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Repeat Fuel Specific Emission Measurements on Two California Heavy-duty Truck Fleets

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Abstract

The University of Denver repeated its 2013 fuel specific gaseous and particle emission measurements on two California heavy-duty vehicle fleets. In 2015 1,457 measurements at the Port of Los Angeles and 694 measurements at the Cottonwood weigh station in northern California were collected. The Port fleet changed little since 2013, increasing the average age (+1.8 years), accompanied by an increase in particle mass (PM) by +266% (0.03 ± 0.01 to 0.11 ± 0.01 gPM/kg of fuel) and black carbon (BC) by +300% (0.02 ± 0.003 to 0.08 ± 0.01 gBC/kg of fuel). Particle number (PN) also increased ($1.5 \times 10^{14} \pm 2.5 \times 10^{13}$ to $2.8 \times 10^{14} \pm 2.8 \times 10^{13}$ PN/kg of fuel) by a smaller percentage (+87%). 2008 and 2009 chassis model year vehicles currently dominate the fleet, accounting for the majority of these increases. The long-haul Cottonwood fleet decreased in fleet age (-0.6 model years), where half the decreases in fuel specific PM (-66%), BC (-65%) and PN (-19%) emissions are due to the newer fleet; an increased fraction of pre-2008 chassis model year vehicles with retrofit diesel particulate filters (DPFs) account for the remaining reductions. These opposing emissions trends emphasize the importance of fully functional DPFs.

Introduction

Traditional heavy-duty diesel vehicle exhaust has been associated with a variety of health problems including lung damage, respiratory diseases, premature death, and has been designated as a carcinogen.¹⁻⁴ Along with negative health implications, oxides of nitrogen ($\text{NO}_x = \text{NO} + \text{NO}_2$), found in diesel exhaust, also contribute to ozone formation and secondary PM, while black carbon (BC) emissions are an important climate forcing agent.⁵⁻⁷ Health risks and environmental deterioration associated with diesel exhaust constituents raised concern from the Environmental Protection Agency, thus amendments were made to the Clean Air Act in 1990 to reduce 6 “criteria pollutant” emissions including PM and NO_x from diesel vehicles.⁸ More recently, Federal and State of California regulations have been enacted for 2007 and newer engines that have further reduced heavy-duty vehicle (HDV) PM (0.1 g/bhp-hr to 0.01 g/bhp-hr) and NO_x (2 g/bhp-hr to 0.2 g/bhp-hr) emissions necessitating the development of new exhaust after-treatment systems.⁹⁻¹¹

The PM reduction regulations began with the 2007 year engines. Diesel particulate filters (DPFs) were utilized exclusively for meeting the lower PM standards and work by physically capturing particles emitted by the engine. DPFs have proved so successful that a recent lifetime animal study found no evidence of carcinogenic lung tumors from exposure to new technology diesel exhaust.¹² Regulations allowed a phase-in of the more stringent NO_x standards until 2010 year engines enabling most 2007 to 2009 year engines to be designed with NO_x emissions between 2 and 0.2 g/bhp-hr. These engines typically have higher engine out PM emissions to suppress NO_x and rely on the DPF to limit tailpipe PM emissions.¹³ Selective catalytic reduction (SCR) systems reduce NO_x emitted from vehicles by reducing it to nitrogen with ammonia generated by thermalizing a urea solution and are generally needed to meet the 0.2 g/bhp-hr NO_x standard. Engines meeting the 2010 standard are generally engineered to suppress engine out PM

emissions, increase fuel economy and rely on the SCR to control higher engine out NO_x emissions.¹⁴

Because the life of a HDV can be as long as 30 years, the State of California, and the Ports of Long Beach and Los Angeles, instituted rules requiring accelerated retirement for pre-2007 HDV engines. The San Pedro Bay Ports Clean Air Action Plan required all HDV entering the Los Angeles and Long Beach ports after January 1, 2012 to meet the 2007 Federal PM emission's standard.^{15, 16} The State of California's Air Resources Board adopted the Truck and Bus rule, which required 1996 and newer federally or privately owned trucks and buses with a gross vehicle weight rating greater than 14,000 pounds to be equipped with DPFs as of January 1, 2014. All pre-1996 models were required to upgrade to a 2010 engine by January 1, 2016, and will be mandatory for all HDV as of 2023.¹⁰ California expects the adoption of these rules to result in an 85% reduction in 2000 PM emission levels by 2020.² Early research results have been promising showing significant reductions in PM and NO_x emissions.^{10, 17-20} For reductions to be truly meaningful, they must persist over the useful life of the HDV. The work described in this paper is concerned with this aspect and is focused on revealing emission changes that may take place as the new HDV technology ages for vehicles that are subject to similar driving patterns.

Experimental

The University of Denver has established two locations in California and have collected repeat measurements of HDV emissions with the On-Road Heavy-Duty Measurement System (OHMS) in 2013 and 2015, with the 2013 data previously reported.²¹ One site is at the Port of Los Angeles with measurements collected at the exit from TRAPAC Inc. container operations, however, the physical location changed in 2015 due to reconstruction of TRAPAC's exit. Both 2013 and 2015 Port sites were located at the exits on a flat roadway, (0° grade) and HDVs were

generally required to stop before the exit, which encouraged acceleration through the tent. The second site is at the Cottonwood weigh station, an inland site in northern California on I-5 south of Redding, CA. Both 2013 and 2015 measurements were collected at the same location within the weigh station on a slight decent (-0.5° grade). These two sites complement one another with measurements at the Port focusing on short-haul drayage operations and the HDVs at the weigh station dominated by long-haul activities.

OHMS measures fuel specific emissions from the exhaust of HDVs with elevated exhaust stacks using a 15.2 m long and 4.6 m high tent for the purpose of containing the vehicle's exhaust (see supporting information, Figure S1). This innovative setup integrates the diluted (~ 1000 fold dilution) exhaust from a HDV as it drives through the tent via a ceiling mounted perforated pipe. The exhaust is drawn through the pipe with an end-mounted exhaust fan that allows the plume to be sampled by various analyzers. A mobile lab houses the analyzers near the exit of the tent set-up. In general OHMS does not measure HDVs with ground level exhaust, however, at the Port some of the liquefied natural gas (LNG) vehicles are measured as their high exhaust temperatures lift the plume quickly enough enabling the pipe to capture some of their exhaust emissions.

A detailed description of the instruments used to analyze the emissions has been previously published.²¹ Briefly, OHMS collects data using a Horiba AIA-240 non-dispersive IR analyzer for carbon dioxide (CO_2) and carbon monoxide (CO). One Horiba FCA-240 instrument collects data on total hydrocarbons (HC) using a flame ionization detector, and ozone chemiluminescence to detect NO, and a second Horiba FCA-240 measures total NO_x by ozone chemiluminescence and NO_2 by difference ($\text{NO}_x - \text{NO}$) between the two. The instruments receive the exhaust gases through a twin piston diaphragm pump (KNF Neuberger, Inc. UN035.1.2ANP, 55 l/min) with a ¼ inch Teflon tubing and a water condensation trap. PM and

particle number concentrations ([PN]) are measured via a Dekati Mass Monitor (DMM-230A, 0-1.2 μ m). A Droplet Measurement Technologies Photoacoustic Extinctionmeter (PAX 0-1 μ m) is used to measure BC mass via absorption at 870 nm using a photoacoustic technique. The particle instruments have individual internal sampling pumps that sample exhaust through separate 1/4 inch copper lines. New to the campaign in 2015, a Fast Mobility Particle Sizer-3091 (FMPS, TSI Inc.) was used to measure particles size distributions between 5.6 and 560nm.

The CO₂ analyzer's maximum span adjustment is set at each site using a certified mixture of 3.5% CO₂ in nitrogen (Air Liquide). The remaining analyzers were calibrated in the field at the beginning and end of each day with multiple injections of Bar-97 certified low-range calibration gas (0.5% CO, 6% CO₂, 200 ppm propane, and 300 ppm NO in nitrogen) into the sampling pipe upstream of the exhaust fan. All measured ratios (CO, HC, NO and NO_x to CO₂) are averaged and divided by the certified ratios to give a scaling factor (0.79 (CO), 2.92 (HC), 0.89 (NO) and 0.91 (NO_x)) that were applied to each HDV measurement. The DMM-230A was factory calibrated by Dekati and the PAX was calibrated according to the manufacturer's procedure in the lab prior to the field measurements. The DMM-230A and the PAX are zero corrected daily as needed.

When a HDV exits the tent, an IR body sensor prompts the start of 15 seconds of data collection at 1Hz for all analyzers. To ensure only one HDV comprised each emission record all CO₂ plumes were graphically post processed and visually inspected. Any multiple plume measurements were excluded from the results. Speed bars record the speed and acceleration at the entrance and exit of the tent, and three cameras take time dependent images as the vehicle passes (see supporting information, Figure S1). One camera in front of the HDV captures the license plate of the vehicle, which is used to retrieve state motor vehicle information such as make, model year, fuel, vehicle identification number (VIN), etc. Vehicle registration

information was acquired from the license plates of California, Oregon and Washington State HDVs. HDVs measured at the Port from additional states (CO, GA, IL, NJ, OH, TX and UT) were acquired using California's Drayage Truck Registry. HDV emission standards are enforced based on the year in which the engine is manufactured. The only information accessible through vehicle registrations is the year the chassis is manufactured. All of the model year data reported here in is for chassis model years and we assume that the engine was built in the prior year. The HDV external exhaust pipe temperature was estimated using an IR camera (FLIR A320) that attempts to image the bottom of elevated exhaust pipes to estimate operating temperatures. Interpretation of the IR camera images utilized a new field emissivity calibration, which significantly lowered the estimated exhaust pipe temperatures previously reported (see supporting information, Figures S2-S5). The final camera captures the driver side of the HDV to locate diesel emission fluid tanks, which are often distinguished by a blue cap, and if visible signifies the vehicle is equipped with an SCR.

All emissions are expressed as a ratio to CO₂ and converted into fuel-specific emissions to give grams of emissions per kg of fuel burned (g/kg of fuel) using the molecular weight of each species and the carbon mass fraction in the fuel. Carbon mass fractions of 0.86 and 0.75 were used for the diesel and LNG fueled vehicles respectively. Fuel specific particle number data is reported for the first time for the previous 2013 measurements and this campaign. [PN] data is collected concurrently with particle mass by the Dekati DMM-230A analyzer but only stored internally requiring the measurements to be post processed. The [PN] data were time-aligned with the gas analyzer data using high emitters as reference points, and the slope of the [PN] and CO₂ data for each HDV was calculated using a linear least squares fit and converted to PN per kg of fuel burned (see supporting information, Table S1). To calculate particle size distributions for

fuel specific PN emissions using the FMPS data, the calculation described in Table S1 was repeated for each FMPS particle size bin.

Results and Discussion

In 2015 fuel specific emission measurements were collected with OHMS at the Port of Los Angeles over five days (March 23-27) and over three days (April 8-10) at Cottonwood. The fewer days at Cottonwood was due to high winds, which prohibited tent set up. This resulted in emission data sets and vehicle information from the Port of Los Angeles of 1,457 measurements and 694 measurements from the Cottonwood weigh station. The mean emissions, with standard errors of the means (SEM) calculated from the daily averages (see supporting information), mean model year, mean exhaust pipe temperature (°C), speeds and accelerations for the 2015 data are in Table 1. The diesel and LNG vehicles measured at the Port have been listed separately in Table 1 for reference but all analyses presented use the entire Port fleet. Table 1 also includes the PN/kg of fuel measurements that were calculated from the 2013 data sets from these two locations that were not previously reported. Exit acceleration at the Port of Los Angeles has been omitted due to an equipment problem.

Emissions Trends

Fuel specific PM, BC and PN trends are shown in Figure 1 for the Port of Los Angeles and the Cottonwood weigh station for the 2013 (blue, left most bars) and 2015 (green, right most bars) measurement years. Fleet PM (solid bars) and BC (hatched bars) data is graphed against the left axis and fleet PN (open bars) means are plotted against the right axis. Uncertainties plotted are SEM calculations from the daily means. Between 2013 and 2015 the fleet age increased at the Port, (mean model year of 2009.1 to 2009.3, 1.8 years older in 2015) which is a major contributor to the increase in mean PM (+266%), BC (+300%) and PN (+87%) emissions.

Table 1. Summary of the Port of Los Angeles and Cottonwood 2015 measurements. Dates, Number of HDV measured, Mean Chassis Model Years, Mean Fuel Specific Emissions (2013 PN data included), Speeds and Accelerations, IR Exhaust Temperatures and Standard Errors of the Mean.

Location Date Roadway slope	HDV Mean MY	gCO/kg	gHC/kg	gNO ^a /kg gNO ₂ /kg gNO _x ^b /kg	gPM/kg	gBC/kg	2015 PN/kg (2013 PN/kg)	Entrance/Exit Speed ^c Acceleration ^d	IR Exhaust Temp (°C)
Port of LA Diesel	1393 2009.2	1.6±0.4	0.8±0.3	13.2±0.5 2.5±1.1 22.2±2.0	0.11±0.01	0.08±0.01	2.9 x 10 ¹⁴ ±2.9 x 10 ¹³	11.2/12.5 0.3/N.A.	88 ± 2
Port of LA LNG	63 2010.1	30.6±2.7	11.5±3.3	3.8±1.2 0.2±0.2 5.3±2.2	0.005±0.001	0.002±0.004	1.7 x 10 ¹³ ±1.6 x 10 ¹³	11.8/13.1 0.5/N.A.	N.A. ^e
Port of LA March 23-27 0°	1456 2009.3	3.0±0.4	1.2±0.4	12.8±0.5 2.3±1.0 21.6±2.1	0.11±0.01	0.08±0.01	2.8 x 10 ¹⁴ ±2.8 x 10 ¹³ (1.5 x 10 ¹⁴ ±2.5 x 10 ¹³)	11.2/12.5 0.3/N.A.	91 ± 2
Cottonwood April 8-10 -0.5°	694 2008.1	3.0±0.2	0.63±0.07	11.9±0.2 4.1±0.5 22.1±0.7	0.22±0.04	0.08±0.002	1.7 x 10 ¹⁵ ±1.4 x 10 ¹³ (2.1 x 10 ¹⁵ ±6.0 x 10 ¹³)	14.4/14.5 0.6/0.5	105 ± 1

^a Grams of NO ^b Grams of NO₂ ^c Kilometers per hour ^d Kilometers per hour/sec ^e LNG exhaust pipe temperatures exceed IR calibration

Figure 1. Mean gPM/kg of fuel (solid bars, left axis) and mean gBC/kg of fuel (hatched bars, left-axis) and mean PN/kg of fuel (open bars, right-axis) at the Port of Los Angeles and Cottonwood locations. Both 2013 (blue, left most bars) and 2015 (green, right most bars) data are shown. The uncertainties are standard errors of the mean calculated from the daily means.

The Cottonwood fleet, which is getting newer, (mean model year of 2005.6 to 2008.1, 0.6 years newer in 2015) saw mean emissions decrease, -66%, -65%, -19% respectively.

Beginning in 2009 and culminating by the beginning of 2010 all HDVs without DPFs serving the Ports of Los Angeles and Long Beach were forced to retire in accordance with the San Pedro Bay Ports Clean Air Action Plan. This resulted in a large percentage of the Ports fleet (88% of these measurements) being composed of 2008 - 2010 chassis model year vehicles purchased to comply with the regulations. Large initial reductions occurred with the installation of DPFs^{22,23}, but our newest measurements from the Port of Los Angeles show an overall increase in fuel specific particle emissions as these HDVs have aged, though these increases are still small relative to the initial reductions.

Figure 2 shows mean gPM/kg of fuel versus chassis model year at the Port of Los

Figure 2. Mean gPM/kg of fuel at the Port of Los Angeles versus chassis model year for the data collected in 2013 (diamonds) and 2015 (circles). The uncertainties plotted are standard errors of the mean calculated from the daily means.

Angeles for the 2013 (diamonds) and 2015 (circles) measurements for model years with at least 20 measurements. The uncertainties plotted are SEM calculated from the daily means. The increases in overall mean gPM/kg of fuel are concentrated in the oldest model years and are statistically significant at the 95% confidence interval for 2008 – 2010 model years with no significant changes in 2011 and newer models. The large increase in 2009 model year emissions is heavily influenced by a single vehicle, to be discussed in detail later, which was measured 6 times over the five day period. If this vehicle were removed, the mean for 2009 model HDVs would lower from 0.18 to 0.07 gPM/kg of fuel. Fuel specific BC and PN (see supporting information, Figure S6) show a similar pattern with increases for the older model year vehicles.

The box and whisker plot in Figure 3 shows the 2013 and 2015 gPM/kg of fuel emissions for chassis model years 2008 – 2014 measured at the Port. The box denotes the 25th and 75th

Figure 3. Box and whisker plot of gPM/kg of fuel versus chassis model year for the 2013 (left, diamonds) and 2015 (right, circles) emission measurements from the Port of Los Angeles. The box encloses the 25th to the 75th percentile and the median is represented by the horizontal line within the box. The whiskers extend from the 10th to the 90th percentile. The black squares denote the mean and the individual points are HDV measurements beyond the 10th and 90th percentiles.

percentiles for each model year and medians are represented by a horizontal line within the box. The whiskers show the 10th and 90th percentiles with measurements outside the whiskers symbolized as diamonds (2013) and circles (2015). The mean for each model year is represented by a filled square. Negative values in the dataset reflect the uncertainties in determining the zero slope emissions, and as such also indicate an equal uncertainty in the positive direction and if omitted would bias the means high. For the two oldest model years in Figure 3 there is an obvious expansion of the interquartile range and an increase in the number of measurements beyond the 2013 90th percentiles. The increased means are a result of a more skewed emissions distribution. This is not due to an overall deterioration in filter efficiency for every HDV, but an increase in the number of vehicles, originally equipped with DPFs, that have unexplained high

particle emissions. In 2013 the highest emitting 1% of the fleet was responsible for 25% of the total gPM/kg of fuel which has increased to 53% in the 2015 data set. 2010 model year emissions show a smaller increase in mean emissions, again as a result of more measurements at higher emission levels. 2011 and newer chassis model years show few, if any, changes over the two year period though they makeup only 11% of the measurements in both years. The observed increases shown here are consistent with previously reported measurements at the Port of Oakland.¹⁸

In contrast, fleet turnover at Cottonwood has resulted in a younger fleet, (0.6 years newer) responsible for approximately half of the observed reductions in fuel specific PM and BC emissions since 2013, though it did not have a significant influence on the fuel specific PN emissions. The 2015 measurements had 25% more HDVs chassis model year 2008 and newer. Cottonwood gBC/kg of fuel emissions versus chassis model year for the 2013 (diamonds) and 2015 (circles) measurements are shown in Figure 4 with each model year grouping shown having at least 10 measurements. The uncertainties plotted are the SEM calculated from the daily means. 2008 and newer model year vehicles show the characteristic drop in BC emissions due to the addition of DPFs, with little change between the two measurement years for the newer models. At Cottonwood interstate truck traffic results in few reoccurring HDV measurements (36 out of 619 unique HDVs). High emitting 2009 model year vehicles observed in 2013 resulting in fuel specific BC and PM mean emissions that are higher than the 2015 mean measurements were not repeated. A similar pattern was observed for fuel specific PM emissions (see supporting information, Figure S7). A decrease in PM and BC at Cottonwood for older HDVs suggests that some vehicles in 2015 have been retrofit with DPFs in accordance with the State's Truck and Bus rule.

Figure 4. Mean gBC/kg of fuel versus chassis model year at Cottonwood for 2013 (diamonds) and 2015 (circles) measurements. The uncertainties plotted are the standard errors of the mean calculated using the daily means.

The State of California has a Truck and Bus Rule Reporting System that records retrofit activity based on information provided by the owner. This system provided information on 109 out of the 142 pre-2008 chassis model year HDVs from California, 24 of which had reported installing retrofit DPFs.²⁴ The mean and SEM for fuel specific PM and BC emissions of those 24 HDVs were 0.06 ± 0.07 and 0.03 ± 0.04 respectively and are comparable to newer DPF-equipped HDV emission levels. The remaining 85 non-retrofit HDVs had mean fuel specific PM and BC emissions of 0.66 ± 0.16 and 0.21 ± 0.001 respectively, which are an order of magnitude larger. Two of the 24 HDVs reported as having a retrofit DPF had PM and BC emissions at pre-DPF levels (0.84 and 0.81 gPM/kg of fuel and 0.45 and 0.35 gBC/kg of fuel) indicating either the time of the installation was misreported, the DPF has failed or has been uninstalled. The

increase in the fraction of pre-2008 HDVs equipped with DPFs in the 2015 Cottonwood fleet accounts for the additional PM emission reductions seen since 2013.

The fuel specific particle emissions from these two locations are significantly lower than similar measurements collected at the Port of Oakland in 2011 and 2013.¹⁸ Directly comparable gBC/kg of fuel emissions from the Port of Los Angeles show similar emission trends by model year with the Port of Oakland data but the OHMS means are exactly an order of magnitude lower. It is important to note that there are a number of differences between these two studies, different BC instrumentation (photoacoustic versus aethalometer), OHMS integrates emissions over 15.2 meters and the Oakland study measures emissions from a single inlet suspended off a bridge, different fleets and the data from the Oakland study was collected at higher operating speeds. However, despite the differences in method and vehicle operating modes, fuel specific NO_x emissions in the two studies are similar.

One possible explanation that has been explored is whether particle loss occurs in the OHMS sampling system, which would lead to underreporting of emissions and be consistent with the direction of the difference. Repeatability experiments were conducted in the lab using the OHMS sampling system, testing for particle losses in the sampling line, before and after the 90° bend, and before and after the exhaust fan. Through these experiments we have been unable to find any significant particle losses in our sampling of PM or BC that could explain the differences (see the supporting information, Figures S8-S13).

The Federal particle standard for HDVs is 0.01g/bhp-hr which translates to approximately 0.07gPM/kg of fuel assuming average fuel consumption at our sites is 0.15kg of fuel/bhp-hr.²¹ In the 2015 measurements for 2008 and newer chassis model years 19% of the measurements at the Port and 17% of the measurements at Cottonwood exceed 0.07 gPM/kg of fuel, indicating that a large majority of the HDVs have PM emissions lower than the certification

standard. In the literature, May et al. reported chassis dynamometer results for a 2010 and 2007 HDV with gPM/kg of fuel of 0.007 ± 0.004 and 0.15 ± 0.14 respectively.^{25, 26} Johnson et al. reported on-road PM measurement results for a 2008 ProStar and Volvo HDV. The ProStar never exceeded 0.01g/bhp-hr while the Volvo's PM emissions ranged as high as 0.04 (0.26 gPM/kg of fuel) but with average emissions well below 0.01g/bhp-hr.²⁶ Quiros et al. have also recently reported on-road measurements on seven additional HDVs that were all below the PM certification level.²⁷ The literature values, though few, are more consistent with the mean values reported here.

The mean emission trends at both sites for CO, HC, NO, NO₂ and NO_x are shown in the supporting information (Figure S14). There were no statistically significant changes in emissions of CO, NO, NO₂ and NO_x at the Port during the intervening two years, however, there was a statistically significant increase in mean HC emissions (152%). This is the result of methane emissions from an increase in the number of liquefied natural gas trucks sampled during 2015 at the Port (see Table 1).¹⁷ These vehicles also increase the fleet gCO/kg of fuel means. At Cottonwood, decreasing CO emissions for the overall fleet average corresponds to the reduction in PM emissions from older trucks. While mean fleet NO_x emissions did not increase significantly, there was an increase for the newer chassis model years, (see supporting information, Figure S14) that is currently unexplained.

High Emitters

We have previously used a standard for high emitting HDVs as ~0.21 gPM/kg of fuel, which is approximately 3 times the equivalent Federal PM Certification limit of 0.07gPM/kg of fuel.²¹ The Port fleet saw increases in the number of HDVs over 0.21 gPM/kg of fuel from 4% in 2013 to over 8% in 2015, contributing to the emission increases shown in Figures 2 and 3. Percentile-percentile plots comparing the two years' emissions distributions for fuel specific PM

and BC emissions at the Port of Los Angeles (see supporting information, Figures S15a and b) show the 2015 emission distributions deviate from the 1:1 line beginning at the 53rd and 35th percentiles respectively. The percentage of HDVs over 0.21 gPM/kg of fuel at Cottonwood decreased from 49% in 2013 to 23% in 2015 as a result of fleet-turnover and retro-fit activities. Percentile-percentile plots (Figures S16a and b) show the large negative percentile changes at Cottonwood for PM and BC fuel specific emissions.

With the observed increases in fuel specific PM and BC emissions at the Port, particularly in the oldest model years, there is also an increase in the variability of the repeat measurements, both within the 2015 measurements and reoccurring trucks measured in both years. In general the emission's variability increases with increasing mean emissions (see supporting information, Figure S17), a pattern that has been previously observed for gaseous emissions from light-duty vehicles.²⁸

One 2009 vehicle at the Port of Los Angeles was measured six times during the 2015 campaign and exhibits an apparent time dependence in its particle emissions. Table 2 summarizes the six emission measurements collected over the course of 4 days in chronological order with measurements made before noon (AM, highlighted) differentiated from those collected after noon (PM). Exit accelerations were invalid for all measurements due to an equipment problem; all other measurements that exceeded confidence limits are denoted by a dash in Table 2. Noticeably the DPF in this HDV is not in perfect working order, as most of the gPM/kg of fuel emissions are significantly higher than the average for any model year at the Port and often resembles pre-DPF HDV emission levels.²¹ However, the two morning measurements on March 26th and 27th (2.0 and 0.14 gPM/kg of fuel) were much lower and the measurement on the morning of the 27th is close to the Port's fleet mean of 0.11 ± 0.01 .

Table 2. 2015 measurement summary for a 2009 model year repeat HDV at the Port of Los Angeles showing the Date, Before or After noon, Fuel Specific Emissions, Speed and Acceleration, IR Exhaust temperatures (°C), Roadside Opacity Percentage and Pass or Fail of the Roadside Test.

Date/AM/PM	gCO/kg	gNO _x /kg	gPM/kg	gBC/kg	gPN/kg	Entrance/Exit		Exh. Temp (°C)	Roadside Test % Opacity (P/F)
						Speed ^a	Accel ^b		
3/23/2015 / PM	-	2.1	21.3	19.2	2.7 E+16	14.2 / 18.2	1.2 / -	90	-
3/24/2015 / PM	220	-	13.4	9.4	1.5E+16	13.8/ 15.8	1.2 / -	70	-
3/26/2015 / AM	-	2.4	2.0	0.9	6.0E+15	- / 12.8	- / -	80	-
3/26/2015 / PM	324	1.5	18.7	14.6	2.0E+16	12 / 14.1	1.2 / -	65	95.5% (F)
3/27/2015 / AM	0	30.0	0.1	0.1	4.0E+14	14.6 / -	1.6 / -	95	10.8% (P)
3/27/2015 / PM	-	24.6	12.3	7.2	7.6E+15	14.4 / 15.2	1.2 / -	130	-

^akilometers per hour ^bkilometers per hour/sec

Concurrent with OHMS measurements the State of California conducted random roadside opacity inspections using a snap-acceleration test which reports an average tailpipe opacity reading for three rapid acceleration events.^{29, 30} The 2009 HDV discussed in Table 2 was tested by the inspection team on the afternoon of the 26th and the morning of the 27th immediately after passing through the OHMS tent. The inspection results mirror the OHMS results with the vehicle having an afternoon average tailpipe opacity of 95.5% and failing the test followed the next morning with a passing opacity test of only 10.8%. If repairs were attempted on the vehicle overnight they were not lasting as we measured the vehicle on the afternoon of the 27th with results that would again far exceed limits.

The extreme variability of the particle emissions from this vehicle, observed by two different testing methods, is difficult to explain. One possibility is that this truck's DPF has been tampered with or removed leaving tailpipe particle emissions strictly a function of engine operation. However, the observed entrance and exit speeds for these measurements are all similar, as well as the State's opacity inspection. Fuel specific CO emissions correlate with the fuel specific PM and BC emissions indicating fuel enrichment for the high PM events. Figure 5 shows FMPS fuel specific particle size distribution data collected in the morning (solid line) and afternoon (dashed line) of March 26th for this HDV post processed with TSI's soot inversion matrix. PM increases in the afternoon result in a shift in the peak particle size from ~70nm to >150nm. This shift in peak particle size is also seen in the morning and afternoon measurements, collected on March 27th, as well as a number of other high emitting HDVs at the Port of Los Angeles in 2015. The shift in the particle distribution is consistent with the use of large amounts of exhaust gas recirculation (EGR) in combustion, which would lower NO_x emissions by enriching the cylinder air to fuel ratio, and has been observed by other researchers.^{31, 32}

Figure 5. Fuel specific particle size distributions collected with a Fast Mobility Particle Sizer using the soot inversion on March 26th before noon (AM, solid line) and afternoon (PM, dashed line) from a 2009 HDV at the Port of Los Angeles in 2015.

Increased EGR in the afternoon could be a consequence of increased ambient temperature and/or may reflect this vehicles particular work cycle.

A second potential explanation has to include the possibility that the DPF remains in the vehicle but only functions sporadically. It has been shown that cracks due to thermal expansion or vibrations over time will reduce filter surface area in a DPF, as well as cause filter “leakages” which may increase as the day progresses.^{33, 34} In addition, the presence of a soot-cake significantly increases the filter efficiency of the DPF, thus it is also within the realm of possibilities that some of the emissions variability is related to its regeneration frequency with lower PM emissions prior to a regeneration event.³⁵

To date there has been no research that has looked at how and why DPFs fail and the resultant emissions reductions that are lost. The Port measurements show the largest increase in emissions are from the 2008 – 2010 model year vehicles which were initially designed with higher engine out PM emissions, to limit NO_x emissions since they do not have a NO_x aftertreatment system.¹³ DPFs in these vehicles therefore will require more frequent active regeneration events, where fuel is introduced into the filter to combust the accumulated soot and restore exhaust flow rates. The increased thermal stress coupled with the likely need to manually remove accumulated ash more often increases the chances for defects to be introduced into these early generation filters. Many of these issues have been addressed in the later model vehicles (2011 and newer) as engines are now designed to limit PM emissions reducing the demand on DPFs. However, ensuring the long term integrity of installed DPFs is paramount to maintaining the particle emissions reductions achieved to date.

ASSOCIATED CONTENT

Supporting Information. Supporting table (S1) and figures (S1-S17) referenced in the text. This material is available free of charge at <http://pubs.acs.org>

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Notes

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Supporting Information For:

Repeat Fuel Specific Emission Measurements on Two California Heavy-duty Truck Fleets

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Summary of Supporting Information:

14 Pages (excluding cover):

Table S1

Figures S1 – S17

Particle Number per Kilogram of Fuel Example Calculation

Table S1. Example of how particle number per kilogram of fuel was calculated

Time	CO ₂ (ppm)	[PN] (#/cm ³)
11:42:38	733	9265
11:42:39	736	9060
11:42:40	737	8726
11:42:41	759	6096
11:42:42	903	187400
11:42:43	919	392000
11:42:44	867	309400
11:42:45	848	221700
11:42:46	826	162600
11:42:47	801	116100
11:42:48	787	84340
11:42:49	780	74180
11:42:50	774	64840
11:42:51	771	56610
11:42:52	768	56610

Slope	R Squared	Standard error
1833.950053	0.874067423	193.0689373
$\frac{Number}{CO_2} \times 10^6 \times 24400 \times \frac{1000}{14} = \frac{PN}{kg\ of\ fuel}$		
$1833.95 \times 10^6 \times 24400 \times \frac{1000}{14} = 3.2 \times 10^{15}$		

The CO₂ and [PN] data sets have been time aligned using high emission vehicles as landmarks. Once aligned, it can be seen that the peaks for [PN] and CO₂ are at the same time. [PN] is plotted against CO₂ and the slope, R² and standard error of the fit are calculated using the LINEST function in excel. The slope of the [PN]/CO₂ is then used to calculate the fuel specific PN emission factor for each vehicle. The bottom equation is an example for this vehicle which had a [PN]/CO₂ slope of 1834 than translates into a PN/kg of fuel of 3.2 x 10¹⁵.

Estimation of Standard Errors of the Mean for Reported Uncertainties

Vehicle emissions from US vehicle fleets are not normally distributed, thus the assigning of uncertainties on fleet emission means involves a process that many readers may not be familiar with. Standard statistical methods that were developed for normally distributed populations, when used on a skewed distribution, results in uncertainties that are unrealistically too small due to the large number of samples. The Central Limit Theorem in general indicates that the means of multiple samples, randomly collected, from a larger parent population will be normally distributed, irrespective of the parent populations underlying distribution. Since we almost always collect multiple days of emission measurements from each site, we use these daily measurements as our randomly collected multiple samples from the larger population and report uncertainties based on their distribution. We calculate means, standard deviations and finally standard errors of the mean for this group of daily measurements. We report the means for all of the emission measurements and then calculate a standard error of the mean for the entire sample by applying the same error percentage obtained from the ratio of the standard error of the mean for the daily measurements divided by the daily measurement mean. An example of this process is provided below for the 2015 Port of Los Angeles, CA gNO/kg of fuel and gPM/kg of fuel measurements. While this example is for a fleet mean we also use this technique when we report standard errors of the mean for individual model years or specific fuel or technology types. For example each model year will have its daily mean calculated and then its standard error of the mean for the daily average computed and that percent uncertainty will be applied to that model year's fleet emissions mean.

Port of Los Angeles, CA 2015

Date	Mean gNO/kg of fuel	Counts	Mean gPM/kg of fuel	Counts
3/22/2016	12.53	319	0.11	319
3/23/2016	13.40	266	0.11	266
3/24/2016	11.03	257	0.06	261
3/25/2016	13.94	349	0.14	341
3/26/2016	12.63	259	0.13	259
Daily Means	12.71		0.11	
Standard Error for the Daily Means	0.5		0.01	
Fleet Mean	12.77		0.11	
Standard Error for the Fleet Means	0.5		0.01	
As Reported in Table 1	12.8 ± 0.5		0.11 ± 0.01

Figure S1. OHMS set-up at Cottonwood, showing the placement of the three cameras used and the tent/pipe location.

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 thus an in-field calibration was conducted with in-use vehicles.

The contraption that was constructed to make these measurements is shown in Figure S2. 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 S3) was assigned a temperature range correlating the measured thermocouple temperatures with the IR image color. 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 S2. 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 the 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 similar to the two locations where we have deployed the OHMS system in California. The brewery location had pipes at lower temperature due to 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 histograms showing the temperatures measured at both locations are shown in Figure S4. 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 S3. Infrared image color scale with associated temperatures determined from thermocouple measurements.

Figure S4. Histogram of exhaust pipe temperatures at Dumont weigh station (green bars) and Coors Brewery (blue bars).

Figure S5 graphs the measured thermocouple temperature against the previously determined in-lab IR image temperature calibration. The markers (+) 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 show 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 S5. 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 black parallel dashed lines showing the 95% prediction bands for that fit. The thick, red dashed 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, and that we have sampled enough exhaust pipes to minimize the emissivity variability associated with the variety of metal formulations in exhaust pipes.

To correct previous 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 in degrees C and x is the temperature previously assigned using the in-lab calibration.

$$y = 0.331x + 28.8$$

Figure S6. Port of Los Angeles mean gBC/kg of fuel (left axis) versus chassis model year shown for 2013 (solid grey diamonds) and 2015 data (solid green circles) and mean PN/kg of fuel data (right axis) versus chassis model year for 2013 (open black elongated diamonds) and 2015 data (open blue circles). Uncertainties plotted are standard errors of the mean determined from the daily samples.

Figure S7. Mean gPM/kg of fuel versus chassis model year at the Cottonwood weigh station for 2013 data (black diamonds) and 2015 data (blue circles). Uncertainties plotted are standard errors of the mean determined from the daily samples.

Tests of PVC Pipe Particle Loss

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 CO₂. This establishes a fixed ratio of particles to CO₂ for each syringe. However, the mixing is inexact and the particle to CO₂ 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 CO₂ ratio would indicate there are potential particle losses due to the sampling system.

Figure S8 shows the measured PM to CO₂ 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 S9 shows the results for the companion BC to CO₂ 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 S10 and S11 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 S10 has PM/CO₂ 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 elbow. These experiments again suggest that there are no large particle losses due to the pipe elbow in the OHMS sampling line.

Figure S8. PM to CO₂ 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 S9. BC to CO₂ 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 S10. PM to CO₂ 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 S11. BC to CO₂ 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.

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 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 S12 and S13, 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 S12. 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 S13. Total particle number concentration for sample intake before the fan (triangles) and after the fan (diamonds). Each trial is a separate syringe injection.

Figure S14. Mean fuel specific CO, HC, NO (grams of NO), NO₂ and NO_x (grams of NO₂) for the Port of Los Angeles (left) and the Cottonwood weigh station (right) with standard error of the mean uncertainties calculated from the daily means. The left bar (blue) represents mean emissions for 2013 measurements and the right bar (green) indicates the 2015 data.

Figure S15. Percentile-percentile plots from the Port of Los Angeles comparing the emissions distributions between the 2015 and 2013 measurements of a) gPM/kg of fuel and b) gBC/kg of fuel. The diagonal line is the 1:1 line indicating perfect agreement. Each point represents a percentile increasing in 2.5% increments from 1 to 99. Deviations from the 1:1 line indicates differences between the two years emission distributions.

Figure S16. Percentile-percentile plots from Cottonwood comparing the emissions distributions between the 2015 and 2013 measurements of a) gPM/kg of fuel and b) gBC/kg of fuel. The diagonal line is a 1:1 ratio of 2015 data (y-axis) and 2013 data (x-axis). Each point represents a percentile increasing in 2.5% increments from 1 to 99. Deviations from the 1:1 line indicates differences between the two years emission distributions.

Figure S17. HDVs that were measured more than once in 2015 at Cottonwood (blue squares) and the Port of Los Angeles (green diamonds). This is plotted by rank-ordering the repeat trucks seen in 2015 at each location by their average gPM/kg of fuel emissions. The larger the truck number is indicative of larger average gPM/kg of fuel for all measurements made on that vehicle.