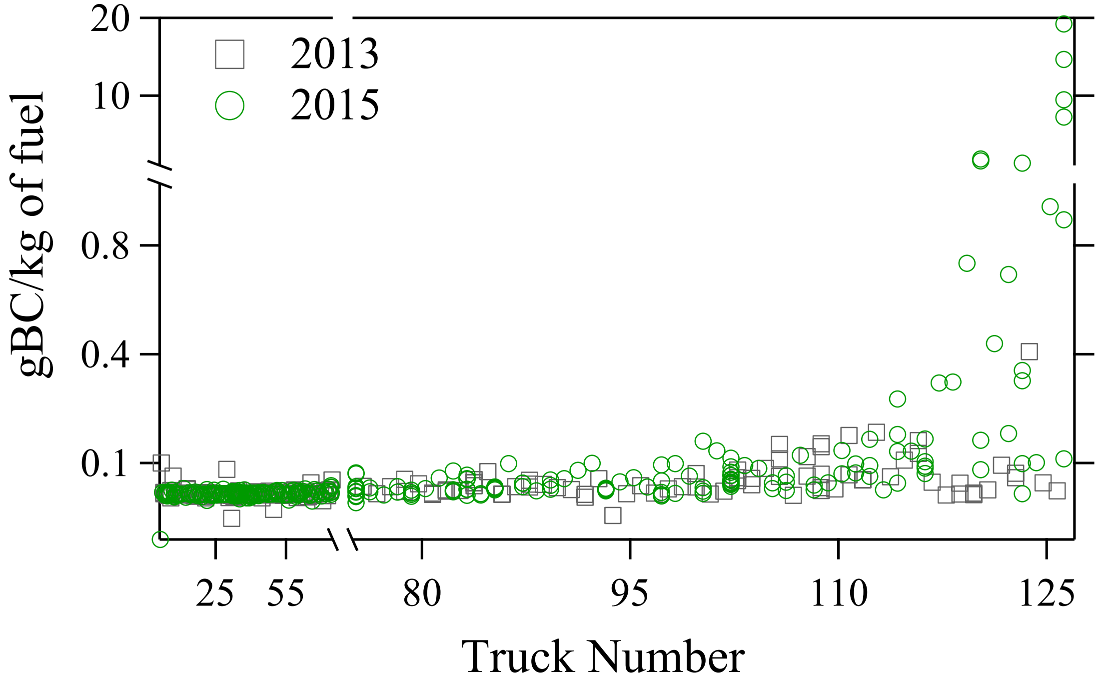

Figure 63. The Port of Los Angeles 127 reoccurring trucks from 2013 (circles) and 2015 (diamonds) for gBC/kg of fuel. Vehicles have been rank ordered by mean gBC/kg of fuel emissions and plotted sequentially on the x-axis. Note that both the x- and y-axis are split.

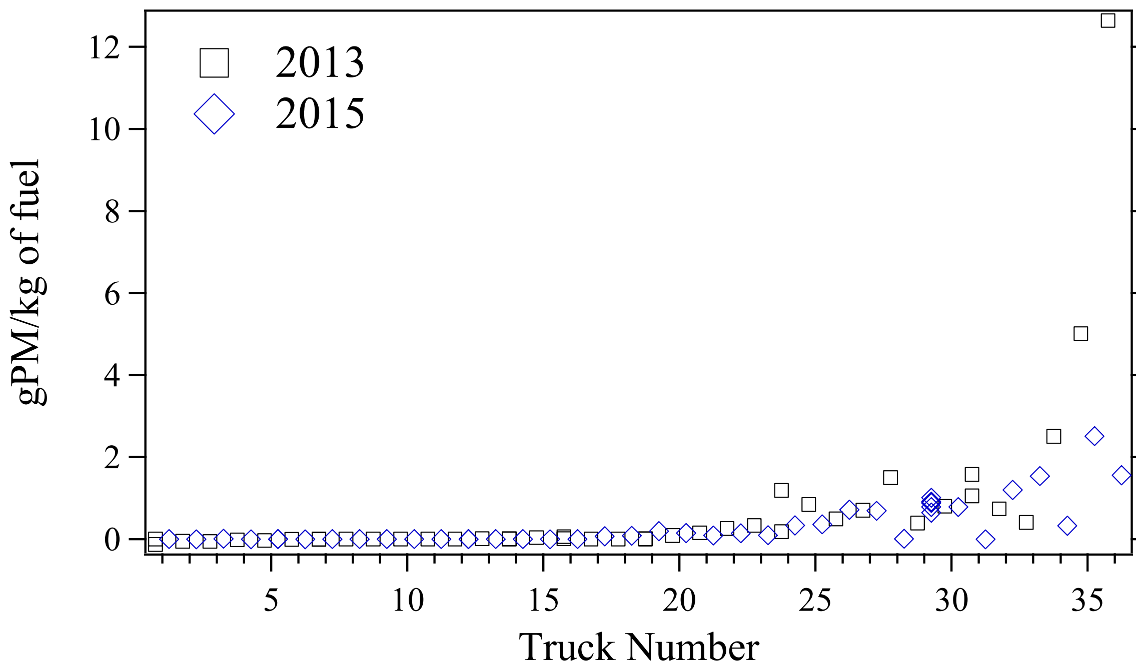

Figure 64. The Cottonwood weigh station 36 reoccurring trucks from 2013 (squares) and 2015 (diamonds) for gPM/kg of fuel. Vehicles have been rank ordered by mean gPM/kg of fuel emissions and plotted sequentially on the x-axis.

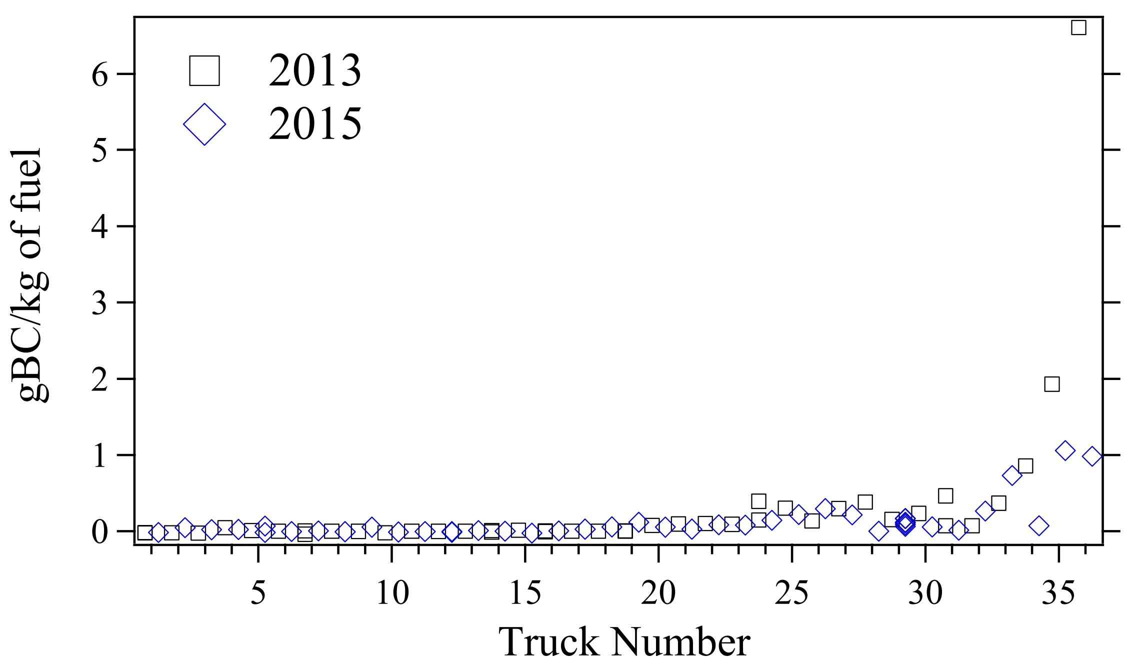

Figure 65. The Cottonwood weigh station 36 reoccurring trucks from 2013 (squares) and 2015 (diamonds) for gBC/kg of fuel. Vehicles have been rank ordered by mean gBC/kg of fuel emissions and plotted sequentially on the x-axis.

in 2015 from their emission readings in 2013. At Cottonwood you will notice that the higher average emitting reoccurring vehicles, largely the pre-2008 trucks that have likely been retrofit with a DPF, have significantly lower emissions in 2015 than they did in 2013.

Finally, the Air Resources Board provided a digital video camera that was used at Cottonwood to locate HDVs whose trailer was equipped with a TRU. These units have a small (usually < 1L) diesel engine that when active will cycle on and off to maintain a preset temperature for the trailer. The University of Denver reviewed the three days of video and indicated the presence of a TRU in a separate field in the 2015 database (see Appendix D). We have no way of knowing if the TRU engine is in use during the OHMS measurements but some of the trailers have green led lights on the driver side of the cab, that if visible, do indicate if the trailer is maintaining the correct temperature. We also indicated in the database if we were able to see a green light on those indicators in the database. Figure 66 shows the gNO_x/kg of fuel emissions by model year for trucks with (182) and without (512) TRUs and for the trucks with a TRU that also had a visible green indicator light (32). Uncertainties plotted are standard errors of the mean determined from the daily means. A single line through a symbol indicates an individual measurement where the uncertainties could not be estimated.

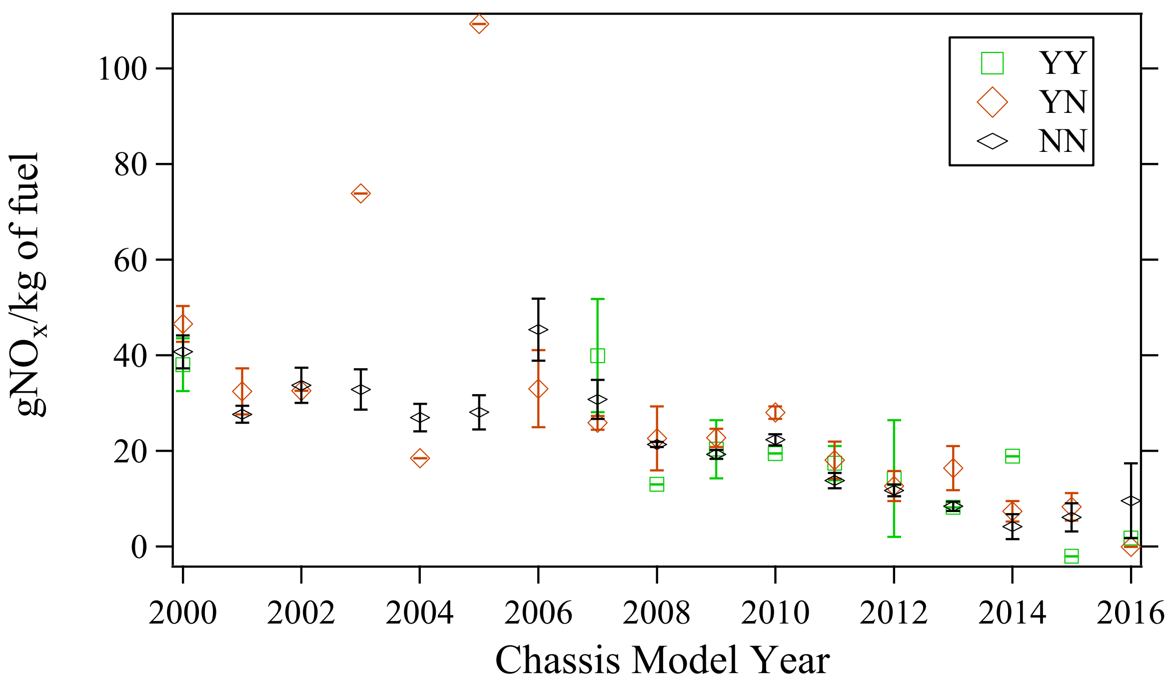

Figure 66. Fuel specific NO_x emissions by chassis model year for Cottonwood weigh station vehicles by TRU status. Vehicles with a TRU (diamonds), without a TRU (flatten diamond) and vehicles with a TRU and a green activation light (squares). Uncertainties plotted are standard errors of the mean using the daily means. A single line through the symbol indicates a single measurement and no estimation of its uncertainty.

The uncertainties increase due to the additional segregation of the data and there are really no clear trends in fuel specific NO_x emissions in Figure 66. If we restrict our comparison to the newest (2010 and newer) and presumably lower emitting vehicles we find that measurements on vehicles with no TRU (209 measurements) averaged 12.9 ± 1.4 gNO_x/kg of fuel. Vehicles with a TRU but without a visible green activity indicator light (83 measurements) averaged 16.8 ± 1.7 gNO_x/kg of fuel. Vehicles with both a TRU and a visible green activity indicator light (16 measurements) averaged 12.8 ± 1.3 gNO_x/kg of fuel. Mean chassis model years for these groupings were nearly identical (2012.1, 2012 and 2012.3) and are not a factor in comparing the means. There is a small statistical increase in NO_x emissions for the vehicles identified as having a trailer with a TRU but for which we can make no determination as to whether the TRU is even in use. For the small number of measurements with both a TRU and an active activity indicator there are no differences between the mean fuel specific NO_x measurements.

2010 and newer vehicles with a TRU and an active TRU do show a small increase in total PM emissions when compared to the vehicles without a TRU. There are 216 measurements for vehicles with no TRU that averaged 0.022 ± 0.008 gPM/kg of fuel. Vehicles with a TRU but without a visible green activity indicator light (84 measurements) averaged 0.073 ± 0.032 gPM/kg of fuel. Vehicles with both a TRU and a visible green activity indicator light (16 measurements) averaged 0.077 ± 034 gNO_x/kg of fuel. The means for both categories with a TRU, though higher than the vehicles without a TRU, are however still at or below the standards for these vehicles.

Comparisons with the Port of Oakland Measurements

In addition to our measurements at the Port of Los Angeles measurements have also been collected in 2011 and 2013 and reported from the Port of Oakland by a University of California Berkley group.[13, 31] The Berkley group collects fuel specific emission measurements from HDV using a snorkel suspended from an overpass as the vehicles pass underneath. We previously discussed the 2011 Oakland BC measurements (see Table 4) as a fleet where DPF technology was just beginning to be introduced. Those mean values where generally consistent with the mean emission levels we observed at the Cottonwood weigh station from the pre-DPF fleet. However, the 2013 Oakland BC and PN measurements included a significant number of DPF equipped trucks and mean gBC/kg of fuel emissions for the 2013 fleet were 0.28 ± 0.05 and PN/kg of fuel were 2.47 x 10^{15} ± 0.48 x 10^{15}. These values are significantly larger than the values measured with the OHMS system at the Port of Los Angeles of 0.020 ± 0.003 and 1.5 x 10^{14} ± 2.5 x 10^{13} for fuel specific BC and PN respectively.

The 2013 Oakland measurements include engine model year enabling a direct comparison with our 2013 Port of Los Angeles measurements with the OHMS system. Figure 67 includes a plot of fuel specific BC (top graph) and PN (bottom graph) versus chassis model year (we add one year to the reported Oakland engine model to convert to chassis model year). The Port of Los Angeles data collected using the OHMS system (squares) is plotted against the left axis while the Port of Oakland data (circles) is plotted against the right axis. Uncertainties for the Port of Los Angeles data are standard errors of the mean calculated using the daily means. If for a moment one ignores the y-scales for the fuel specific BC measurements the trends and emission comparison looks quite similar. However, the y-axis scaling is different by an exact factor of 10 with the OHMS measurements being lower by this factor. A similar comparison is made for PN in the lower graph

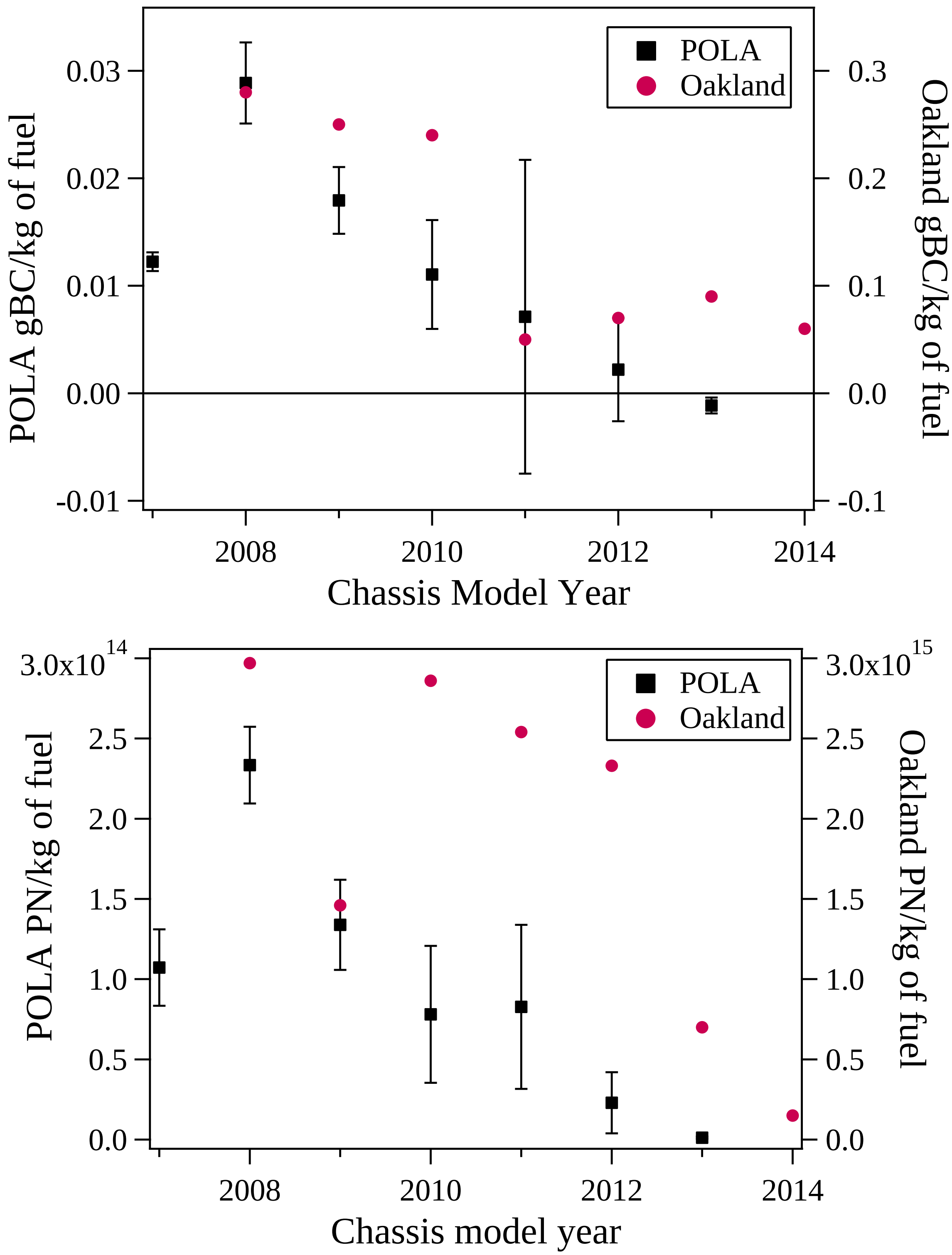

Figure 67. Fuel specific BC (top panel) and PN (bottom panel) emissions by model year collected at the Port of Los Angeles (left axis) in 2015 and data collected at the Port of Oakland (right axis) in 2011 and 2013. Uncertainties for the Port of Los Angeles data are standard errors of the mean calculated from the daily means.

and while the comparison is not as good as it is for BC taking into account all of the myriad of differences between these two studies the comparison is again not too bad.

The differences between the LA and Oakland studies includes BC instruments, photoacoustic versus an aethalometer, integrated emission samples versus a single inlet sample, different fleets, and different operating modes with the Oakland data being collected at higher speeds. However, despite all these differences the fuel specific NO_x emission measurements were much closer with the Port of Los Angeles means of 20.7 ± 0.8 versus 15.4 ± 0.9 for the Oakland measurements. It is possible that particle losses in the OHMS sampling plumbing would lead to underreporting of emissions which would be consistent with the direction of the differences in Figure 67. To evaluate this possibility we performed a series of particle challenges with the OHMS sampling lines setup in the lab. Appendix E details the test conducted investigating whether there are any significant particle losses induced because of the length of the pipe, the presence of the 90° elbow and the use of the in-line fan at the end of the sampling system. The tests consisted of injecting a quantity of soot particles mixed with CO_2 with and without the sampling systems feature being investigated and then comparing the measured ratios. We had no reason to suspect that any of these features would negatively impact the CO_2 measurements and therefore any large changes in the measured ratios would indicate the loss of particles. Through these tests we were unable to find any significant particle losses in our sampling system.

This begs the question as to which measurements are accurate? The Federal particle standard for HDV is 0.01g/bhp-hr which translates to approximately 0.07 gPM/kg of fuel using the previously discussed average fuel consumption rate of 0.15 kg of fuel/bhp-hr. In 2013 measurements for 2008 and newer chassis model years approximately 12% of the measurements at the Port of Los Angeles and 16% of the Cottonwood weigh station measurements exceed the Federal standard. Indicating that based on the OHMS measurements a large majority of the HDVs have particle emissions within the certification limits which is consistent with other values reported in the literature (see Table 4).[28, 32, 33] We do not know the true reason for the observed differences in the two data sets but believe that it is likely not happen stance that the values appear to be off by almost exactly an order of magnitude suggesting a possible calculation error as the source for the difference.

Results and Discussion for 2017 Measurements

The 2017 campaign continued the study of fleets from the Port of Los Angeles, CA and Cottonwood weigh station in northern California. The OHMS setup duplicated the 2015 setup with one major exception. At the Port of Los Angeles there had been a permanent speed bump added across all of the exit lanes that was located at the very end of the OHMS sampling setup (see Figure 68). This unavoidable change to the location caused a significant change in the observed driving pattern with vehicles decelerating at the tent exit when reaching the speed bump, diminishing the volume of exhaust emitted from the vehicles. This was particularly problematic for HDVs that were leaving the port with empty containers and or only trailers as many did not meet the minimum required threshold of CO_2 for a valid measurement, which is a 75 ppm rise in CO_2 above

Figure 68. Photograph at the Port of Los Angeles of the OHMS setup in 2017 used to detect exhaust emissions from heavy-duty diesel trucks. The perforated exhaust sampling and integration tube is again visible on the left side of the tent and the new speed bump is located at the nearest end of the tent.

background levels. This resulted in fewer HDVs measured at the Port of Los Angeles location in 2017 than in previous years.

Sampling took place at the Port of Los Angeles between Monday, April 3 and Friday, April 7. The measurements were made from approximately 8:00 to 17:00, with 795 total successful measurements made during the week. The number of successful measurements were down in 2017 from previous campaigns due to a number of factors. In addition to the instillation of a speed bump previously mentioned, the additional automated exit gate that was install in 2015 was in full use in 2017. This often allowed HDV drivers the choice of going through the OHMS tent, or going out of the exit adjacent to the tent. Depending on the congestion and the officers working, the latter option was used frequently. Additional downstream measurements and snap idle testing by the Air Resources Board further complicated the exit process leading to traffic slow-downs (lower HDV CO_2 emissions) and the presence of the California Highway Patrol on the OHMS exit lane the first day increased the number of trucks bypassing the OHMS exit lane for the remainder of the week and further lowered our measurement opportunities.

Sampling was conducted at the Cottonwood weigh station on I-5 near Redding CA from Monday, April 10th to Friday, April 14th. During the five days of work we collected emission measurements on a total of 1085 HDV. At Cottonwood weigh station, the setup from previous years was recreated, and was ongoing with CARB's remote sensing and opacity testing. CARB again placed their sensors downstream of OHMS, but eliminated their bottom strip from their data collection system eliminating the slowdowns experienced at the Port.

The licenses for both locations were read for the HDV with CO_2 emissions levels that exceeded our minimum plume criteria. The OHMS validity criterion are detailed in Appendix C. Readable license plates were matched against registration records for California, Illinois, Oklahoma, Oregon, Texas, Washington and the British of Columbia. Readable plates from additional states were looked up using an online reverse lookup database and retrieved vehicle information which matched the video image make were included in the database. Vehicles with valid CO_2 emissions and a matched license plate have their emissions measurements graphically reviewed one final time to exclude any measurements that indicate the presence of more than one vehicle. If the presence of a second vehicle plume is found the vehicle is eliminated from the final data set.

Tables 10 and 11 give the distribution of plates successfully read and matched at the Port of Los Angeles and the Cottonwood weigh station. Measurements with visible license plates are denoted as "readable plates," and of those readable plates, the unique plates represent individual plates that were seen at that location. "Unique matched plates" are license plates that were successfully matched to vehicle identification information such as make, model year, etc. The "total measurements" column displays the number of measurements from each state that are represented in the final database for each location with vehicle information. Plates counted "Out of State" had state origins that could not be identified. California, as expected, has the most number of plates that comprise each location's database.

Table 10. Distribution of Identifiable Plates at the Port of Los Angeles.

State	Readable Plates	Unique Plates	Unique Matched Plates	Total Measurements
California	774	608	607	773
Illinois	1	1	1	1
Indiana	14	13	13	14
Kansas	1	1	1	1
Ohio	5	5	5	5
Texas	1	1	1	1
Washington	1	1	0	0
Totals	797	630	628	795

The number of times vehicles were measured by location is shown in Table 12. Although 2017 had a lower number of unique measurements, there was a higher percentage of HDVs that were measured more than once compared to the other campaign years. Repeat vehicle emissions will be discussed later.

Table 11. Distribution of Identifiable License Plates at the Cottonwood Weigh Station.

State / Country	Readable Plates	Unique Plates	Unique Matched Plates	Total Measurements
Arizona	7	7	7	7
British Columbia	67	66	61	62
California	644	557	550	599
Florida	4	4	0	0
Georgia	4	4	2	2
Iowa	2	2	0	0
Idaho	8	7	6	7
Illinois	17	16	16	17
Indiana	86	80	73	79
Louisiana	1	1	0	0
Michigan	2	2	2	2
Minnesota	9	7	5	7
Mississippi	1	1	0	0
Missouri	4	4	0	0
Montana	1	1	0	0
Nebraska	3	3	3	3
Nevada	4	3	0	0
New Hampshire	2	2	2	2
North Carolina	2	2	2	2
Ohio	7	6	5	6
Oklahoma	10	10	7	7
Oregon	154	143	140	151
Pennsylvania	2	2	1	1
Tennessee	5	4	1	1
Texas	3	3	3	3
Utah	3	3	0	0
Virginia	1	1	0	0
Washington	94	92	82	84
Wisconsin	1	1	1	1
Canada	3	3	0	0
Out of State	2	2	0	0
Totals	1153	1039	969	1043

Table 13 shows the 2017 data summary for both the Port of Los Angeles and Cottonwood weigh station with mean CO, HC, NO, NO_2, NO_x, PM, BC and PN as a ratio over CO_2 and as fuel specific values as grams of pollutant per kg of fuel burned. Fuel specific medians for these pollutants are also shown. Average model year, exhaust pipe temperature, entrance and exit speed, entrance and

Table 12. Number of Repeat Measurements by Site and Year.

Times Measured	Port of Los Angeles			Cottonwood		
	2013 Number (%)	2015 Number (%)	2017 Number (%)	2013 Number (%)	2015 Number (%)	2017 Number (%)
1	711 (78%)	654 (70.7%)	511 (64.3%)	1578 (92.3%)	557 (88.8%)	912 (87.4%)
2	134 (14.7%)	149 (16.1%)	82 (20.6%)	110 (6.4%)	64 (10.2%)	48 (9.2%)
3	43 (4.7%)	58 (6.3%)	23 (8.7%)	16 (1.0%)	3 (0.5%)	6 (1.7%)
4	14 (1.5%)	27 (2.9%)	9 (4.5%)	5 (0.3%)	0	0
5	7 (0.8%)	19 (2.1%)	3 (1.9%)	0	0	1 (0.5%)
6	2 (0.2%)	11 (1.2%)	0	0	3 (0.5%)	2 (1.2%)
7	0	3 (0.3%)	0	0	0	0
8	1 (0.1%)	1 (0.1%)	0	0	0	0
9	0	0	0	0	0	0
10	0	2 (0.2%)	0	0	0	0
11	0	0	0	0	0	0
12	0	1 (0.1%)	0	0	0	0

exit acceleration, and roadway slope at each location are also included. The uncertainties are standard errors of the mean calculated using the daily averages.

The fleet at the Port of Los Angeles had an average model year of 2009.8, which is only half a year newer than it was in 2015 and 0.7 years newer than in 2013 indicating that the age of the Port fleet has been steadily increasing (+3.3 years older) since 2013. This fleet is characterized by slow turnover, as might be expected since most of these trucks were purchased in 2008 – 2010 and HDV generally have long useful lives. One can probably expect this fleet to continue to change little until the Truck and Bus rule requirement that all trucks have 2010 compliant engines by the end of 2022. Contrary to the fleet at the Port of Los Angeles, the Cottonwood fleet has experienced significant turnover with a 2017 mean model year of 2011.3 (1.8 years newer than the 2015 fleet and 5.7 years newer than the 2013 fleet). 2011 and newer vehicles make up 59% of the 2017 measurements, an increase of 70% from the 2013 measurements.

As previously mentioned the new speed bump at the Port lowered both the speed (4.5 mph vs 7.8 mph) and caused a negative acceleration at the exit which undoubtedly lowered CO_2 plumes levels and increased the number of vehicles that we were unable to measure. The uncertainties on the BC measurements at the port are significantly larger for the 2017 data than previous measurements. The first day of data collection at the Port included very noisy black carbon measurements due to a shared inlet for both the black carbon instrument and the fast mobility particle sizer. This was a plumbing arrangement that was successfully used in 2015, however, this time it resulted in excessive noise and the solution was to use separate inlets. The problem was addressed the morning of the second day of collection and was used for the remainder of the campaign. This issue only

Table 13. OHMS 2017 Data Summary and Comparison.

Study Site	Port of Los Angeles	Cottonwood Weigh Station
Mean CO/CO_2 (g/kg of fuel ± SEM)	0.0010 (1.74 ± 0.3)	0.0014 (2.8 ± 0.4)
Median gCO/kg	0.61	0.35
Mean HC/CO_2 (g/kg of fuel ± SEM)	0.00013 (0.41 ± 0.08)	0.0001 (0.28 ± 0.04)
Median gHC/kg	0.22	0.11
Mean NO/CO_2 (g/kg of fuel ± SEM)[a]	0.0068 (14.6 ± 0.2)	0.004 (9.6 ± 0.7)
Median gNO/kg[a]	12.7	6.6
Mean NO_x/CO_2 (g/kg of fuel ± SEM)[b]	0.0084 (27.6 ± 0.4)	0.0057 (18.6 ± 1.2)
Median gNO_x/kg[b]	25.3	12.3
Mean NO_2/CO_2 (g/kg of fuel ± SEM)	0.0011 (3.7 ± 0.3)	0.001 (2.94 ± 0.1)
Median gNO_2/kg	2.3	1.7
Mean Mass NO_2/NO_x	0.14	0.16
Mean gPM/kg ± SEM	0.04 ± 0.01	0.09 ± 0.005
Median gPM/kg	0.0003	0.0003
Mean gBC/kg ± SEM	0.03 ± 0.01	0.06 ± 0.003
Median gBC/kg	0.007	0.004
Mean PN/kg ± SEM	$2.2 \times 10^{14} \pm 2.6 \times 10^{13}$	$7.7 \times 10^{14} \pm 9.5 \times 10^{13}$
Median PN/kg	9.7×10^{12}	3.2×10^{12}
Mean Model Year	2009.8	2011.3
Mean IR Estimated Exhaust Temperature (°C) ± SEM	86 ± 3	108 ± 3
Mean Entrance Speed (mph)	5.3	7.0
Mean Exit Speed (mph)	4.5	7.4
Mean Entrance Accel (mph/s)	0.19	0.14
Mean Exit Accel (mph/s)	-0.42	0.10
Mean VSP (kw/tonne)[c]	0.6 / 0.1	0.8 / 0.9
Slope (degrees)	0°	(-0.5)°

[a]grams of NO
[b]grams of NO_2
[c]calculated using equation from Jimenez et al., 1999.

served to increase the uncertainties of the measurements and did not affect the fleet, model year, or daily averages.

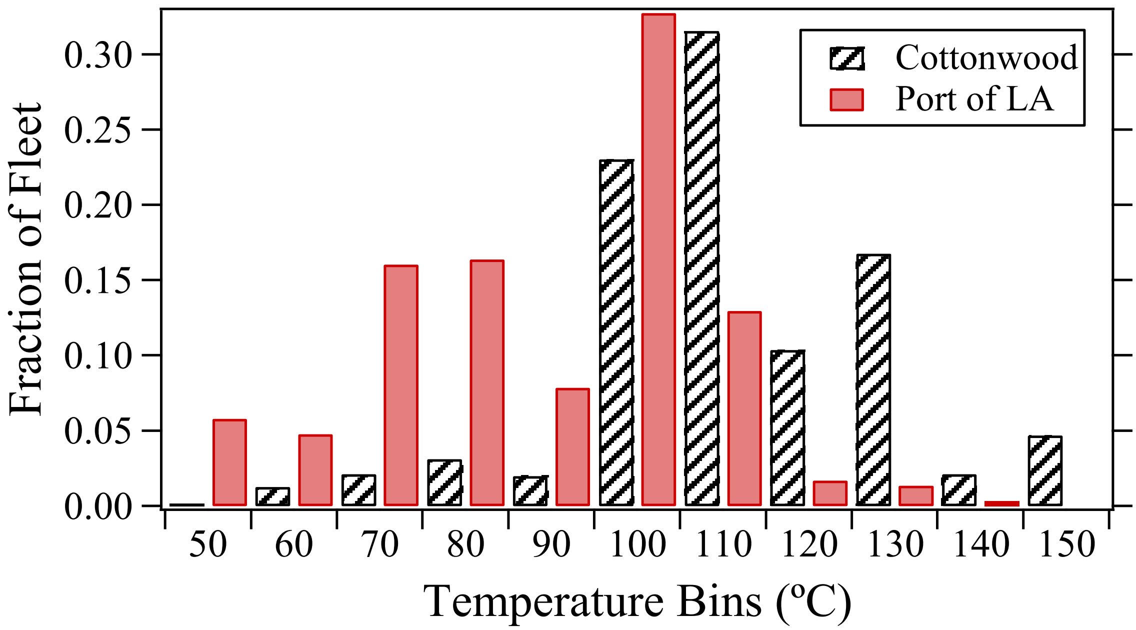

Figure 69. Cottonwood (black diagonal) and the Port of Los Angeles (red solid) estimated infrared exhaust pipe temperature by fleet fraction for readable IR images of elevated exhaust pipes.

IR estimated exhaust pipe temperatures for elevated exhaust systems, estimated from an infrared camera, are shown by location in Figure 69. The fleet fraction is calculated from the number of HDVs that have readable IR images for each bin divided by the total number of readable IR images by location. 36.9% of the fleet at the Port of Los Angeles and 67.3% at Cottonwood had readable exhaust pipe IR images. As seen in previous years the Port of Los Angeles HDVs have lower exhaust pipe temperatures, mode of 100°C, than the HDVs at Cottonwood, mode of 110°C. The majority of the observed fleet at the Port of Los Angeles is below the mode of 100°C (65.5%) while the majority of the fleet at Cottonwood is above the mode of 110°C (65.6%).

Figure 70 and Figure 71 compare the fleet fraction of IR estimated exhuast pipe temperatures from valid IR images at the Port and Cottonwood respectively for all three measurement campaigns. Vehicles at the Port have an increased estimated exhuast pipe mode in 2015 from 2013, but maintain that mode temperature in 2017. This suggests that the more automated exit at the Port decreased wait times and positively affected HDV operating temperatures. At Cottonwood, the mode temperature increased in all three measurement years as well as the number of vehicles at higher temperatures when compared to the Port of Los Angeles vehicles.

Figure 72 compares the fuel specific fleet averages for measurement years 2013 (grey-left bars), 2015 (green-middle bars) and 2017 (red-right bars) at both locations for all of the gaseous emissions. Uncertainties are standard errors of the mean calculated from the daily means. CO (solid) and HC (diagonal) are traditionally low in diesel vehicles and while there is some variability from year to year both species are low in these measurements. One source of increased variability

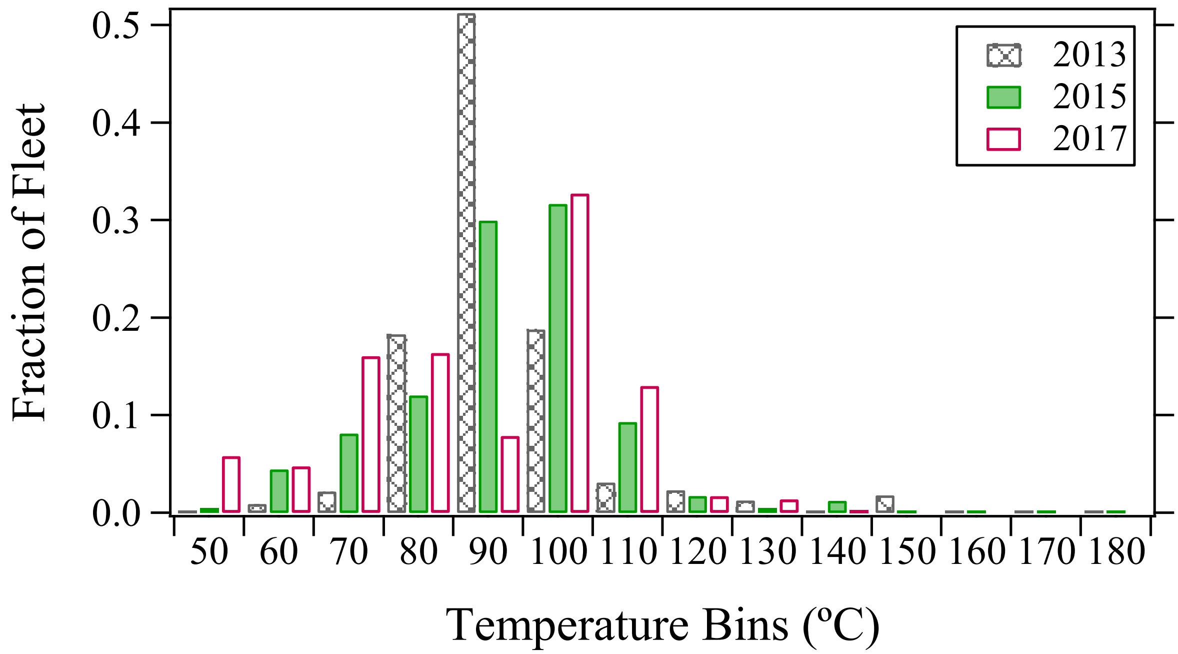

Figure 70. Estimated infrared exhaust pipe temperature distribution comparison at the Port of Los Angeles for 2013 (hatched), 2015 (solid) and 2017 (open).

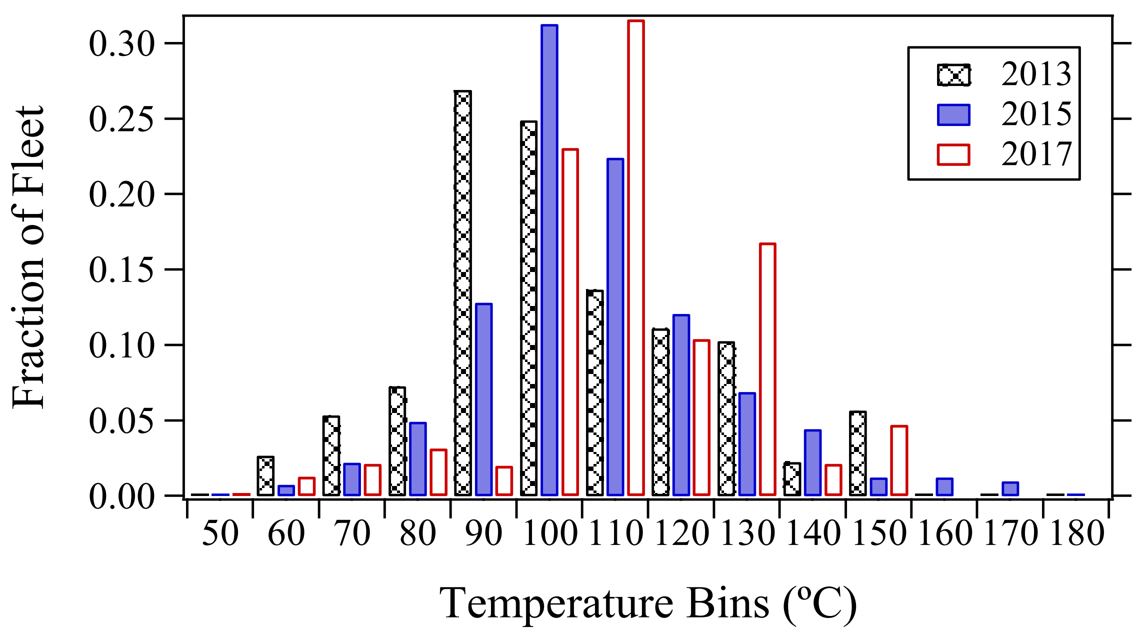

Figure 71. Estimated infrared exhaust pipe temperature distribution comparison at Cottonwood weigh station for 2013 (hatched), 2015 (solid) and 2017 (open).

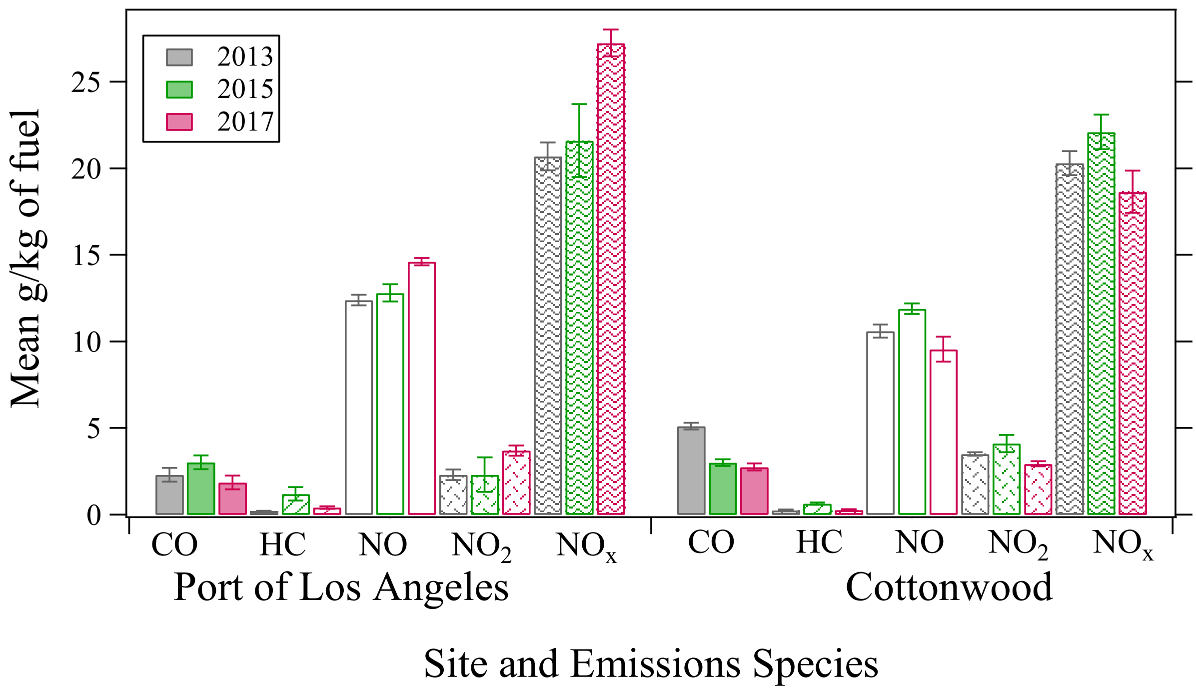

Figure 72. Mean fuel specific emissions for gaseous species, CO (solid), HC (diagonal), NO (open), NO_2 (hatched) and NO_x (wavy) at the Port of Los Angeles and Cottonwood Weigh Station for 2013 (grey-left bar), 2015 (green-middle bar) and 2017 (red-right bar) HDV fleets. Uncertainties are standard errors of the mean calculated from the daily means.

at the Port are changes in the fraction of natural gas powered trucks as they generally have considerably higher CO and HC emissions when compared with the diesel vehicles and 2015 had the highest fraction (4.3%). The oxides of nitrogen emissions have generally been found to be higher at the Port and the comparison with Cottonwood shows a similar trend.[10, 11] Low exhaust temperatures at the Port are likely a contributing factor as they make it more difficult for SCR systems to perform well but at the Port we do not have a large number of SCR equipped vehicles (only 15% of the HDV are 2011 or newer). The increases in the Port NO_x emissions may be a result of a sampling bias introduced by the speed bump. The presence of the bump made it unmistakable as to whether the container being moved was full or empty and it was our unscientific impression that our measurement success rate was lower on empties which could mean that our sample is skewed toward vehicles under higher loads which we would expect to increase NO_x emissions. NO_x emissions at Cottonwood have been inconsistent with a slight increase in 2015 followed with a decrease in the latest measurements. The most recent decreases follow a newer fleet but 2015 also saw a newer fleet compared to 2013. As we will discuss in more detail later we do know that overall SCR performance is better at Cottonwood and that has to be one factor contributing to the NO_x decreases in 2017.

A comparison of fleet average particle emissions trends are shown in Figure 73 for both locations and all three measurement campaigns, 2013 (grey), 2015 (green) and 2017 (red). Uncertainties are standard errors of the mean calculated from the daily means. The particle emissions story at the

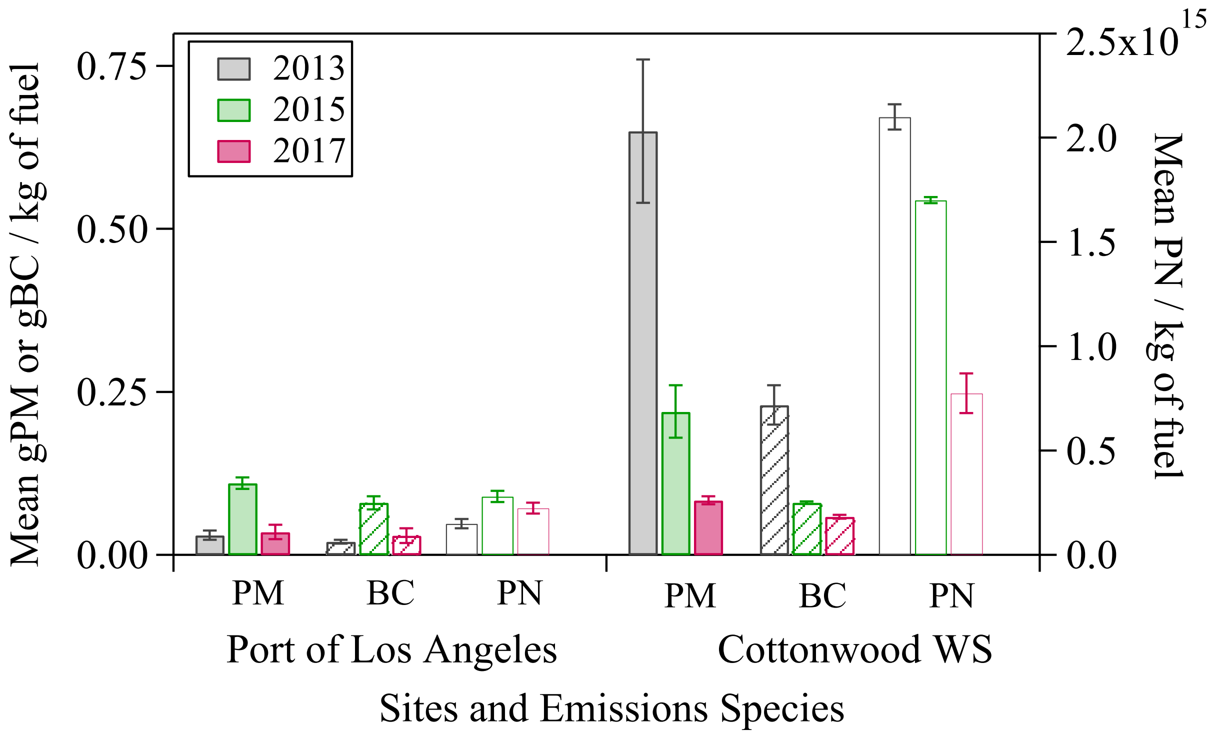

Figure 73. Fuel specific mean emissions for PM (solid), BC (diagonal) and PN (open) at the Port of Los Angeles and Cottonwood Weigh Station for 2013 (grey-left bar), 2015 (green-middle bar), 2017 (red-right bar) HDV fleets. Uncertainties are standard errors of the mean calculated from the daily means.

Port is one of increases followed by recovery. Overall fuel specific PM (solid) and BC (diagonal) from the 2017 Port of Los Angeles fleet decreased from 2015 by 68% and 61% respectively returning to near 2013 levels. Fuel specific PN emissions were down 21%. At Cottonwood the trends have been consistently decreasing with fuel specific PM emissions decreasing 63%, BC emissions falling 27% and PN emissions dropping 57% from the 2015 measurements. These emission levels are approaching those observed in 2013 at the Port which would signify a completely DPF equipped fleet. Since 2013 we have observed decreases of 87%, 76% and 64% for fuel specific PM, BC and PN emissions.

Figures 74 and 75 show the fuel specific CO emission by model year for the Port of Los Angeles (See Figure 74) and the Cottonwood weigh station (see Figure 75) for 2013 (circles), 2015 (diamonds) and 2017 (squares). The uncertainties shown, when applicable, for these and the following figures are standard errors of the mean calculated from daily means. Figure 74 shows that gCO/kg of fuel by model year at the Port of Los Angeles has changed little for the three measurement years and is at very low levels. The one exception is for the 2012 model year in the 2015 data set where a significant fraction of natural gas powered trucks skew the mean. However, at Cottonwood, shown in Figure 75, CO emission levels remain very low and relatively unchanged for model years 2008 and newer, or model years that have been manufactured with DPFs. Vehicles older than the 2008 model year show consistent increases from the 2013 and 2015 levels. The

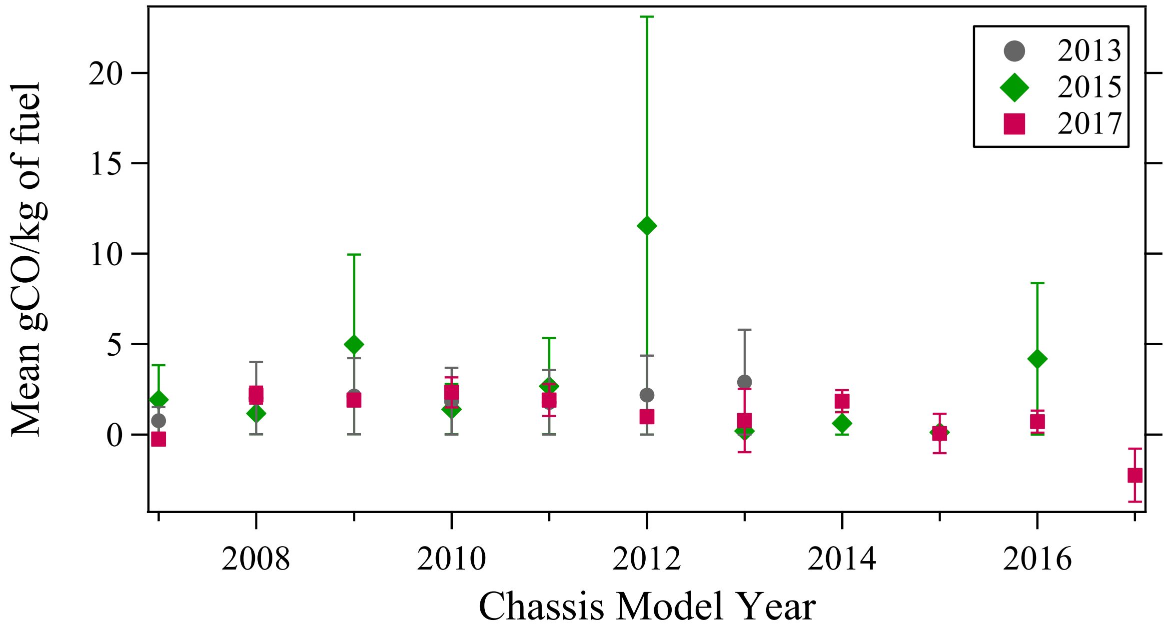

Figure 74. Mean gCO/kg of fuel emissions by model year at the Port of Los Angeles for measurement years 2013 (circles), 2015 (diamonds) and 2017 (squares). Uncertainties are standard errors of the mean calculated from the daily means.

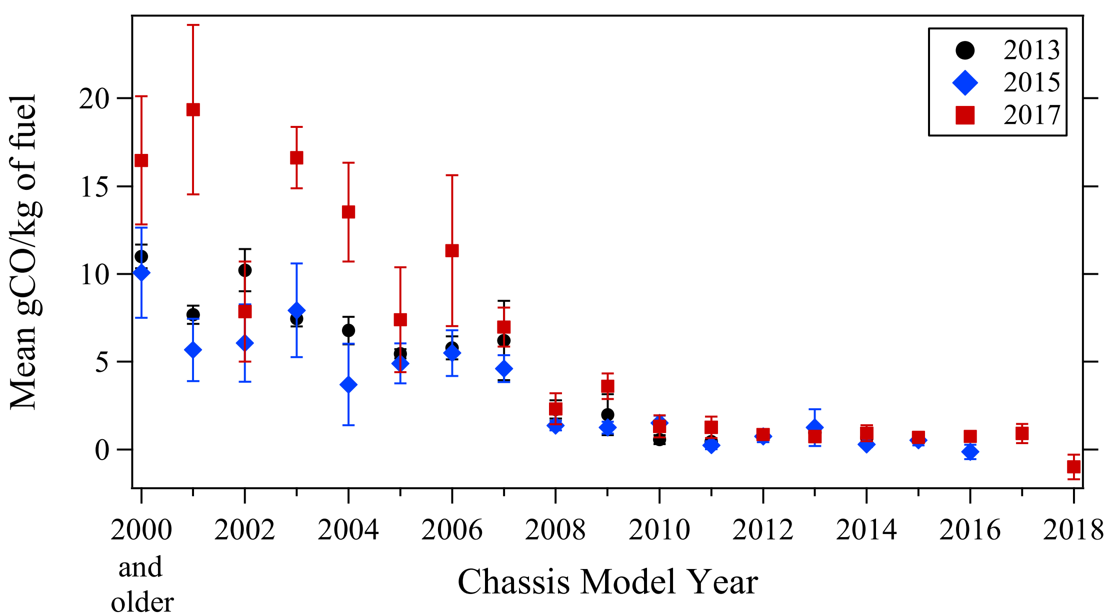

Figure 75. Mean gCO/kg of fuel emissions by model year at Cottonwood weigh station for measurement years 2013 (circles), 2015 (diamonds) and 2017 (squares). Uncertainties are standard errors of the mean calculated from the daily means.

uncertainties are large for this group as there representation in the Cottonwood fleet has fallen from 61% of the measurements in 2013 to only 12.6% of the 2017 measurements.

Fuel specific HC emissions by model year are shown in Figure 76 and 77 for the Port of Los Angeles and Cottonwood fleet respectively. HC emissions are generally very low for diesels and aside from model year 2012 in 2015, which contains a third of the natural gas vehicles measured (44% of this model year's measurements with a mean of 10.1 gHC/kg of fuel) at the Port of Los Angeles in 2015, HC has remained low and unchanged in all measurement years. At Cottonwood, HC emissions in 2017 have followed the CO emissions trend with slight increases in the older trucks between the 2015 and 2017. However, as with CO there is significant variability associated with HC measurements due to a low number measurements for these model years.

Total NO_x ($NO + NO_2$) is displayed in Figure 78 and 79 for the Port and Cottonwood fleets by model year for 2013 (solid-left bar), 2015 (diagonal-middle bar) and 2017 (hatched-right bar) data sets with the uncertainties as the standard error of the daily means. The open bars for each measurement and model year represent the amount of NO_2 and the filled portion represent the amount of NO reported as NO_2 equivalents so the total height of each bar is equal to the total gNO_x/kg of fuel measured. At the Port there is no discernable emissions trend with model year as would be expected with models newer than 2010. As discussed previously the majority of vehicles at the Port are 2010 and older chassis model years due to the forced early retirement program. Newer HDV model year vehicles are trickling into the fleet, as 2012 and newer HDV comprised 6.9% of the 2015 measurements and now make up 15.1% of the 2017 measurements. However, operating temperatures of these vehicles are low as shown in Figure 69 which works against a fully functioning SCR system. However, the mean gNO_x/kg of fuel for the Port fleet of 27.6 ± 0.4 is still approximately 40% less than the pre-control fleet measured by remote sensing in 2008 (45.4 ± 1.2).[10] Though some deterioration in fuel specific NO_x emissions has resulted since the 2012 remote sensing measurements of 20.6 ± 0.6 gNO_x/kg of fuel, which were nearly identical to the OHMS 2013 mean of 20.7 ± 0.8 measured at the original Trapac exit.[11]

Cottonwood's fuel specific nitric oxide emissions (see Figure 79) for all three data campaigns are plotted in a similar manner as the Port data with the combination of NO_2 (open portion) and NO as NO_2 (filled portion) equaling the total gNO_x/kg of fuel by model year. Uncertainties are standard errors of the mean calculated from the daily means. Unlike the Port data there is a steady decline in total NO_x emissions for the newer model years, indicating better SCR performance for the trucks with them installed.

Figure 80 compares the 2017 data for our two sites with the Port of Los Angeles' gNO_x/kg of fuel emissions (grey-left bars) to Cottonwood's (red-right bars) by model year for the 2008 and newer chassis model year vehicles. The total heights of the bars are total NO_x separated by oxide species, NO_2 (open portion) and NO as NO_2 equivalent (filled portion). With the data plotted side by side the lack of an emissions trend by model year at the Port is more obvious. We showed earlier that vehicles at the Port have colder on average elevated exhaust pipes than at Cottonwood (see Figure 69) and we suspect this is one factor that limits the performance of the SCR systems at the Port.

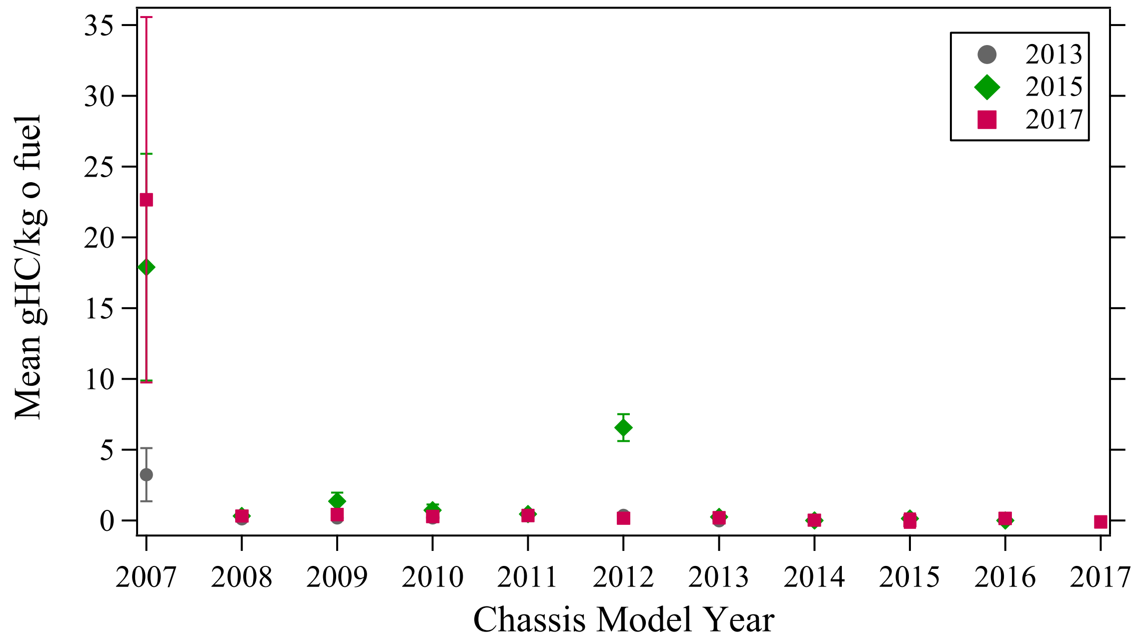

Figure 76. Mean gHC/kg of fuel emissions by model year at the Port of Los Angeles for uncertainties measurement years 2013 (circles), 2015 (diamonds) and 2017 (squares). Uncertainties are standard errors of the mean calculated from the daily means.

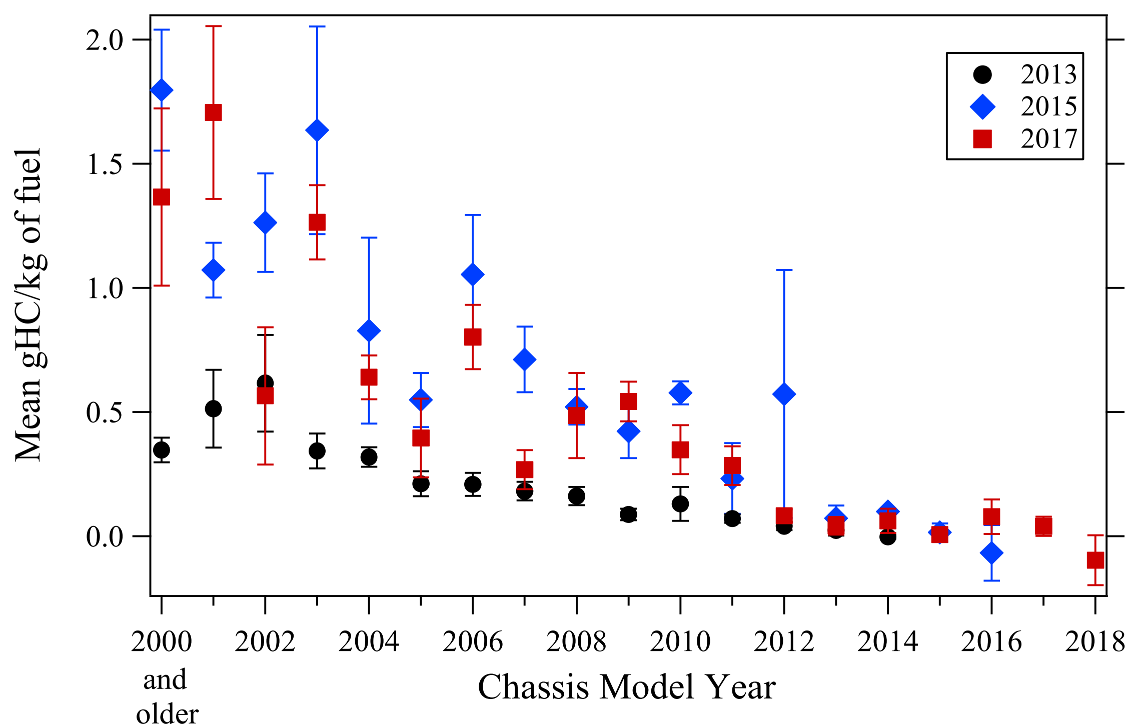

Figure 77. Mean gHC/kg of fuel emissions by model year at Cottonwood weigh station for measurement years 2013 (circles), 2015 (diamonds) and 2017 (squares). Uncertainties are standard errors of the mean calculated from the daily means.

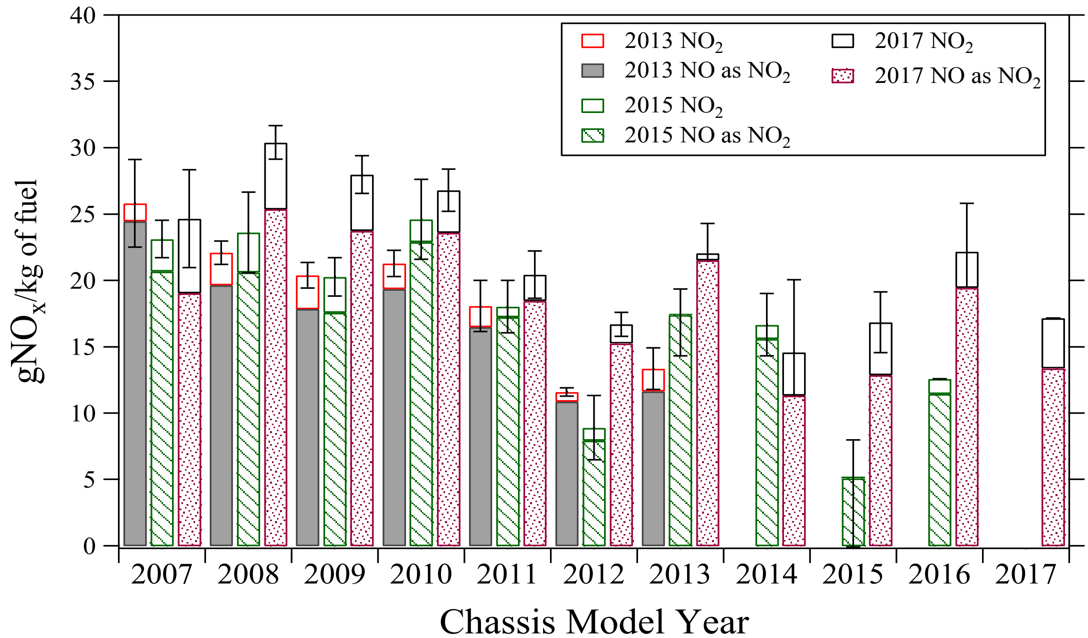

Figure 78. Fuel specific nitric oxides by model year at the Port of Los Angeles for measurement years 2013 (left bars), 2015 (middle bars) and 2017 (right bars). Open portion represent gNO_2/kg of fuel, filled portion represent the amount of NO expressed as NO_2, and the height of each bar represents the total gNO_x/kg of fuel for the given model year. Uncertainties are standard errors of the mean determined from daily means of total NO_x.

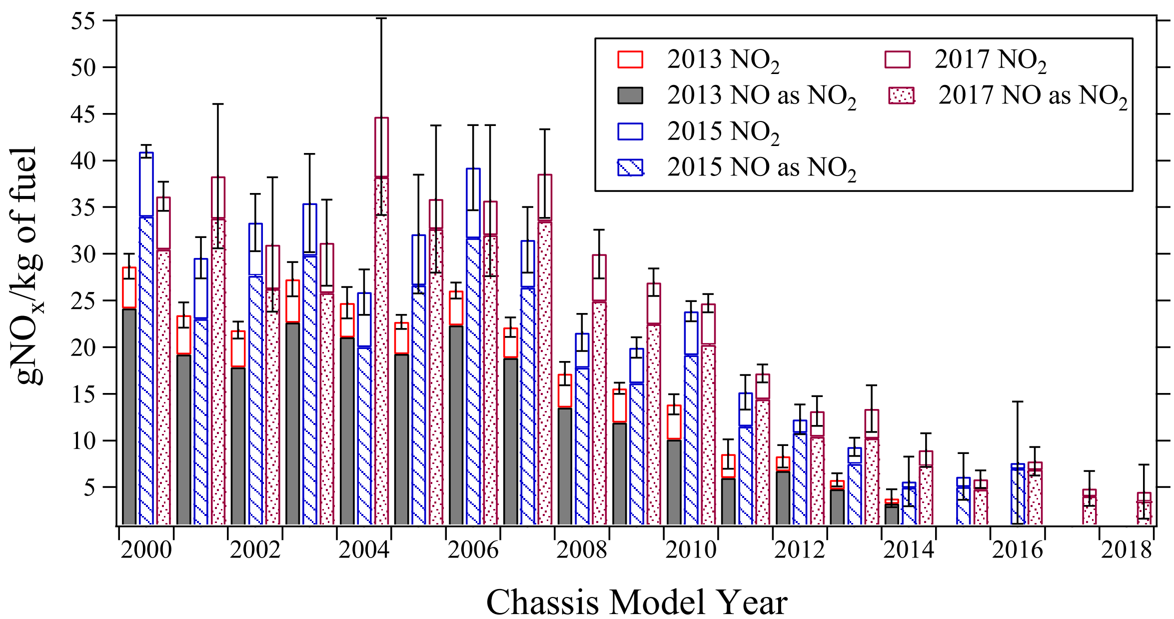

Figure 79. Fuel specific nitric oxides by model year at Cottonwood weigh station for measurement years 2013 (left bars), 2015 (middle bars) and 2017 (right bars). Open portion represent gNO_2/kg of fuel, filled portion represent the amount of NO expressed as NO_2, and the height of each bar represents total gNO_x/kg of fuel for the given model year. Uncertainties are standard errors of the mean determined from the daily means of total NO_x.

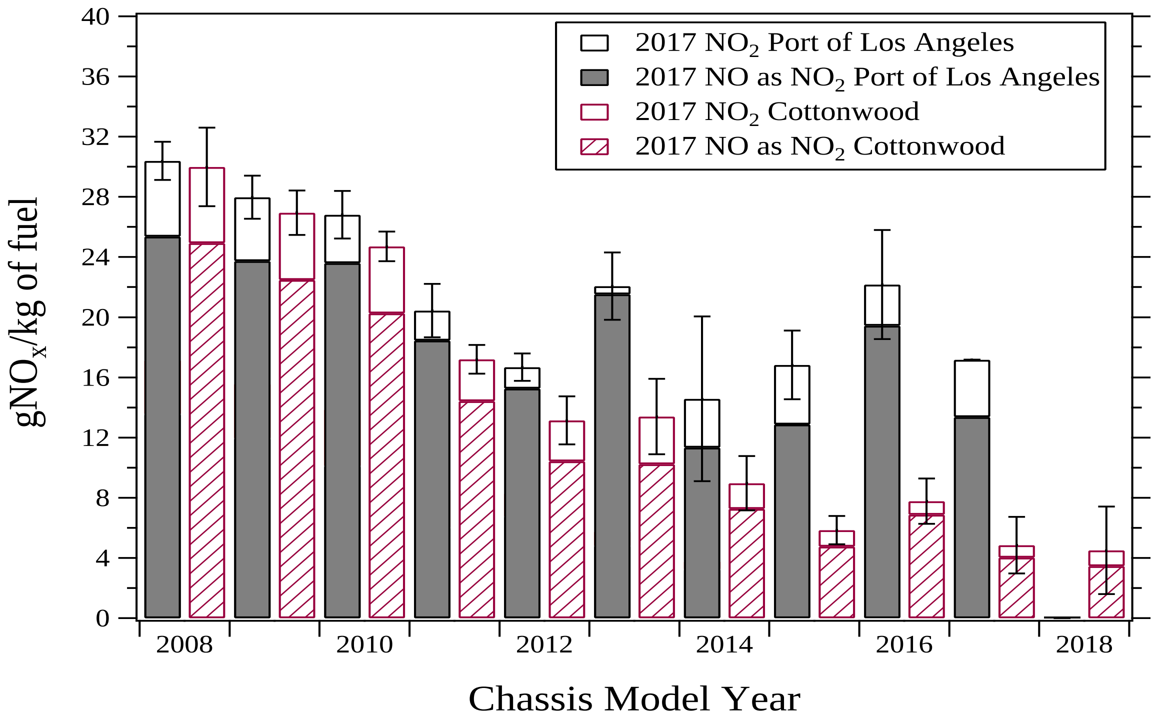

Figure 80. gNO_x/kg of fuel for 2017 data for the Port of Los Angeles (grey-left bars) and Cottonwood (red-right bars). Filled/hatched portions are gNO/kg of fuel as NO_2 and open portions are gNO_2/kg of fuel. Uncertainties are standard errors of the mean for the total gNO_x/kg of fuel calculated from the daily measurements.

One additional clue that the higher NO_x emissions at the Port are due to limited SCR performance is the higher levels of NO_2 (2.2 versus 1.6 gNO_2/kg of fuel for 2012 and newer trucks) in the Port trucks NO_x emissions. A properly performing SCR system generally has a higher conversion efficiency for reducing NO_2 to N_2 over the reduction of NO to N_2.[34]

Particle Measurements

Figure 81 presents the 2013 (circles), 2015 (diamonds) and 2017 (squares) data by model year from HDVs measured at the Port of Los Angeles for fuel specific PM (top), BC (middle) and PN (bottom) emissions. The uncertainties are standard errors of the mean calculated from the daily means. Elevated PM emissions in 2015 returned to near 2013 levels in the 2017 measurement year, with BC and PN mirroring that trend for all model years. Newer model years have consistently low particle emissions across all measurement years. The reduction in particle emissions for older model years is due to previously observed high emitting vehicles either controlling their emissions more effectively (i.e. being repaired) or being eliminated from the fleet. The older model years, 2008 - 2011, also have more variable emission levels for PN, indicating the continued presence of higher emitters. Total particle number has a greater dependence on smaller particles than the measured PM or BC values, because small particles with low mass and large particles with high mass contribute equally to total particle count. Therefore, the oldest, and theoretically most used DPFs could have small cracks due to regeneration, vibration, and or influence from driving mode

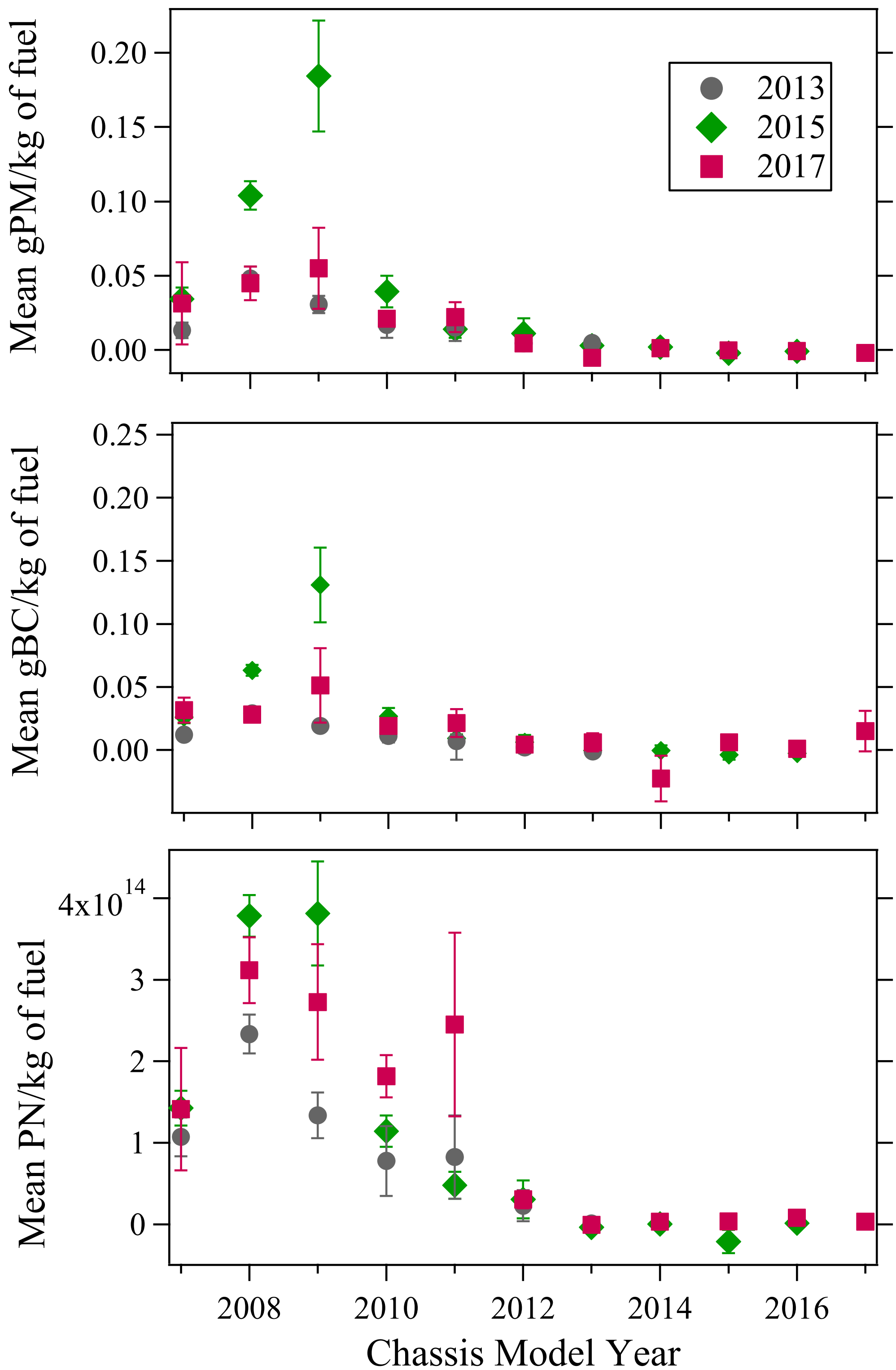

Figure 81. Mean gPM (top), gBC (middle) and PN/kg of fuel emissions (bottom) by model year at the Port of Los Angeles for measurement years 2013 (circles), 2015 (diamonds) and 2017 (squares). Uncertainties plotted are standard errors of the mean calculated from the daily means.

that could allow these smaller particles to escape, which would not severely influence PM and BC emissions.

Particle emissions at Cottonwood, Figure 82, for 2013 (circles), 2015 (diamonds) and 2017 (squares) data has not changed for model years 2009 and newer throughout the three campaigns. Uncertainties are the standard errors of the mean calculated from the daily measurements. The large uncertainties in older model years are in part the result of the low number of vehicles measured for those model years. HDVs that were not manufactured with DPFs (model year 2007 and older) have maintained their low in PM emissions from measurement year 2015. Pre-DPF models have continued to show decreases in fuel specific PM and BC emissions from the previous measurements which has been attributed to retrofit DPF installations first observed in 2015.

Figure 83 is a box and whisker plot for fuel specific PM, BC and PN showing all measurements taken at the Port of Los Angeles. The mean is represented by a black box and a horizontal line indicates the median for the model year. The box denotes the 25^{th} to the 75^{th} percentile and the whiskers are the 10^{th} to the 90^{th} percentiles. All other measurements are signified with symbols. The interquartile ranges for model years 2008 and 2009 decreased in 2017, again highlighting that the Port of Los Angeles had fewer high emitting vehicles than in the previous measurement year. The range for particle emissions at the Port though are relatively similar for all years with the exception of a single 2009 HDV measured in 2015 that is responsible for the four highest measurements of PM and BC. This of course is one gigantic exception as those 4 readings (12.3, 13.4, 18.7 and 21.3 gPM/kg of fuel and 7.2, 9.4, 24.6 and 19.2 gBC/kg of fuel) accounted for 41% of the total PM emitted and 47% of the total BC emitted from all of the measurements in 2015.

The BC trends mirror the PM trends, however there were 13 HDVs in 2017 above 0.21 gBC/kg of fuel (an arbitrary high emitter line we have chosen to use as its three times the approximate fuel specific certification standard of 0.07 g/kg of fuel), whereas 24 HDVs had gPM/kg of fuel above the same threshold. The differences are likely the result that some HDVs are not solely emitting black carbon, or soot. As mentioned previously, there are a higher number of HDVs, specifically model years 2009-2011, in which PN measurements deviate from PM and BC measurements in 2017 and increased.

Figure 84 shows individual PM, BC and PN measurements at Cottonwood in a box and whisker plot for 2013 (left, diamond), 2015 (middle, circles) and 2017 (right, squares) data. The y-axis has been split. The filled square represents the mean for the model year, the horizontal line indicates the median, the open box signifies the 25^{th} to the 75^{th} percentiles, the whiskers encompass the 10^{th} to the 90^{th} percentile and the symbols are the remaining measurements. Model years are grouped inclusively.

As with the mean emissions overall the 2017 measurements have a downward trend for all species when compared to the emission distribution observed in the 2015 measurements. The inter-quartile range has contracted significantly for the oldest HDVs as DPFs have been retrofit and this coupled with the shift from older to newer models is responsible for the reductions in the fleet means. One apparent increase in emissions is for model years 2012 – 2014. There are slight increases,

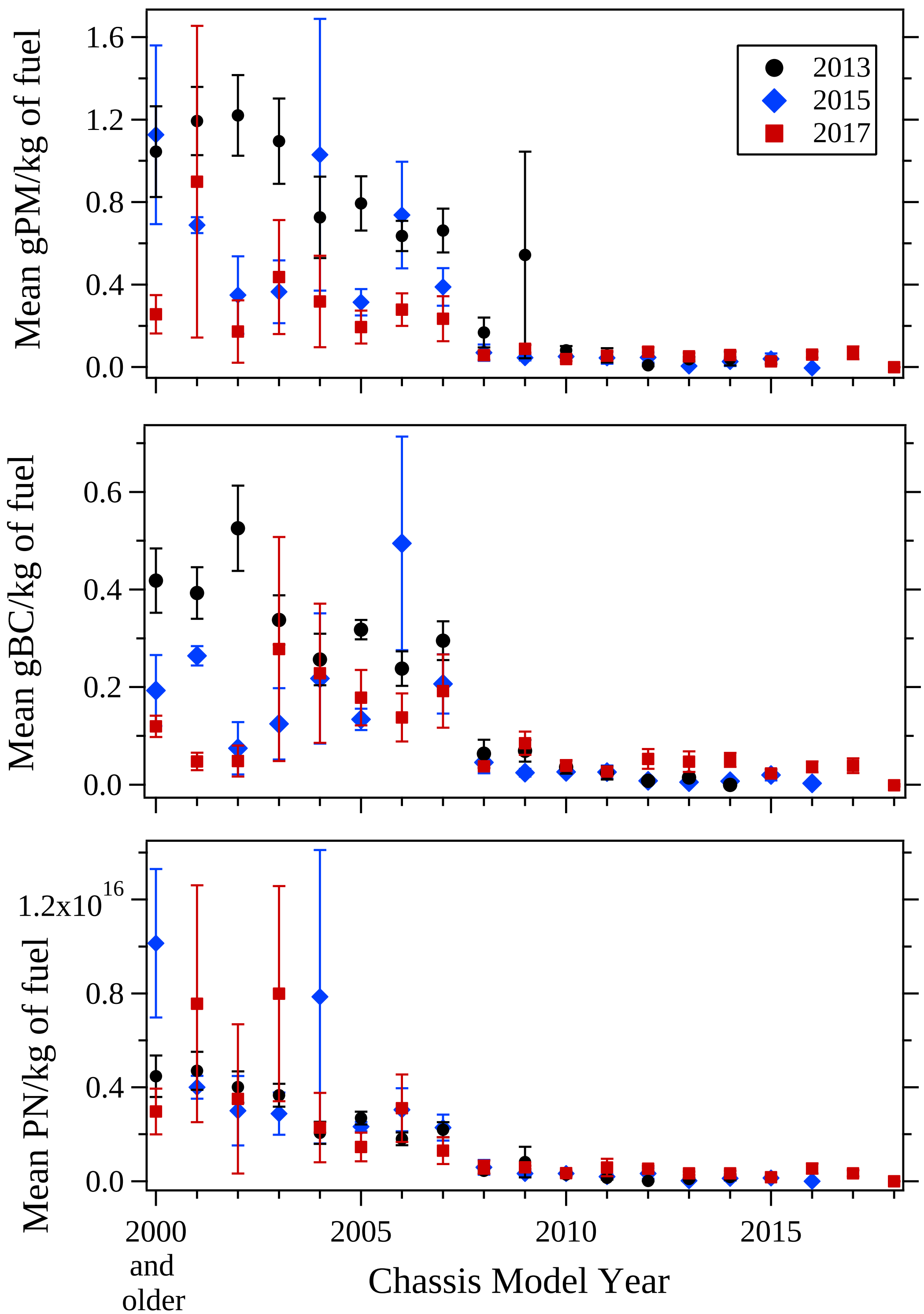

Figure 82. Mean gPM (top), gBC (middle) and PN/kg of fuel emissions (bottom) by model year at Cottonwood weigh station for measurement years 2013 (circles), 2015 (diamonds) and 2017 (squares). Uncertainties are standard errors of the mean calculated from the daily means.

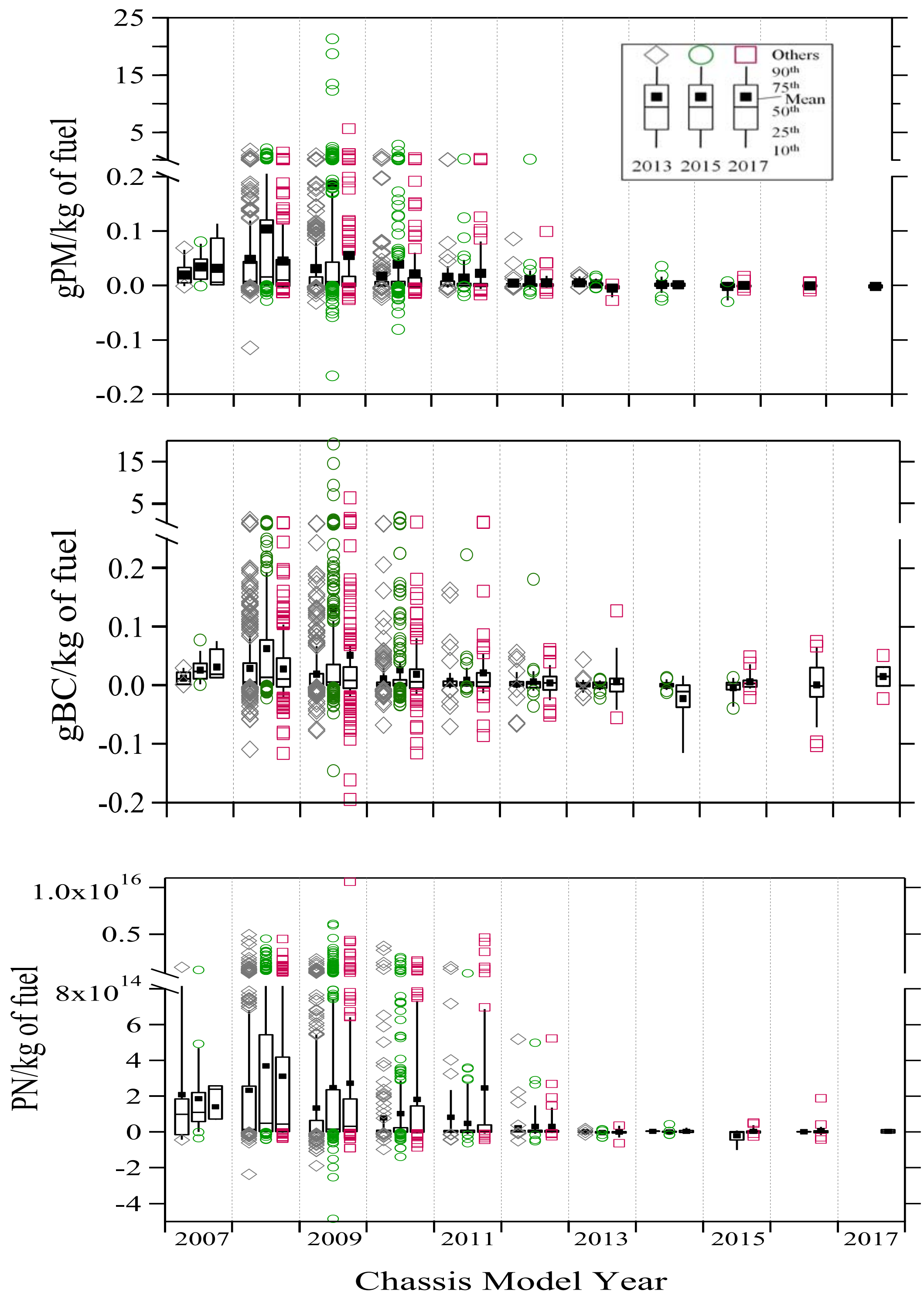

Figure 83. Box and whisker plot for gPM (top), gBC (middle) and PN/kg of fuel (bottom) for 2013 (left, diamonds), 2015 (middle, circles) and 2017 (right, squares) at the Port of Los Angeles with a split y-axis. Black squares represent the model year mean, horizontal lines denote the median, the box encloses the 25th to the 75th percentiles, the vertical lines represent the 10th to the 90th percentile with symbols representing the other individual measurements.

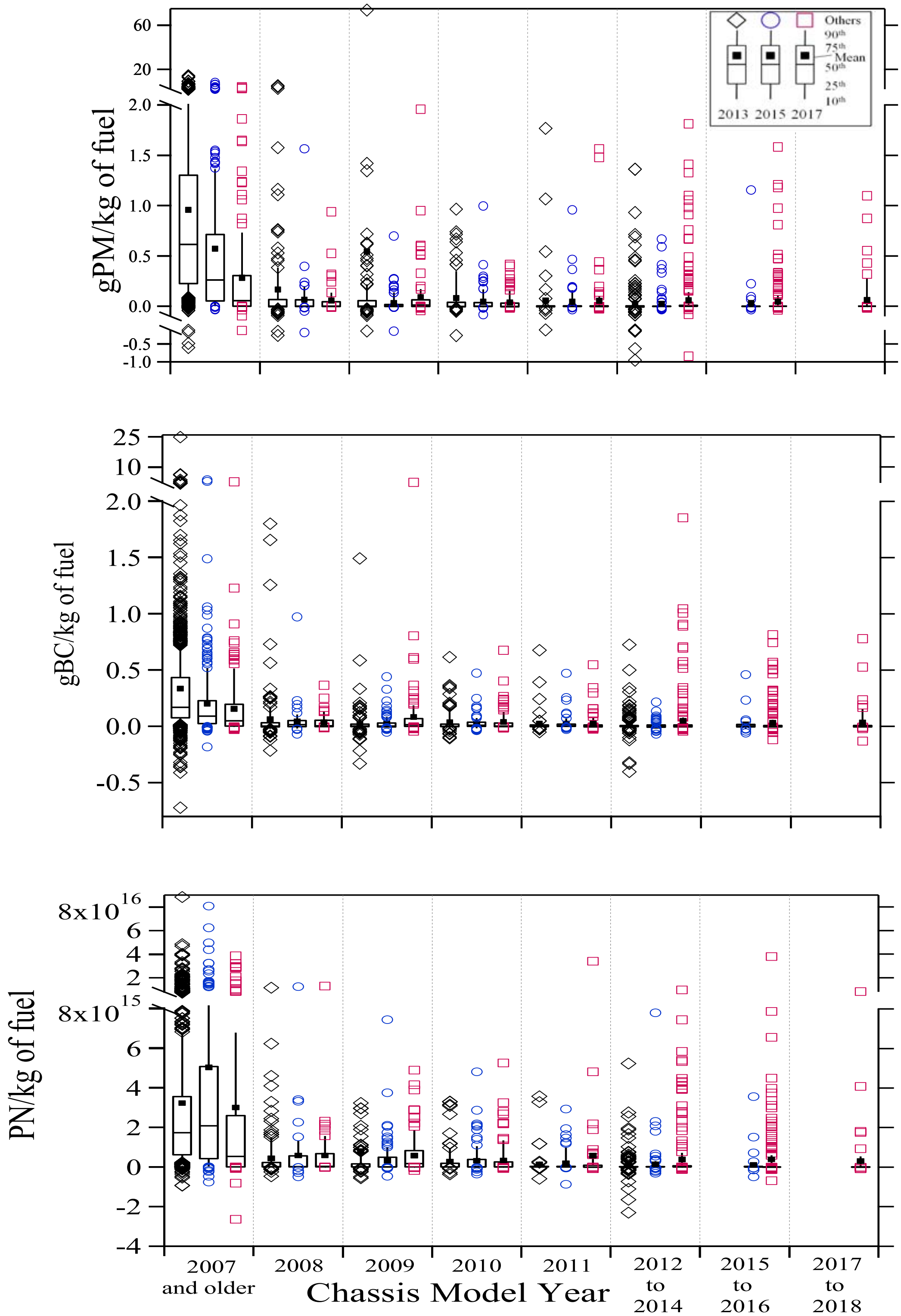

Figure 84. Box and whisker plot for gPM (top), gBC (middle) and PN/kg of fuel (bottom) for 2013 (left, diamonds), 2015 (middle, circles) and 2017 (right, squares) at the Cottonwood scales with a split y-axis. Black squares are the model year means, horizontal lines denote the median, the box encloses the 25th to the 75th percentiles, the whiskers extend to the 10th and 90th percentiles with symbols representing the other individual measurements.

especially in the extent of the range of values observed, in both PM and BC emissions, however, the number of vehicles observed in these model years has more than doubled since 2015. We do not see increases in the mean particle emissions for these groups because of the large number of low emitters contained below the 90th percentile.

Figure 85 reveals how changes in vehicle age and HDV engine and after-treatment technologies in the Port of Los Angeles fleet affects mean fuel specific PM (diagonal, left-axis) and NO_x (solid, right-axis) emissions. All uncertainties are the standard error of mean calculated from the daily means. These two species are historically inversely related, especially for pre-SCR HDVs. At the Port measurement statistics are still dominated by 2008 – 2010 model year vehicles with the 2011 and newer group accounting for only 25% of the 2017 measurements (up from 11% in 2013). For these two age groupings, fuel specific PM decreases by 79% and NO_x decreases by 33% as vehicles move from one category to the other. The reductions gained from an increased number of newer trucks has been more than offset by increased emissions in the older trucks.

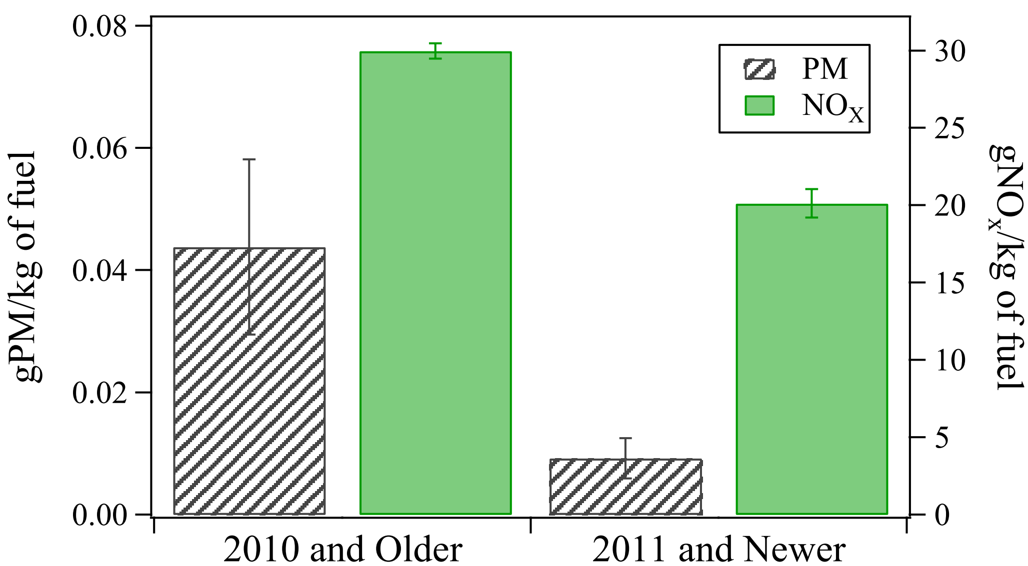

Figure 85. The Port of Los Angeles fuel specific PM (diagonal, left axis) and NO_x (solid, right axis) emissions for HDVs model year 2010 and older compared to model years 2011 and newer. Uncertainties are standard errors of the mean calculated from the daily means.

Consistent with the Port of Los Angeles, Figure 86 displays the similar relationship between mean fuel specific PM and NO_x trends at Cottonwood for three model year groups in 2017. Vehicles 2006 and older (left), 2007 to 2010 (middle) and 2011 and newer (right) show decreases in both PM and NO_x emissions. Fuel specific PM decreased by 74% from 2006 and older vehicles to 2007-2010 vehicles with an additional 36% decreases for the newest vehicles. Fuel specific NO_x emissions had the order of decreases reversed as NO_x only decreased by 21% for the oldest group to the 2007-2010 HDVs followed by a 55% decrease to the newest vehicle grouping. The larger reduction in NO_x emissions for the newest HDVs of course coincides with the introduction of NO_x after-treatment systems and the increased size of the NO_x reductions reflecting better performance

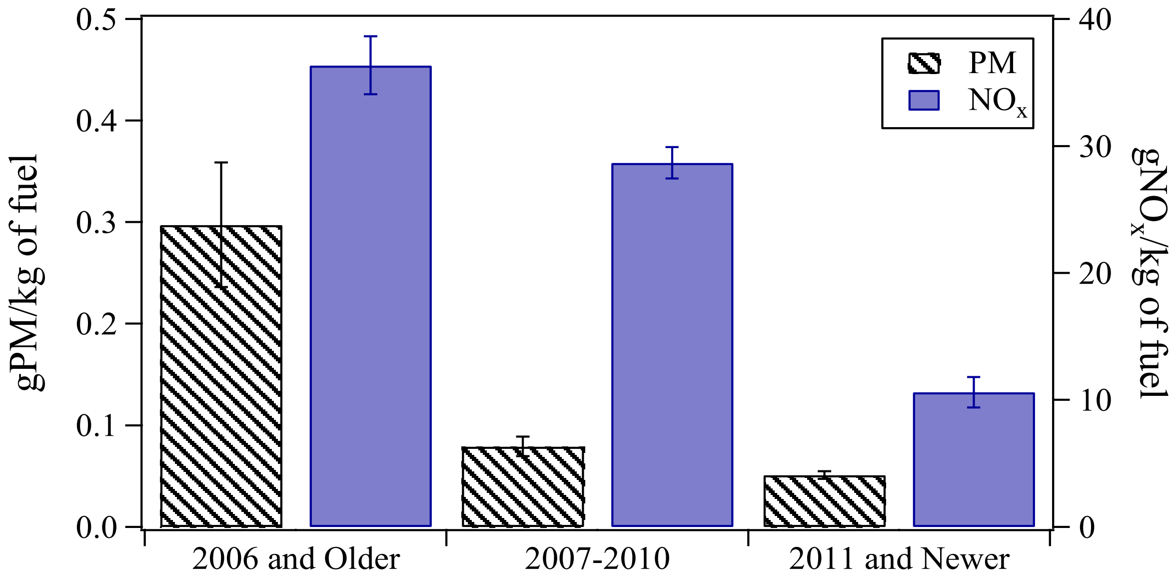

Figure 86. Cottonwood weigh station fuel specific PM (diagonal, left axis) and NO_x (solid, right axis) emissions for HDVs model year 2006 and older compared to model years 2007 to 2010 and model years 2011 and newer. Uncertainties are standard errors of the mean calculated from the daily means.

than observed at the Port. As the Cottonwood fleet has become newer the changes in the model year distribution of the fleet has lowered the mean emissions.

Reoccurring HDV Measurements

Particle emissions variability were explored in detail with the 2015 measurements (see Figures 58 – 65) and trends similar to those previously presented were found with the 2017 measurements. In order to limit some of the repetitiveness we have chosen to only discuss the measurement variability for reoccurring trucks that were at least seen in the last two measurement campaigns. Reoccurring vehicles (see Table 12) are more common at the Port of Los Angeles location than at Cottonwood because the Port trucks are just transfer agents picking up containers at the Port and then delivering them locally and then repeating the process. Figures 87 – 89 graph the fuel specific PM, BC and PN measurements for Port vehicles with valid measurements measured in 2015 (circles) and 2017 (squares) displayed with a split y-axis. A few of these vehicles were also measured in 2013 (diamonds) and those measurements are also included. The vehicles were rank ordered and plotted along the x-axis using the 2017 average gPM/kg of fuel.

As with the previously discussed analysis from 2015 as vehicle average gPM/kg of fuel emissions increases so does the variability of repeat measurements. The reoccurring measurements also show what many of the previous analysis have discussed, the reductions in average emissions for all three species in 2017 when compared with 2015. It is very noticeable that there are more 2015 (circles) measurements that are above the general 2017 emissions trend than there are elevated 2017 measurements. Table 14 illustrates this in tabular form with the percent of total measurements

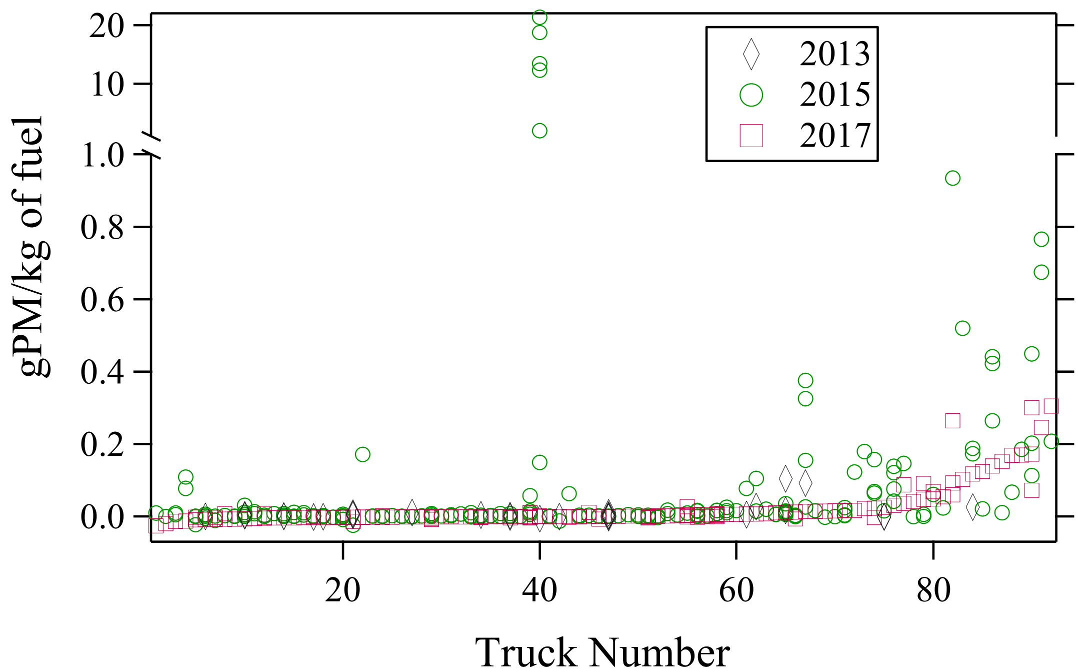

Figure 87. Fuel specific PM emissions for reoccurring HDVs measured in 2015 (circles) and 2017 (squares) at the Port of Los Angeles with a split y-axis. A few vehicles were also measured in 2013 (diamonds). Trucks are rank ordered using the 2017 average gPM/kg of fuel.

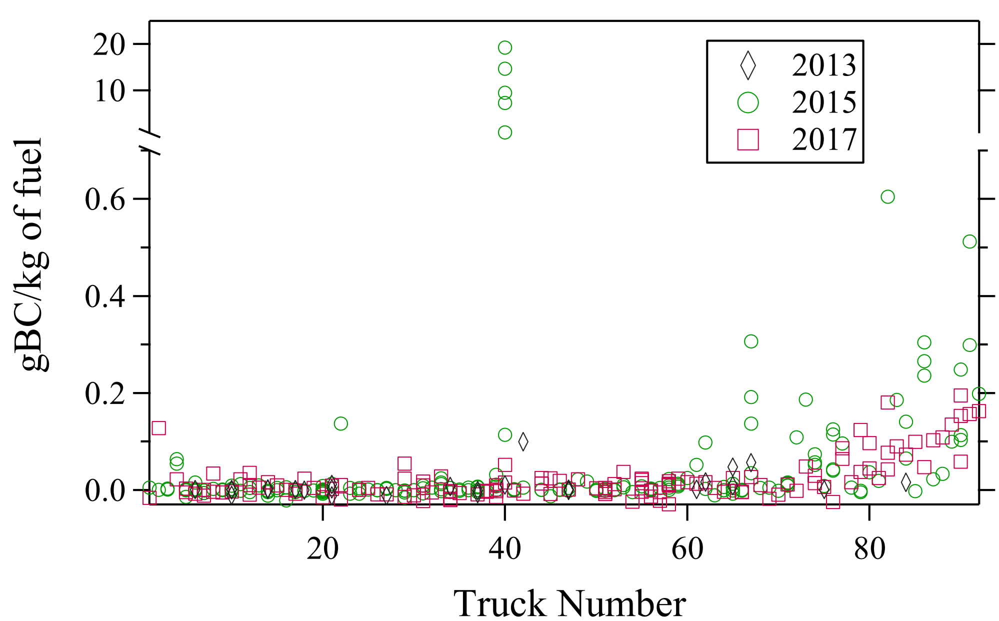

Figure 88. Fuel specific BC emissions for reoccurring HDVs measured in 2015 (circles) and 2017 (squares) at the Port of Los Angeles with a split y-axis. A few vehicles were also measured in 2013 (diamonds). Trucks are rank ordered using the 2017 average gPM/kg of fuel.

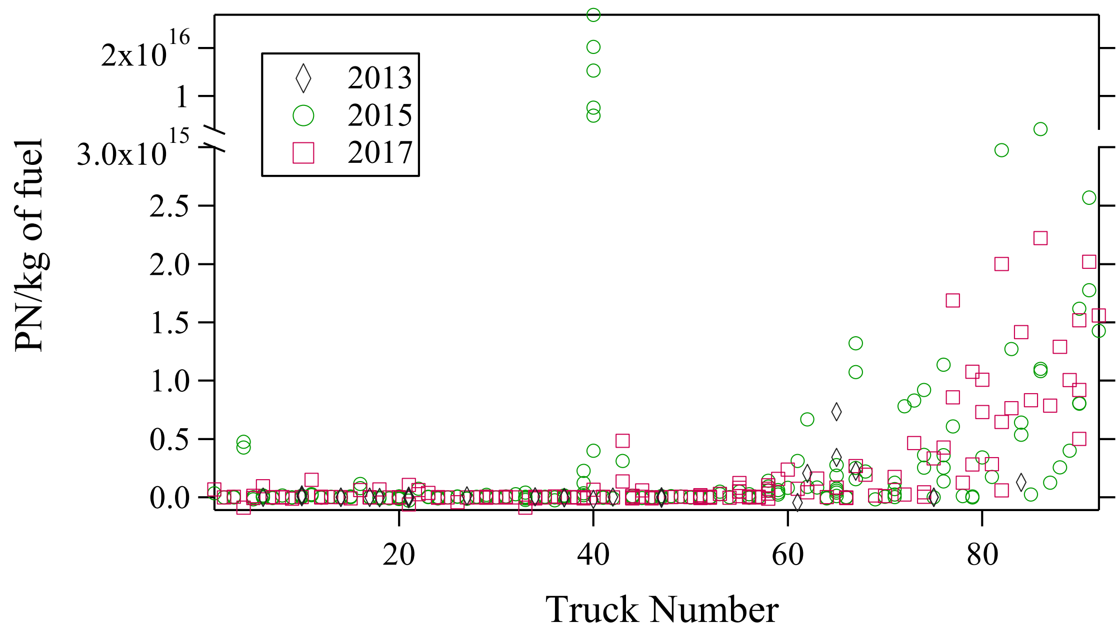

Figure 89. Fuel specific PN emissions for reoccurring HDVs measured in 2015 (circles) and 2017 (squares) at the Port of Los Angeles with a split y-axis. A few vehicles were also measured in 2013 (diamonds). Trucks are rank ordered using the 2017 average gPM/kg of fuel.

Table 14. Percent of HDV above the 2013 90th Percentile at the Port of Los Angeles and Cottonwood weigh station.

Model Year	Emissions	Port of Los Angeles			
2008		2013 90th Percentile	2013	2015	2017
	gPM/kg	0.12	3.6%	6.5%	2.2%
	gBC/kg	0.08	3.8%	6.1%	3.3%
	PN/kg	6.8E+14	3.4%	5.2%	3.8%
2009					
	gPM/kg	0.08	3.8%	7.7%	2.9%
	gBC/kg	0.07	2.2%	6.4%	3.1%
	PN/kg	5.4E+14	3.1%	6.1%	3.8%
2010					
	gPM/kg	0.02	1.8%	3.5%	3.8%
	gBC/kg	0.03	1.8%	2.5%	5.7%
	PN/kg	6.4E+13	1.8%	4.1%	6.0%

for each particle species that exceeds the 2013 90^{th} percentile for the three most common model years of Port trucks (2008 – 2010) in each measurement year. As discussed the number of high emitters increased by about a factor of 2 in 2015. In 2017 model year 2008 and 2009 saw reductions in the numbers to levels that were generally comparable to 2013. The one exception is the 2010 models which continued to see an increase in vehicles emitting beyond the 2013 90^{th} percentile.

2017 BC measurements follow the trends seen for PM but appear to have higher variability than the PM measurements. Some of that variability arises from the first day and half of measurements in 2017 using the inlet shared with the FMPS. As previously discussed this greatly increase the measurement noise on the BC measurements. In addition the lower portion of the y-axis in Figure 87 is expanded approximately 30%, when compared with the PM graph (Figure 86), increasing the apparent variability. The PN measurements are the one species where we still see some increases in 2017 compared to the 2015 measurements especially among the higher PM emitters.

Figures 90 – 92 are the same analysis performed using the multi-year measurements collected at the Cottonwood weigh station for PM, BC and PN. Reoccurring trucks measured in 2015 (circles) and 2017 (squares) data is shown along with any measurement data collected on the same vehicle in 2013 (diamonds). Truck number is calculated from the measured 2017 gPM/kg of fuel average. There are far fewer reoccurring HDVs measured at Cottonwood and the HDVs at Cottonwood include older model years that were not originally equipped with DPFs. Figure 90 shows the PM emissions for HDVs measured in 2015 and 2017 at Cottonwood with a few 2013 measurements included when applicable. Truck numbers 34 and higher have increasing PM emissions from 2015 to 2017. These vehicles, with exception of truck number 36 and 37, are 2008 to 2010 HDVs and all are from the same chassis manufacturer. A number of the observed large decreases in 2017 are from older vehicles believed to have likely installed a retrofit DPF to comply with the California Truck and Bus rule. The general pattern from the PM measurements are repeated for the fuel specific BC and PN measurements.

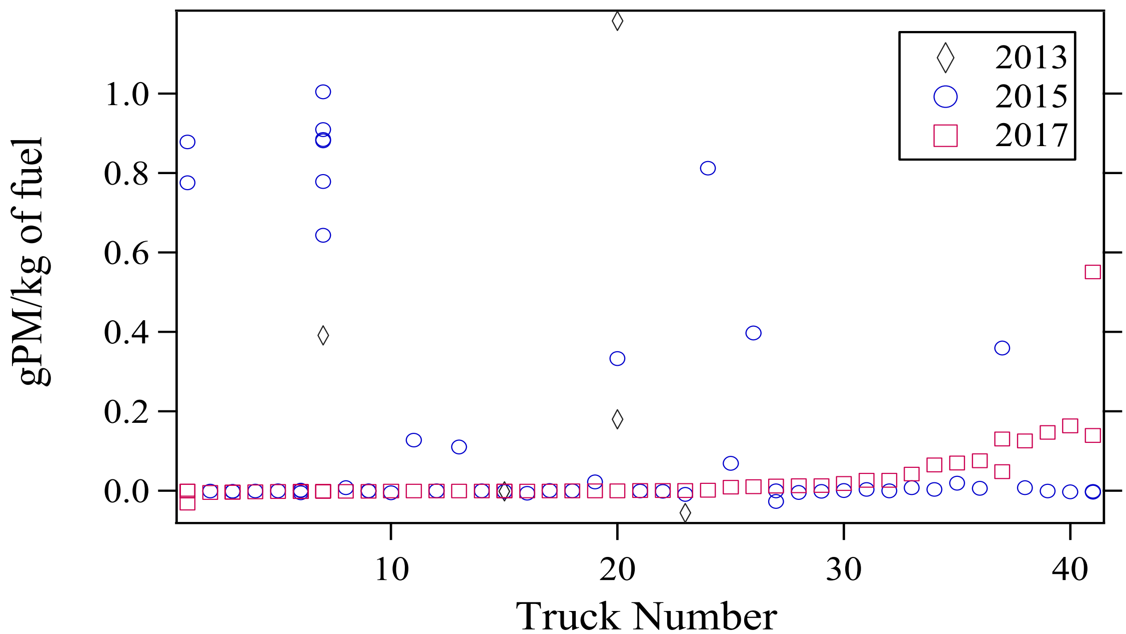

Figure 90. Reoccurring HDVs measured in 2015 (circles) and 2017 (squares) at the Cottonwood weigh station for gPM/kg of fuel. A few vehicles were also measured in 2013 (diamonds). Truck number is calculated from average gPM/kg of fuel.

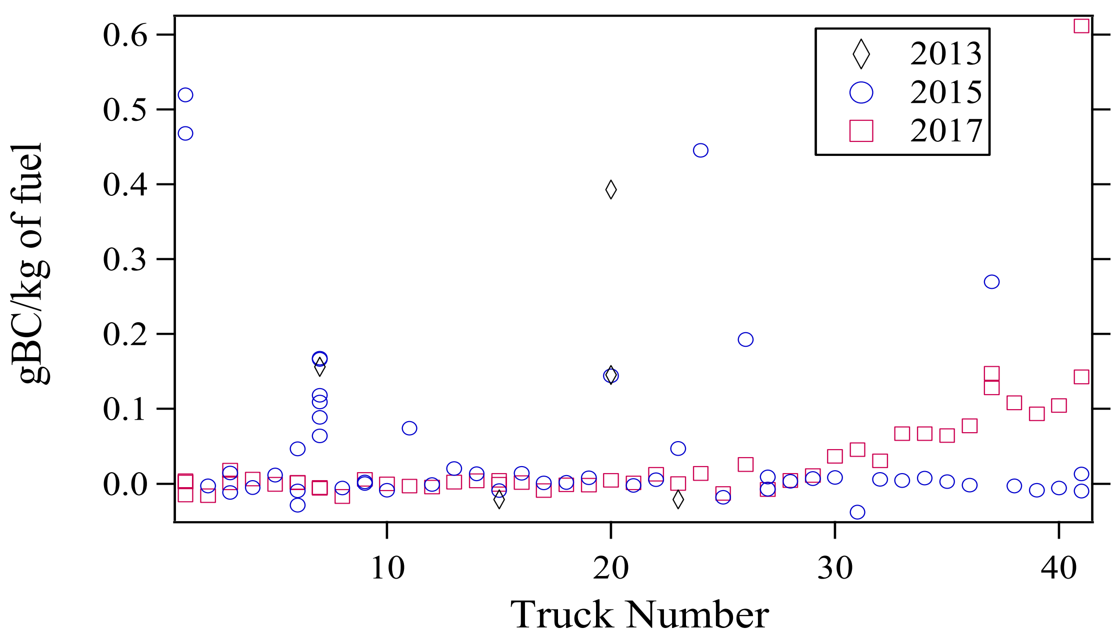

Figure 91. Reoccurring HDVs measured in 2015 (circles) and 2017 (squares) at the Cottonwood weigh station for gBC/kg of fuel. A few vehicles were also measured in 2013 (diamonds). Truck number is calculated from average gPM/kg of fuel.

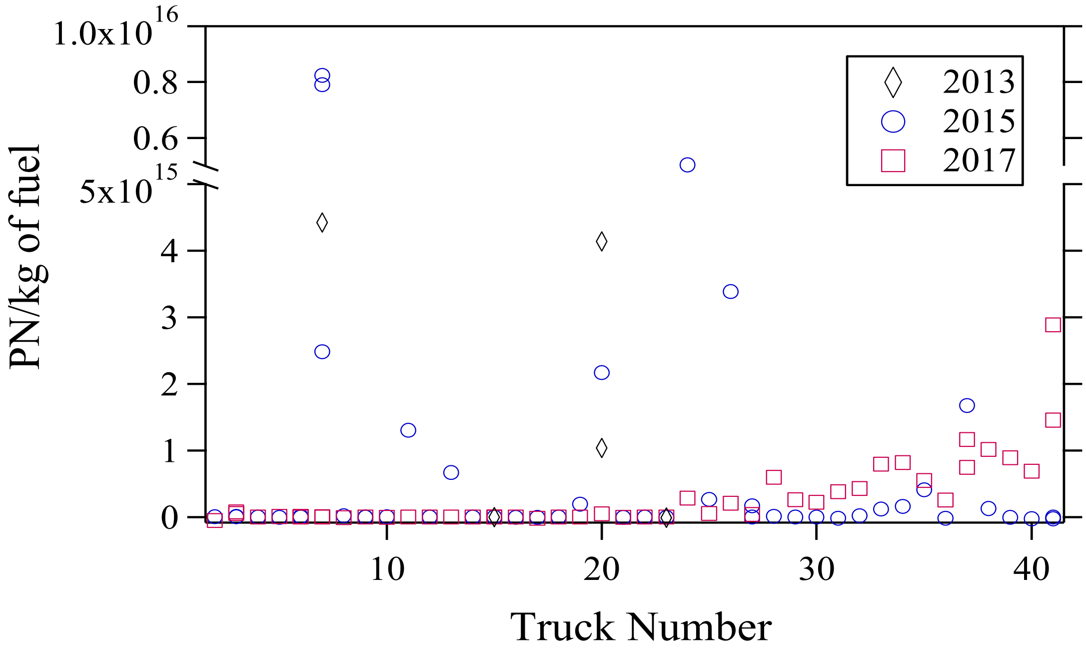

Figure 92. Reoccurring HDVs measured in 2015 (circles) and 2017 (squares) at the Cottonwood weigh station for PN/kg of fuel with a split y-axis. A few vehicles were also measured in 2013 (diamonds). Truck number is calculated from average gPM/kg of fuel.

Conclusions

The University of Denver has pioneered the use of a new and novel method to collect in-use tailpipe emission measurements of HDVs. The system, dubbed OHMS (On-road Heavy-duty Measurement System), measures the integrated exhaust from vehicles with elevated exhaust pipes using a modified events tent as an exhaust containment system. The approach utilizes a 50ft. long and 15ft high tent structure under which the truck drives and, as the exhaust disperses in the roof of the tent, it is captured by a perforated pipe which integrates the trucks emissions over the length of the tent and then delivers the exhaust sample to a small suite of analyzers in a mobile lab parked at the exit of the tent. The system used in these studies is capable of simultaneous measurements of carbon dioxide (CO_2), carbon monoxide (CO), total hydrocarbons (THC), nitric oxide (NO), total nitrogen oxides (NO_x), nitrogen dioxide (NO_2) by difference (NO_x – NO), total particle mass (PM), particle number (PN) and black carbon (BC).

The method determines fuel specific emission rates of pollutants using the ratio of pollutant to CO_2 for each vehicle and converting these ratios using carbon balance into mass emissions for each pollutant per mass or volume of fuel consumed. The system was also configured to determine the speed and acceleration of the vehicle at the entrance and exit of the tent, and was accompanied by three video systems used to record the license plate of the vehicle, infrared images of elevated exhaust pipes to estimate operating temperature and to look for the presence of urea tanks indicating that the vehicle is equipped with a SCR system. Vehicle license plates were matched with state registration databases when available to provide vehicle information.

Using the OHMS system the University of Denver has successfully conducted three data collection campaigns for HDV at two California sites in the spring of 2013, 2015 and 2017. The first site was located at the exit from Trapac, LLC. container operations at berths 136 - 147 at the Port of Los Angeles in Wilmington, CA. The second was at the California Highway Patrol's Cottonwood scales along I-5 in northern California just south of Redding CA. These sites provided contrasting fleets with the Port location having a short-haul drayage fleet that had only recently been required to retire any HDV which was not equipped with a DPF. The Cottonwood location consisted of an interstate long-haul fleet subject to more traditional fleet turnover changes. The Port fleet provided an opportunity to follow the aging process on emissions from a relatively new vehicle fleet all equipped with DPFs. While at the Cottonwood site we observed changes in the fleet emission trends that took place during the introduction of new technology vehicles via fleet turnover.

These three campaigns have resulted in the collection of a total of 7,076 HDV emission measurements and vehicle information being compiled for study. This comprises one of the largest in-use emissions data set collected to date on HDVs. These databases, as well as any previous data our group has obtained for HDVs can be found at www.feat.biochem.du.edu. With any longer term study it is not always possible to control all of the variables from year to year that can impact the data sampling and this study is no exception. Our Port location experienced changes in each of the last two data sets as Trapac modernized their facility in 2015 with a new physical exit location and an automated exit process. A speed bump was added across the end of the exit lanes between the

2015 and 2017 campaigns slowing the exit speeds of the vehicle. The new exit facility added an additional exit lane that was little used in 2015 but was fully operational in 2017. That along with the addition of the speed bump reduced the number of measurement attempts and is why the last years Port measurements have fewer trucks. At Cottonwood there were no physical changes from year to year but high winds limited the data collection in 2015 and Patrol operational considerations in 2017 reduced the number of HDV with driving modes that optimized successful measurements.

Since the first measurements were collected in 2013 the fleet sampled at the Port of Los Angeles has increased in age by approximately 3.3 years as the fleet's mean model year only changed from 2009.1 to 2009.8 over the five year period. The fleets dominant vehicle chassis model years are 2008 and 2009 models that were purchased prior to the 2010 San Pedro Clean Ports Clean Air Action Plan deadline to upgrade to a 2007 PM compliant engine. In 2013 these models made up 70% of the measurements and in 2017 these two models still represented 57% of the measurements though 2011 and newer chassis model year vehicles have increased from just 11% of the measurements to 42%. Despite the fleet age increases the 2017 fleet sampled at the Port is still significantly younger than the nonregulated drayage fleet sampled at this location in 2008 (7.2 vs. 12.4 years old).[10] In contrast the fleet at the Cottonwood weigh station has gotten steadily newer as the fleet has turned over. In 2013 the mean model year of 2005.6 corresponded to an approximate fleet age of 7.4 years. In 2015 the mean model year observed was 2008.1 (~6.9 years old) and in 2017 that further improved to 2011.3 (~5.7 years old).

At the Port the only gaseous species consistent trend is for increasing oxide of nitrogen emissions with NO_x emissions increasing ~25% since the 2013 measurements. We have found that NO_x emissions at the Port are generally higher and less affected by model year than similarly aged vehicles at Cottonwood as the Ports activity cycle and subsequent lower operating temperatures are not conducive to SCR operation. CO and HC emissions at the Port are sensitive to the number of natural gas powered vehicles measured as they have characteristically higher emissions of CO and HC (CH_4) than diesels and the means for both of these species rose (4.5% of the measurements in 2015) and fell (1% of the 2017 measurements) with the number of CNG vehicles in the database.

For the HDV measured at Cottonwood overall all of the gaseous species showed reductions over the five year period, though HC and the oxides of nitrogen did not have consistent trends in this regards. The observed increases in oxides of nitrogen emissions in 2015 were the result of unexplained systematic increases for all model years. The 2017 measurements by model year are more consistent with the 2015 measurements and the reductions in the mean are a result of the age decrease of the fleet with newer and lower emitting HDV replacing older and higher emitting HDV. Indirectly indicating that SCR performance at Cottonwood is significantly better than at the Port.

Particle emissions trends at the two locations have followed different paths with emissions at the Port location increasing in 2015 and then decreasing in 2017 while Cottonwood has consistently declined with each successive measurement. After the Port's particle emissions experienced significant increases in emissions in 2015 due to an increase in the number of high emitters in the 2008 to 2010 chassis model year vehicles, the 2017 data saw those high emitter fractions significantly reduced to levels nearer those observed in 2013 with fuel specific PM, BC and PN emissions decreasing 64%, 63% and 20% respectively (0.11 to 0.04 gPM/kg of fuel, 0.08 to 0.03 gBC/kg of fuel and 2.8 x 10^{14} to 2.2 x10^{14} PN/kg of fuel). One potential explanation for fewer high emitting vehicles in 2017 at the Port of Los Angeles is that the Air Resources Board increased roadside compliance testing, which included concurrent information only opacity testing at the Port during the 2015 campaigns, and the issuance of statewide citations since 2015 have increased significantly. This may have encouraged corrective maintenance or relocation for some of the high emitting trucks observed in 2015. Of the 38 HDV observed in 2015 with fuel specific PM emissions greater than 0.5 gPM/kg of fuel only 4 were observed again in 2017. One was the highest emitting vehicle measured in 2015 and while its two repeat measurements were essentially zero there is some question as to whether it is the same truck as the video images of the trucks front are noticeably different (see Appendix F). The emissions distribution at the Port still has a higher skewness in 2017 than in 2013 indicating the continued presence of high emitters, just not as many as seen in 2015.

At Cottonwood the combination of a newer fleet and continued DPF retrofitting of older vehicles continued a consistent reduction in particle emissions. Reductions of almost a factor of 3 over the 2015 fuel specific PM (0.22 to 0.08 gPM/kg of fuel) emission levels, a 57% reduction for PN (1.7x 10^{15} to 7.7 x 10^{14} PN/kg of fuel) emissions and smaller but continued reductions for BC (0.077 to 0.056 gBC/kg of fuel) emission levels were observed. Since 2013 we have observed decreases of 87%, 76% and 64% for fuel specific PM, BC and PN emissions respectively. These sustained reductions have brought the Cottonwood fleets mean particle emissions to levels that are approaching those observed at the Port indicating that the vast majority of HDV operating through the Cottonwood scales are now DPF equipped. Noticeable reductions from the 2007 and older group, that while the range of observed fuel specific PM emissions is similar for each data set, show significant reductions in the number of the higher readings. This has dramatically shrunk the size of the interquartile range for each successive measurement campaign and lowered mean emissions by more than a factor of 2 for this group.

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Appendix A – Manufacturers Instrument Specifications

Model Horiba AIA-240

Principle Non-dispersive infrared absorptiometry

Ranges

CO 0 – 1.0 vol%

CO_2 0 – 4.0 vol%

Repeatability Within ± 1% of the maximum value

Response Within 1.5 seconds

Zero Drift Within ± 1% of the maximum value/ 8 hours (temp ±5°C)

Span Drift Within ± 1% of the maximum value/ 8 hours (temp ±5°C)

Operating Temp. 0 to 40°C

Model	Horiba FCA-240
Principle	Hydrogen Flame Ionization Detection method
Ranges	
THC	0 – 2000 ppm-C
Repeatability	Within ± 1% full scale, for successive measurements of identical samples under identical conditions
Response (T_{90})	Within 1.5 seconds
Zero Drift	Within ± 1% of the maximum value/ 8 hours (temp ±5°C)
Span Drift	Within ± 1% of the maximum value/ 8 hours (temp ±5°C)
Noise Level	1% full scale with no external noise
Linearity	Within ± 1% full scale
Relative sensitivity	Within ± 15% (C_3H_8 reference)
O_2 interference	Within ± 5% (C_3H_8 gas)
Operating Temp.	0 to 40°C

Model Horiba FCA-240

Principle Chemiluminescent method

Ranges

NO/NO_x 0 – 500 ppm

Repeatability Within ± 1% full scale, for successive measurements of identical samples under identical conditions

Response (T_{90})

NO line Within 1.0 seconds

NO_x line Within 3.0 seconds

Zero Drift Within ± 1% of the maximum value/ 8 hours (temp ±5°C)

Span Drift Within ± 1% of the maximum value/ 8 hours (temp ±5°C)

Noise Level 1% full scale with no external noise

Linearity Within ± 1% full scale

Interference

CO_2 interference Within – 2% (CO_2 5%)

H_2O interference Within – 2% (H_2O 3%)

NO_x connector eff. 95% or more (500 ppm)

Model Dekati DMM-230A

Principle Density measurement principle

Size Range 0 – 1.2μm

Number of Stages 6 impactor stages + 1 mobility channel

Response Time <5 seconds with 400,000 fA measurement range
~15 seconds with 10,000 fA measurement range

Concentration 1 – 1000 μg/m^3 (momentarily up to 5000 μg/m^3)

Operating Conditions

Temperature 15 - 35°C

Humidity 0 – 70%, non-condensing

Model Droplet Measurement Technologies PAX

Principle Photoacoustic Extinctiometer 870nm

Size Range < 1Mm^{-1} – 100,000 Mm^{-1} (870nm, 60 sec. averaging)

Response Time < 10 seconds; 1 second resolution

Concentration 1 – 1000 µg/m^3 (momentarily up to 5000 µg/m^3)

Operating Conditions

Temperature 0 - 40°C

Humidity 0 – 90%, non-condensing

The FLIR A320 infrared camera used in the OHMS system was initially calibrated in the lab using a single stainless steel exhaust pipe that was heated on a hot plate. A thermocouple was attached to the pipe and the IR image color was then assigned to the temperature read by the thermocouple. There was concern regarding the representativeness of a single stainless steel pipe and an in-field calibration was conducted.

The contraption that was constructed to make these measurements is shown in Figure B1. The device consisted of a long wooden pole with a thermocouple spring mounted on one end and the IR camera, a color video camera and a volt meter mounted on the other. The pink box highlights the FLIR IR camera and its video monitor, and the visible video camera and its monitor is shown with the green box. Below and between the cameras is the thermocouples voltage reading (blue box) and at the end of the pole is the thermocouple respectively (red box). The camera and thermocouple signals were passed to a computer with dual imaging boards and an analog to digital converter. A trigger in the handle was pulled when the volt meter had reached a steady reading to signal the computer to acquire the IR image, visible image and thermocouple temperature. The FLIR IR cameras color scale (see Figure B2) was assigned a temperature range by assigning the measured thermocouple temperatures to the IR image color collected. Thus allowing the camera images to be used to estimate exhaust pipe temperatures without having to physically touch the exhaust pipe with a thermocouple and eliminate any material emissivity differences.

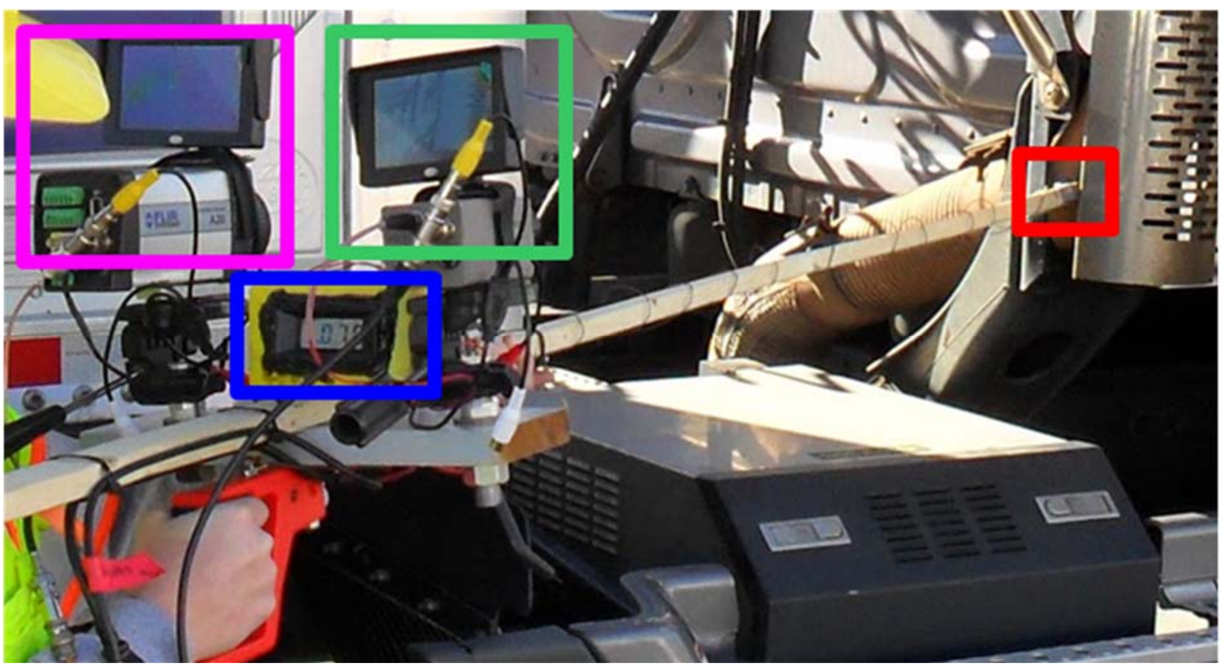

Figure B1. Device used for measuring temperature of exhaust pipes on HDV. In the upper left is the FLIR A320 IR camera and video monitor (pink box), to its right is the color video camera and monitor (green box), below is the thermocouple voltage readout (blue box) and to the far right is the thermocouple (red box) pressed up against the trucks exhaust pipe.

Measurements were taken at two locations, the Dumont weigh station on I-70 in the Rocky Mountains, approximately 35 miles West of Denver and at Coors Brewery's distribution plant in Golden, CO. Over the course of four days, December 2, 3, 5 and 8, 2014, 226 exhaust pipes were measured.

The two locations measured are representative of the two locations where we have deployed the OHMS system in California. The brewery location had lower temperature pipes due to the short haul and stop and go nature of the distribution yard operations much like the Port of Los Angeles site. The Dumont weigh station had a fleet comprised of HDV on an interstate highway route where measurements were collected after the vehicles were required to drive up the mountainous road resulting in hotter exhaust pipes more like the Cottonwood weigh station site in northern CA. The histogram showing the temperatures measured at both locations is shown in Figure B3. The HDV at Dumont, as expected were on average warmer and had more vehicles that extended into hotter regions of the color scale than observed in the Coors fleet.

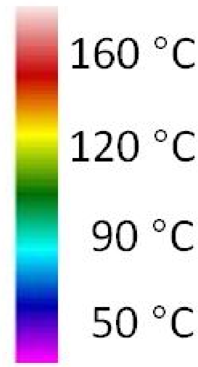

Figure B2. Infrared image color scale with associated temperatures determined from the thermocouple measurements.

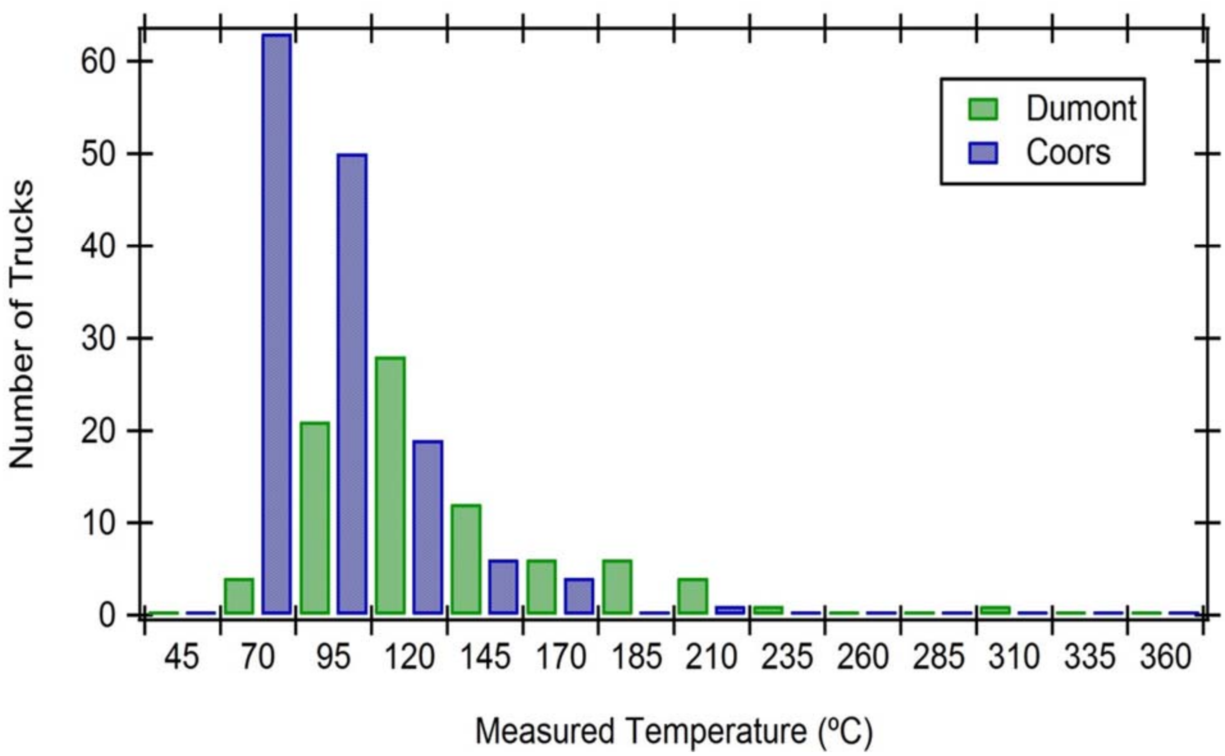

Figure B3. Histogram of exhaust pipe temperatures at Dumont weigh station (green bars) and Coors Brewery (blue bars).

Figure B4 graphs the measured thermocouple temperature against the previously determined IR image temperature calibration. The crosses plot are the individual thermocouple measurements collected from each truck with the solid black line showing the least squares best fit line. The parallel black dashed lines how the 95% prediction bands for the best fit line. The red solid line is the 1:1 line showing the previously determined IR temperature calibration.

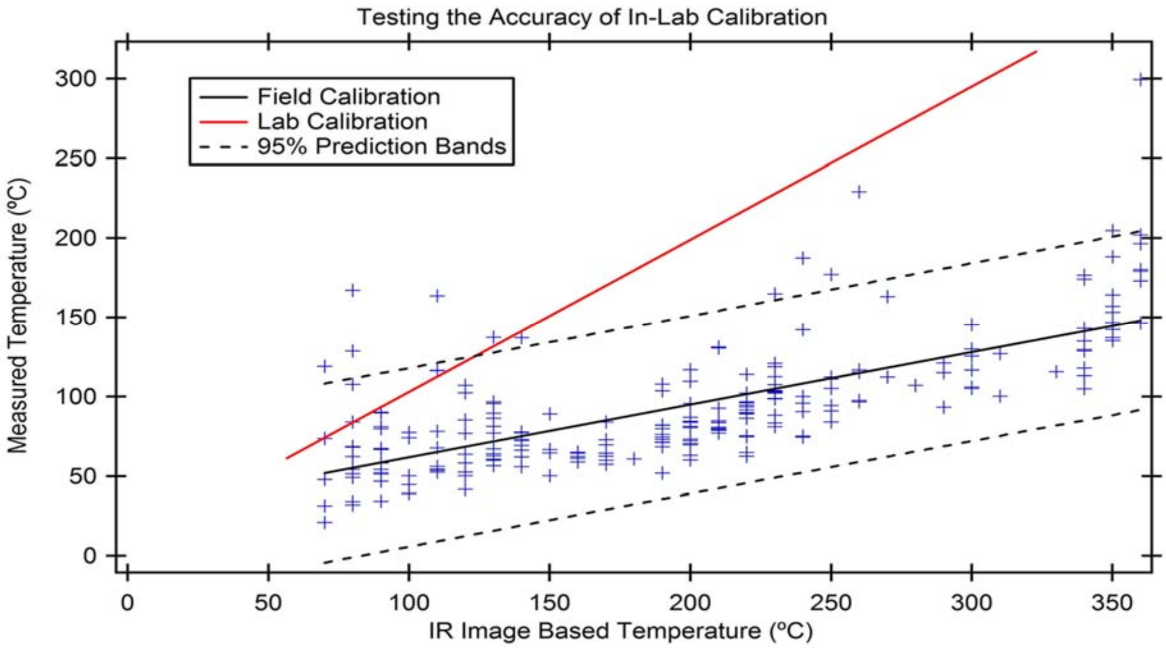

Figure B4. Thermocouple temperature measurements (+) versus the previous in-lab calibrated IR image-based temperature in degrees C. The solid black line is the least squares best fit line to the data with the parallel dashed lines showing the 95% prediction bands for that fit. The red line is the 1:1 line showing the previous in-lab calibration line.

We believe that this field calibration has greatly improved the temperature accuracy assigned to the IR images in the OHMS system. We believe that we have sampled enough exhaust pipes to minimize the emissivity variable associated with different metals that exhaust pipes are made out of in order to improve the temperature estimates.

To correct the 2013 IR image temperature data that used the in-lab calibration the equation below was used, where y is the temperature represented by the field calibration and x is the temperature previously assigned using the in-lab calibration.

$$y = 0.331x + 28.8$$

Appendix C – OHMS g/kg Measurements Validity Criteria

Not measured:

1) Body sensor blocked and after 15 or 20 seconds of data collection the maximum increase in CO_2 is less than 80ppm over background.

Invalid:

1) gCO/kg < -2;
   gCO/kg <= 6 and error > 1.5;
   gCO/kg > 6 and percent error > 25%

2) gHC/kg < -10;
   gHC/kg <= 10 and error > 2;
   gHC/kg > 10 and percent error > 20%

3) gNO/kg < -10
   gNO/kg <= 10 and error > 2
   gNO/kg > 10 and percent error > 20%

4) gNO_x/kg < -10
   gNO_x/kg <= 10 and error > 2
   gNO_x/kg > 10 and percent error > 20%

5) gNO_2/kg < -10
   gNO_2/kg invalid if either gNO/kg or gNO_x/kg values invalid

6) gPM/kg < -2
   gPM/kg <= 2 and error > 1
   gPM/kg > 2 and percent error > 50%

7) gBC/kg < -2
   gBC/kg <= 2 and error > 1
   gBC/kg > 2 and percent error > 50%

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>1mph and 14mph/s>accel>-13mph/s.

Appendix D – Explanation of the Databases.

The Cwood13.dbf and LAPort13.dbf are Microsoft FoxPro database files, and can be opened by any version of MS FoxPro. These files can 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.
Nox_co2	Measured nitrogen oxides / carbon dioxide ratio.
Nox_err	Standard error of the NO_x/CO_2 measurement.
Gpm_kg	Calibrated grams of particulate matter per kilogram of fuel.
Gpm_error	Standard error of the Gpm_kg measurement.
Gbc_kg	Calibrated grams of black carbon per kilogram of fuel.
Gbc_error	Standard error of the Gbc_kg measurement.
Co2_max	Delta CO_2 plume maximum observed in ppm.
Banr_flag	Indicates a single vehicle was measured. "V" = single, "X" = more than one.
Co_flag	Indicates a valid carbon monoxide measurement by a "V', invalid by an "X".
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".
Nox_flag	Indicates a valid nitrogen oxide measurement by a "V", Invalid by an "X".
Pm_flag	Indicates a valid total particulate measurement by a "V", Invalid by an "X".
Bc_flag	Indicates a valid black carbon measurement by a "V", Invalid by an "X".
File_name	File name for a CSV file containing the vehicles second by second data.
Speed1_flg	Indicates a valid speed measurement at the tent entrance by a "V", an invalid by an "X".
Speed1	Measured speed of the vehicle at the tent entrance, in mph.

Accel1	Measured acceleration of the vehicle at the tent entrance, in mph/s.
Speed2_flg	Indicates a valid speed measurement at the tent exit by a "V", an invalid by an "X".
Speed2	Measured speed of the vehicle at the tent exit, in mph.
Accel2	Measured acceleration of the vehicle at the tent exit, in mph/s.
Tag_name	File name for digital image file of the front of the vehicle measured.
Exh_temp	Estimated temperature in Celsius of the vehicles elevated exhaust pipe.
Scr_cap	Indicates the presence of an observable urea tank by a "Y".
Reefer_on	Indicates an observable refrigeration unit green light by a "Y". (only at Cottonwood)
Cattle	Indicates an observable cattle transport trailer by a "Y". (only at Cottonwood)
Gco_kg	Calibrated grams of carbon monoxide per kilogram of fuel.
Gco_error	Standard error of the Gco_kg measurement.
Ghc_kg	Calibrated grams of total hydrocarbons per kilogram of fuel.
Ghc_error	Standard error of the Ghc_kg measurement.
Gno_kg	Calibrated grams of nitric oxide per kilogram of fuel.
Gno_error	Standard error of the Gno_kg measurement.
Gno2_kg	Calibrated grams of nitrogen dioxide per kilogram of fuel.
Gnox_kg	Calibrated grams of nitrogen oxides per kilogram of fuel.
Gnox_error	Standard error of the Gnox_kg measurement.
Body_type	DMV designation of vehicle body type. (not all states provided this)
Year	Model year of the vehicles chassis.
Vin	Vehicle identification number.
Model	DMV designation of vehicle model.
Make	Manufacturer of the vehicle.
Fuel	DMV fuel type designation.
City	City where vehicle is registered. (not all states provided this)
Zipcode	Zipcode where vehicle is registered. (not all states provided this)
County	County code where vehicle is registered. (not all states provided this)
Gvw	Vehicle gross vehicle weight. (not all states provided this)

The Cwood15.dbf and LAPort15.dbf are Microsoft FoxPro database files, and can be opened by any version of MS FoxPro. These files can 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:

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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.
Nox_co2	Measured nitrogen oxides / carbon dioxide ratio.
Nox_err	Standard error of the NO_x/CO_2 measurement.
Gpm_kg	Calibrated grams of particulate matter per kilogram of fuel.
Gpm_error	Standard error of the Gpm_kg measurement.
Gbc_kg	Calibrated grams of black carbon per kilogram of fuel.
Gbc_error	Standard error of the Gbc_kg measurement.
Co2_max	Delta CO_2 plume maximum observed in ppm.
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No_flag	Indicates a valid nitric oxide measurement by a "V", invalid by an "X".
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Gco_kg	Calibrated grams of carbon monoxide per kilogram of fuel.
Gco_error	Standard error of the Gco_kg measurement.
Ghc_kg	Calibrated grams of total hydrocarbons per kilogram of fuel.
Ghc_error	Standard error of the Ghc_kg measurement.
Gno_kg	Calibrated grams of nitric oxide per kilogram of fuel.
Gno_error	Standard error of the Gno_kg measurement.
Gno2_kg	Calibrated grams of nitrogen dioxide per kilogram of fuel.
Gnox_kg	Calibrated grams of nitrogen oxides per kilogram of fuel.
Gnox_error	Standard error of the Gnox_kg measurement.
Num_co2	Calibrated particle number / carbon dioxide ratio.
Num_co2err	Standard error of the Num_co2 measurement.
Num_kg	Calibrated particle number per kilogram of fuel.
Num_kgerr	Standard error of the Num_kg measurement.
Num_flag	Indicates a valid particle number measurement by a "V', invalid by an "X".
Body_type	DMV designation of vehicle body type. (not all states provided this)
Year	Model year of the vehicles chassis.
Vin	Vehicle identification number.
Model	DMV designation of vehicle model.
Make	Manufacturer of the vehicle.
Fuel	DMV fuel type designation.
Body_style	DMV body style designation.
Body_model	DMV body model designation.
Engine_my	Engine model year from drayage registry (Port only).
Engine_mfg	Engine manufacturer from drayage registry (Port only).
Eng_model	Engine model from drayage registry (Port only).
City	City where vehicle is registered. (not all states provided this)
Zipcode	Zipcode where vehicle is registered. (not all states provided this)

County County code where vehicle is registered. (not all states provided this)

Exp_date Expiration date of registration (not all states provided this)

Gvw Vehicle gross vehicle weight. (not all states provided this)

Tru Refrigeration unit (Y or N). (Cottonwood only)

Tru_green Refrigeration unit activity light green (Y or N). (Cottonwood only)

Retro_stat Retrofit status from the TRUCRS database (Y/N/other NO_x retrofit status)

The Cwood17.dbf and LAPort17.dbf are Microsoft FoxPro database files, and can be opened by any version of MS FoxPro. These files can 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.
Nox_co2	Measured nitrogen oxides / carbon dioxide ratio.
Nox_err	Standard error of the NO_x/CO_2 measurement.
Gpm_kg	Calibrated grams of particulate matter per kilogram of fuel.
Gpm_error	Standard error of the Gpm_kg measurement.
Gbc_kg	Calibrated grams of black carbon per kilogram of fuel.
Gbc_error	Standard error of the Gbc_kg measurement.
Banr_flag	Indicates a single vehicle was measured. “V” = single, “X” = more than one.
Co_flag	Indicates a valid carbon monoxide measurement by a “V’, invalid by an “X”.
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”.
Nox_flag	Indicates a valid nitrogen oxide measurement by a “V”, Invalid by an “X”.
Pm_flag	Indicates a valid total particulate measurement by a “V”, Invalid by an “X”.
Bc_flag	Indicates a valid black carbon measurement by a “V”, Invalid by an “X”.
File_name	File name for a CSV file containing the vehicles second by second data.
Speed1_flg	Indicates a valid speed measurement at the tent entrance by a “V”, an invalid by an “X”.
Speed1	Measured speed of the vehicle at the tent entrance, in mph.

Accel1	Measured acceleration of the vehicle at the tent entrance, in mph/s.
Speed2_flg	Indicates a valid speed measurement at the tent exit by a “V”, an invalid by an “X”.
Speed2	Measured speed of the vehicle at the tent exit, in mph.
Accel2	Measured acceleration of the vehicle at the tent exit, in mph/s.
Tag_name	File name for digital image file of the front of the vehicle measured.
Exh_temp	Estimated temperature in Celsius of the vehicles elevated exhaust pipe.
Def_cap	Indicates the presence of an observable urea tank by a “Y”.
Gco_kg	Calibrated grams of carbon monoxide per kilogram of fuel.
Gco_error	Standard error of the Gco_kg measurement.
Ghc_kg	Calibrated grams of total hydrocarbons per kilogram of fuel.
Ghc_error	Standard error of the Ghc_kg measurement.
Gno_kg	Calibrated grams of nitric oxide per kilogram of fuel.
Gno_error	Standard error of the Gno_kg measurement.
Gno2_kg	Calibrated grams of nitrogen dioxide per kilogram of fuel.
Gnox_kg	Calibrated grams of nitrogen oxides per kilogram of fuel.
Gnox_error	Standard error of the Gnox_kg measurement.
Num_co2	Calibrated particle number / carbon dioxide ratio.
Num_co2err	Standard error of the Num_co2 measurement.
Num_kg	Calibrated particle number per kilogram of fuel.
Num_kgerr	Standard error of the Num_kg measurement.
Num_flag	Indicates a valid particle number measurement by a “V’, invalid by an “X”.
Body_type	DMV designation of vehicle body type. (not all states provided this)
Year	Model year of the vehicles chassis.
Vin	Vehicle identification number.
Model	DMV designation of vehicle model.
Make	Manufacturer of the vehicle.
Fuel	DMV fuel type designation.
Body_style	DMV body style designation.
Series	DMV model series designation.
Gvw	Vehicle gross vehicle weight category. (not all states provided this)
City	City where vehicle is registered. (not all states provided this)
Zipcode	Zipcode where vehicle is registered. (not all states provided this)
Vsp1	Entrance vehicle specific power calculated using equation from Jimenez.
Vsp2	Exit vehicle specific power calculated using equation from Jimenez.

Appendix E – Tests of OHMS Sampling System for Particle Losses

An in-lab study was performed to test for any significant particle losses caused by the materials and or arrangement of our emissions sampling pipe used to draw exhaust into the suite of instruments used in OHMS. The 50-foot long pipe was secured to the ceiling on the first floor of the University of Denver Chemistry building and sampling lines for the gaseous and particulate instruments mirrored the set-up used for field testing with OHMS.

Soot particles were generated using an oxygen starved propane torch and extinguishing the tip of the flame with a wire mesh for roughly five minutes and capturing the particles in a large plastic bag. A large diameter syringe was then used to extract particles from this bag; half of the syringe was filled with air from the particle bag and the rest was filled with CO_2. This establishes a fixed ratio of particles to CO_2 for each syringe. However, the mixing is inexact and the particle to CO_2 ratio did change from syringe to syringe. The syringe is large enough for multiple injections of the mock-exhaust at various positions along the pipe. Any changes in the particle to CO_2 ratio would indicate there are potential particle losses due to the sampling system.

Figure E1 shows the measured PM to CO_2 ratio from an individual syringe versus where the mock-exhaust was injected along the PVC pipe. “Long” indicates injections from the far end of the pipe, meaning the particles were required to travel the entire length of the pipe, injections coming from the middle of the PVC pipe are reported as “middle” and “short” is representative of injections from the close end of the pipe just prior to the 90° bend. While there are some issues for us to repeatedly inject a well-mixed sample, on average this analysis shows that there was no dependence on where the exhaust started in the sampling system. The ratio for injections inserted at the long end of the PVC pipe to injections from the short end of the pipe was 1.02, and the ratio for injections made from the long end to the middle of the PVC pipe was 0.97.

Figure E2 shows the results for the companion BC to CO_2 measurements. As with PM we see similar results, again showing that there was no significant dependence on where the first injection was along the pipe indicating no particle losses due to the sampling tube.

Figures E3 and E4 show PM and BC, respectively, for mock exhaust injected before and after the 90° elbow in the PVC pipe used in OHMS. We planned to have three injection for each trial, repeating the first injection a second time to reveal any changes that might occur in the syringe with time that are independent of the elbow. Trial 1 is comprised of only two injections, one of which was invalid for BC, but both had valid PM readings. Trials 2 and 3 consisted of the three injections, and all measurements were valid. Trial 3 in Figure E3 has PM/CO_2 ratios that increased with time indicating a loss of particles in the syringe for some reason but that are not consistent with the elbow causing particle losses. This is because the final injection below the elbow showed additional particle losses which could not be the result of the fan. These experiments again suggest that there are no large particle losses due to the pipe elbow in the OHMS sampling line.

An experiment was conducted to determine whether or not there was particle loss due to the fan in the OHMS setup. The inlet for the particle instruments was moved to sample before (triangles) and after (diamonds) the fan. Separate injections of mock exhaust were used for each trial, and

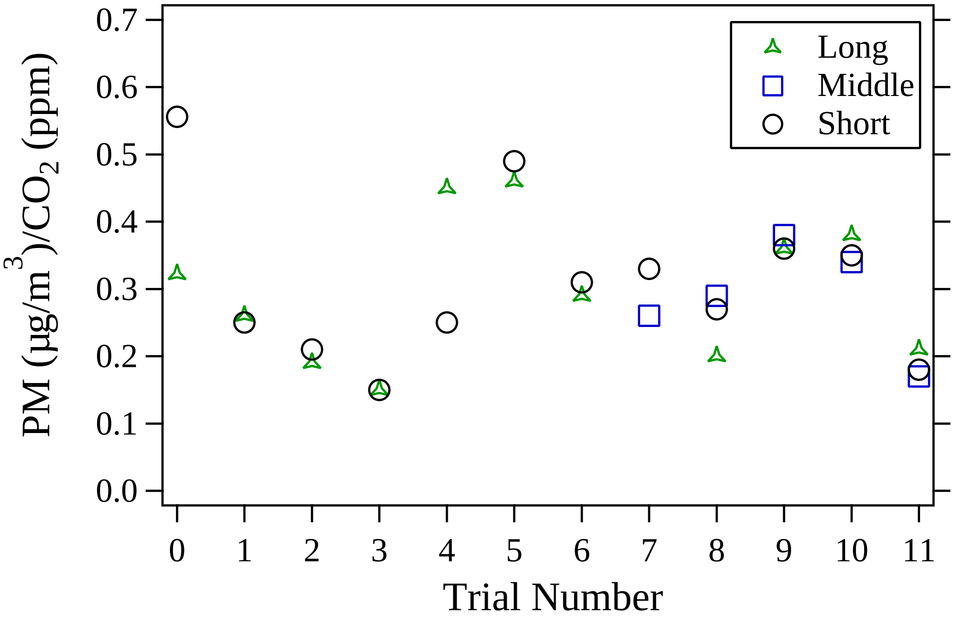

Figure E1. PM to CO_2 ratio shown for mock exhaust inserted at the long (green triangles), middle (blue squares) and short (black circles) end of the PVC pipe. Each trial is one syringe of mock exhausted divided between the number of positions.

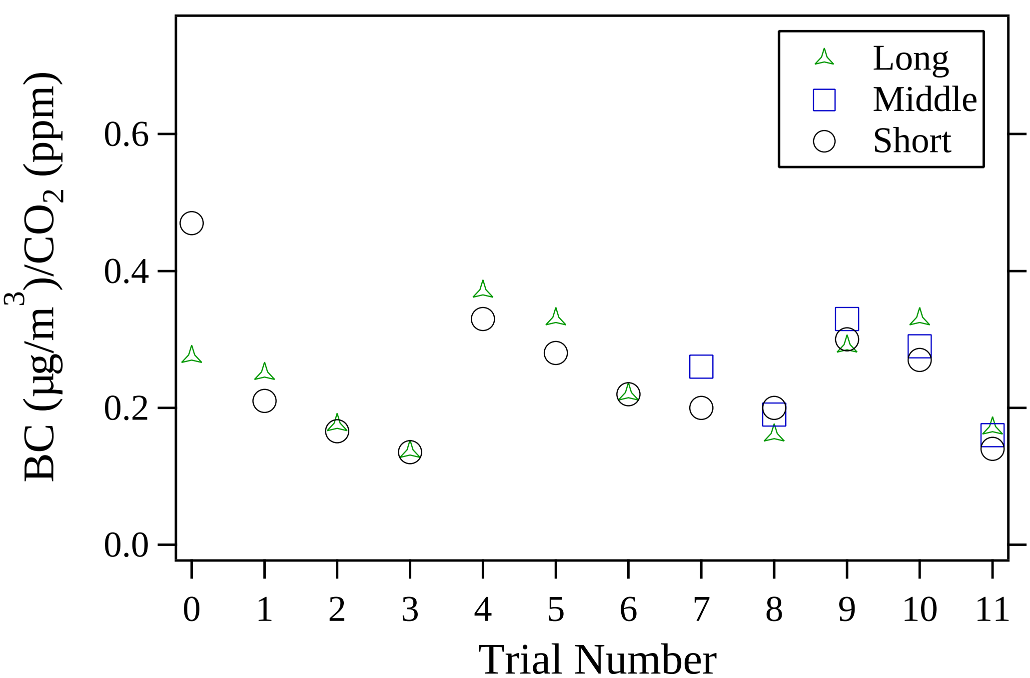

Figure E2. BC to CO_2 ratio shown for mock exhaust inserted at the long (green triangles), middle (blue squares) and short (black circles) end of the PVC pipe. Each trial is one syringe of mock exhausted divided between the number of positions.

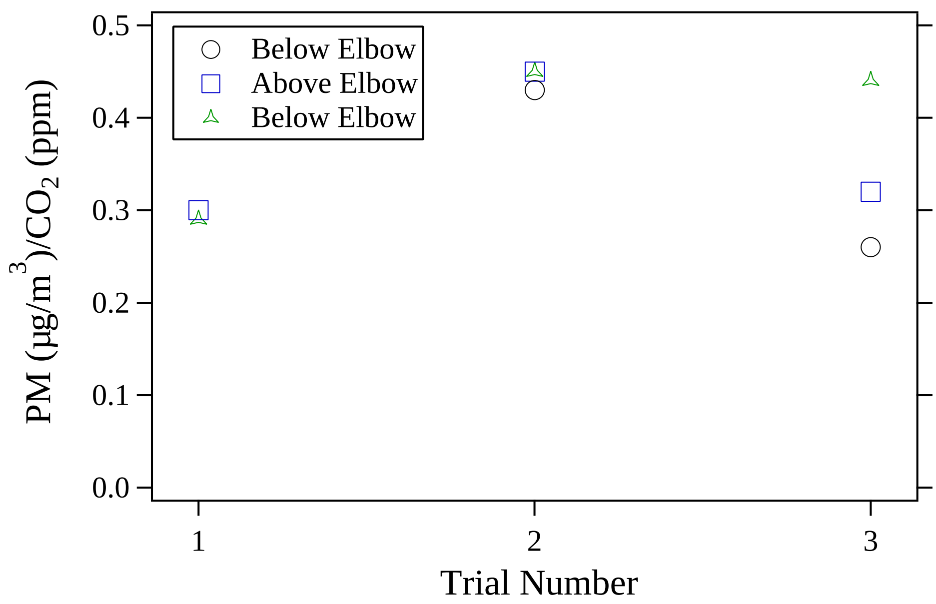

Figure E3. PM to CO_2 measured ratio for mock exhaust injected below and above the 90° elbow in the OHMS set-up. The first injection is below the elbow (circles), the second injection is above the elbow (squares) and we repeat the injection below the elbow (triangles) to empty the syringe. Each trial is one syringe of mock exhausted divided between all the positions. Trial 1 is comprised of only two injections, whereas trials 2 and 3 each have 3 injections.

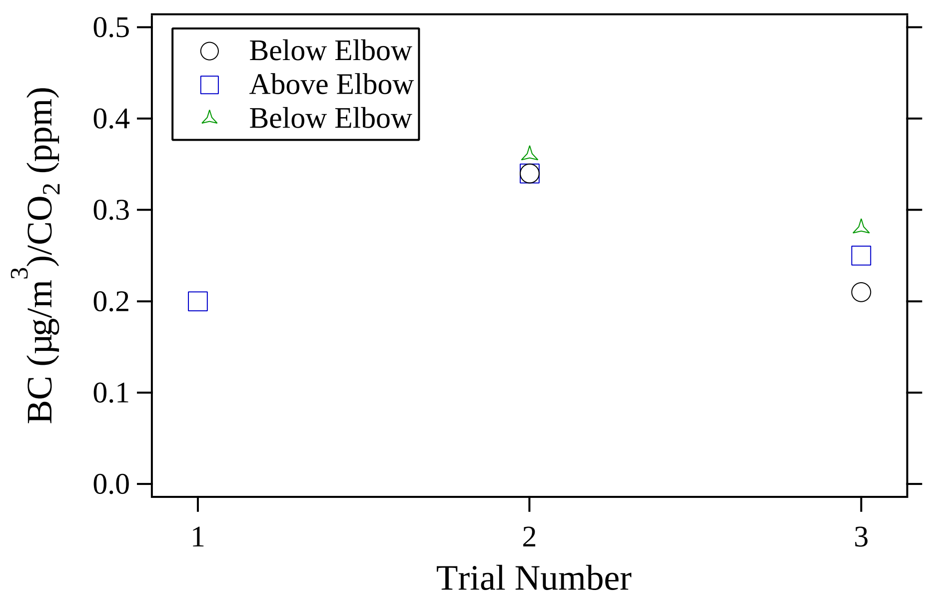

Figure E4. BC to CO_2 measured ratio for mock exhaust injected below and above the 90° elbow in the OHMS set-up. The first injection is below the elbow (circles), the second injection is above the elbow (squares) and we repeat the injection below the elbow (triangles) to empty the syringe. Each trial is one syringe of mock exhausted divided between all the positions. Trial 1 is comprised of only two injections, one of which was invalid for BC, and trial 2 and 3 each have 3 injections.

with each extraction from the garbage bag of particles, the concentration within the bag was diluted. This explains why the concentration decreases for sequential trials, regardless of where the sample was introduced into the sampling line. The total particle mass and particle number was determined for each injected by integrating the area under the respective peaks from the Dekati Mass Monitor to give micrograms of particle mass per cubic centimeter and particle number per cubic centimeter. As shown in Figure E5 and E6, aside from particle depletion from the artificial exhaust source, the placement of the inlet in relation to the OHMS fan also does not appear to influence the PM and PN measured. Again these experiments show that there are not any large sources of soot particle losses in our emissions sampling plumbing in OHMS.

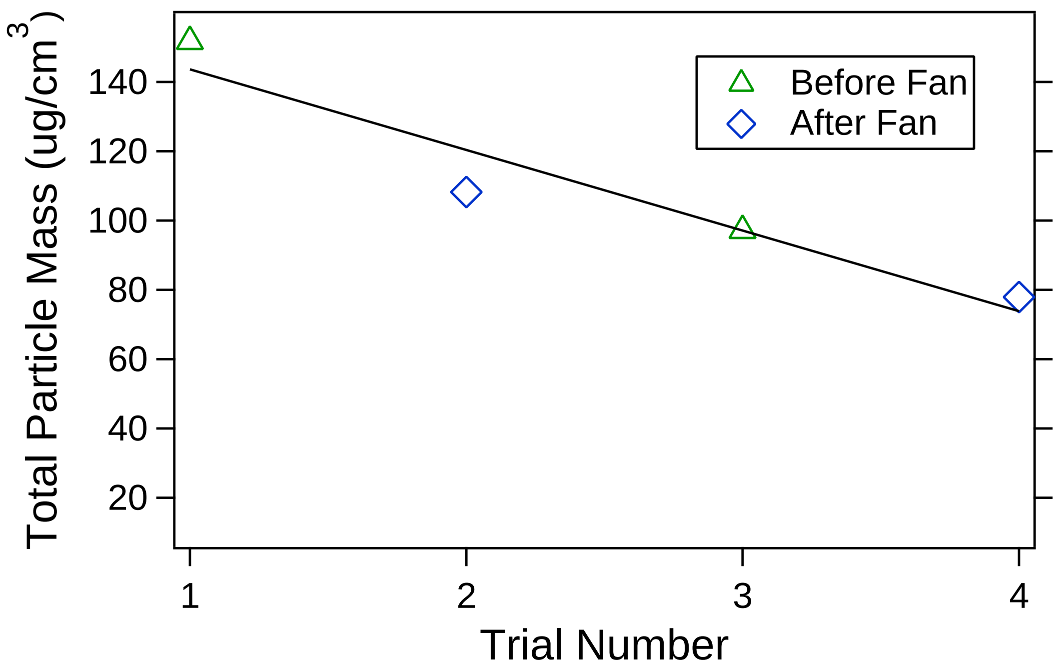

Figure E5. Total particle mass concentration for samples collected before the exhaust fan (triangles) and after the fan (diamonds). Each trial is a separate syringe injection.

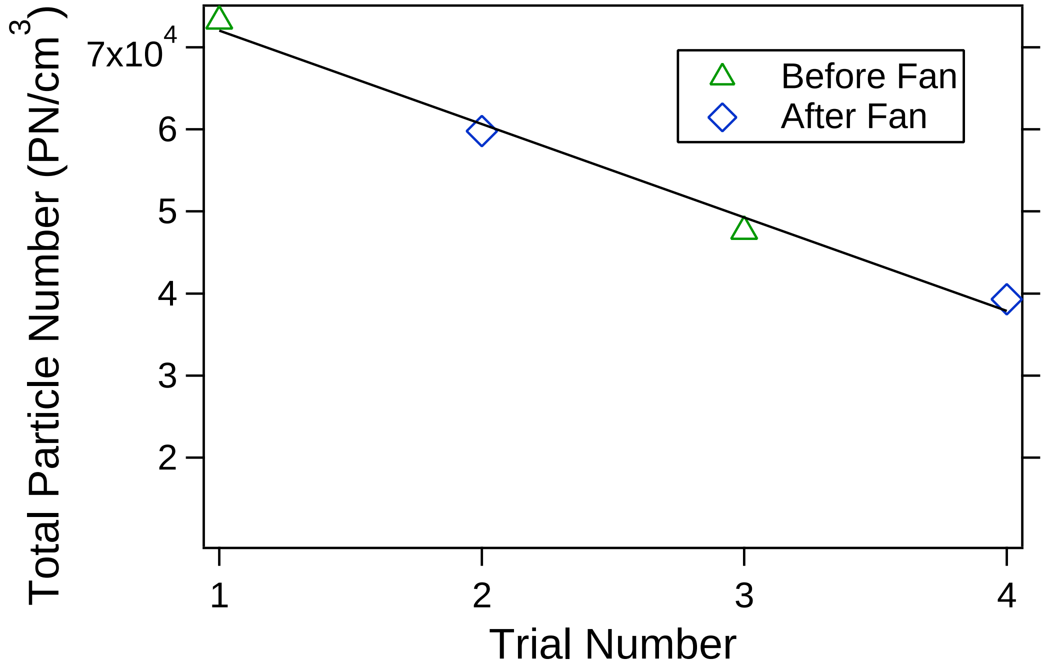

Figure E6. Total particle number concentration for sample intake before the fan (triangles) and after the fan (diamonds). Each trial is a separate syringe injection.

Appendix F – Images of 2015 High Emitter and the 2017 Repeat Image

One of the plate images of the highest emitter at the Port in 2015.

This truck below has the same license plate as the truck above. While the make and model of these two trucks appears to be identical, the location of the license plate has change (the 2017 picture has the plate centered in the bumper) and the decal on the bumper (TLKN0031 in 2015) is missing the number in the 2017 picture and it is not in the same place. The Clean Truck program at the Port has this license plate registered in 2015 and 2016 but it was not registered for 2017 as of October.