Final Report

Measuring Real-World Emissions from the On-Road Passenger Fleet

Contract No. 12-303

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Disclaimer

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Abstract

A nine year record of on-road emission measurements at a West Los Angeles site (La Brea Ave. and I-10) was continued with two additional data collection campaigns in the spring of 2013 and 2015. The University of Denver collected 27,247 (2013) and 22,124 (2015) emission measurements of carbon monoxide (CO), carbon dioxide, hydrocarbons (HC), nitric oxide (NO), ammonia (NH_3) and nitrogen dioxide (NO_2) from light and medium-duty vehicles. Since 1999 the CO mean emissions have decreased by 82% (70.3 to 13 g/kg), the HC mean emissions by 81% (7.0 to 1.3 g/kg) and the NO mean emissions by 71% (6.6 to 1.9 g/kg). These decreases have happened despite the fact that fleet age has increased by 2 model years as a result of the lost vehicle sales during the 2008 – 2009 recession. Over the same period the 99th percentiles have dropped by more than a factor of three for CO and HC (773 to 258 g/kg, HC (93 to 24 g/kg) and a factor of 1.5 for NO (53 to 34 g/kg). There are concerns however, that the reductions in the 99th percentiles may be leveling out which would also stall future fleet emissions reductions. These data sets were also used to document that 2009 and newer Volkswagen and Audi diesel vehicles had excessive on-road NO and NO_2 emissions.

Executive Summary

The University of Denver has completed two measurement collection campaigns at the West Los Angeles sampling site in the spring of 2013 and 2015. This site is located at the intersection of La Brea Ave. and I-10 and emissions are collected from vehicles travelling from southbound La Brea Ave. to eastbound I-10. The remote sensor used in this study measures the molar ratios of carbon monoxide (CO), hydrocarbons (HC), nitric oxide (NO), sulfur dioxide (SO_2), ammonia (NH_3) and nitrogen dioxide (NO_2) to carbon dioxide (CO_2) in motor vehicle exhaust. From these ratios, we can derive the fuel specific emissions in grams per kilogram of fuel for CO, HC, NO, SO_2, NH_3 and NO_2 in the exhaust. Because of the recent reductions in fuel sulfur for both diesel and gasoline fuels we did not calibrate the system for SO_2 and do not report those measurements. In addition, the system used in this study was configured to determine the speed and acceleration of the vehicle, and was accompanied by a video system to record the license plate of the vehicle for matching with state records to identify vehicle make and model year.

The first campaign collected measurements between April 27- May 4, 2013 resulting in a vehicle and emissions database containing 27,247 records. The second sampling campaign was conducted March 28 – April 3, 2015 at the same location and resulted in a vehicle emissions database containing 22,124 records. These two data sets make the sixth and seventh data set that has been collected at this site since 1999. New for these sampling campaigns the data collection was also carried out on Saturday and Sunday. These databases, as well as all of the previous compiled by the University of Denver, can be found at our website www.feat.biochem.du.edu.

Since the first measurements were collected in the fall of 1999 the CO mean emissions have dropped 82% (70.3 to 13 g/kg), the HC mean emissions have decreased by 81% (7.0 to 1.3 g/kg) and the NO mean emissions by 71% (6.6 to 1.9 g/kg). These decreases have happened despite the fact that fleet age has increased by more than 1.5 model years as a result of the lost vehicle sales during the 2008 – 2009 recession. Figure E1 plots the g/kg of fuel emissions for CO, HC and NO for the 1999 and 2015 data sets against vehicle age. The zero year model years are 2000 for the 1999 data and 2015 for the 2015 data set. The uncertainties plotted are the standard errors of the mean calculated for each model year grouping using the daily means measured in each data set. When comparing emissions by the age of the vehicle one finds that 24 year old vehicles measured in 2015 (1991 models) have emissions that are very similar to 10 year old vehicles in 1999 (1990 models). This indicates that not only have large reductions in emissions taken place over this time period but emissions deterioration on a fleet mean basis is not significant.

While these large reductions have taken place the emissions distribution has become more skewed. The 99th percentile in 1999 was responsible for 14% and 17% of the CO and HC emissions. In 2015 the same 1% of the fleet is now responsible for 35% and 46% of the CO and HC emissions. Figures E2 and E3 plot the 99th percentiles for CO, HC and NO emissions for all of the data sets collected at the West LA site. 99th percentile emissions for CO and HC have dropped by more than a factor of three (773 to 258 g/kg, HC (93 to 24 g/kg). NO (53 to 34 g/kg) 99th percentiles have also dropped but not to the degree of CO and HC. While the reductions are impressive the more concerning trend is that all three species show signs that they may be leveling out. This is important because as the 99th percentile goes so goes fleet emission means. Additional data sets will be needed to fully answer this question.

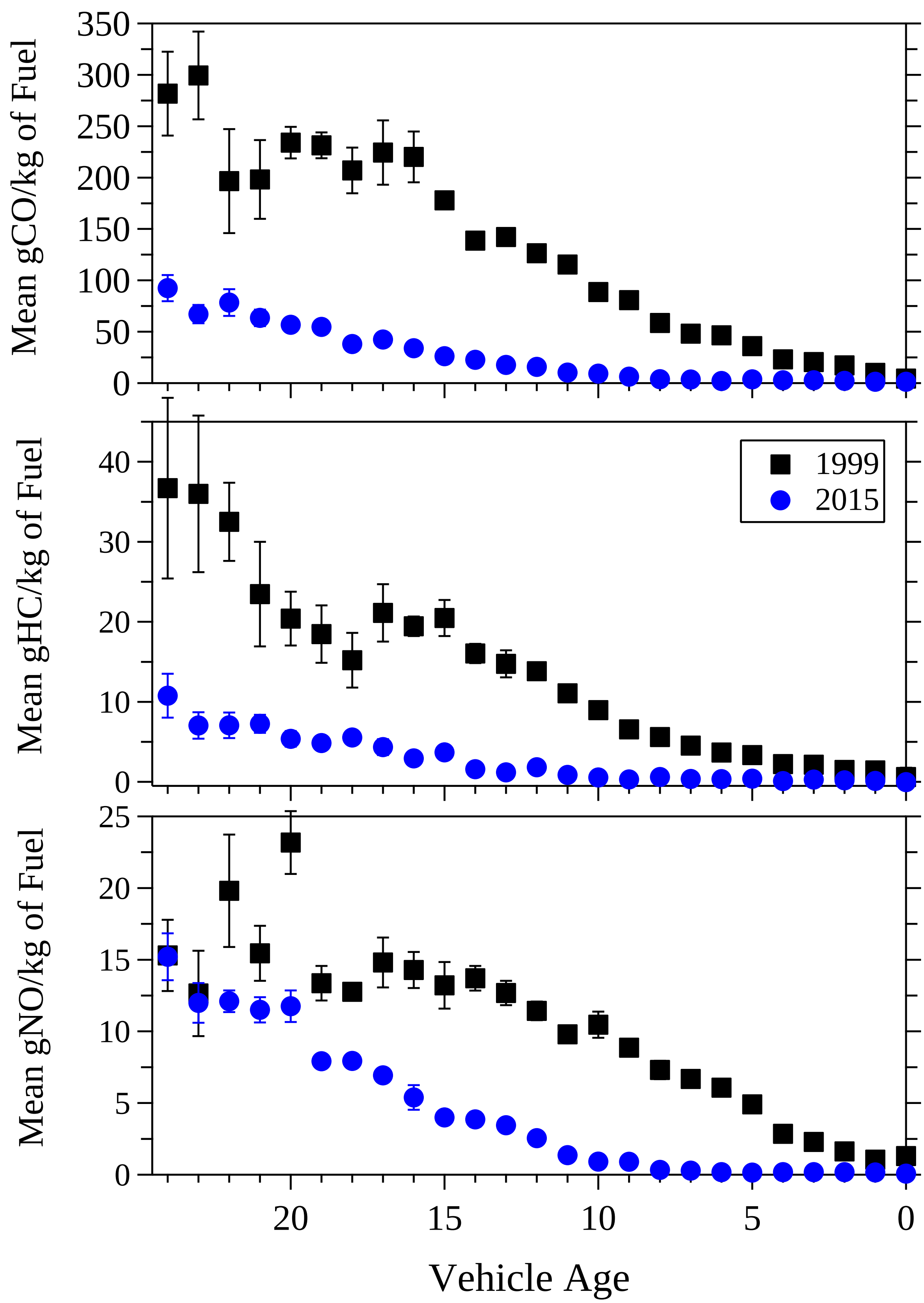

Figure E1. Fuel specific CO (top panel), HC (middle panel) and NO (bottom panel) emissions versus vehicle age for data sets collected at the West Los Angeles site in 1999 (squares) and 2015 (circles). The uncertainties plotted are standard errors of the mean estimated from the daily measurements. Zero model years are 2000 (1999 data) and 2015 (2015 data).

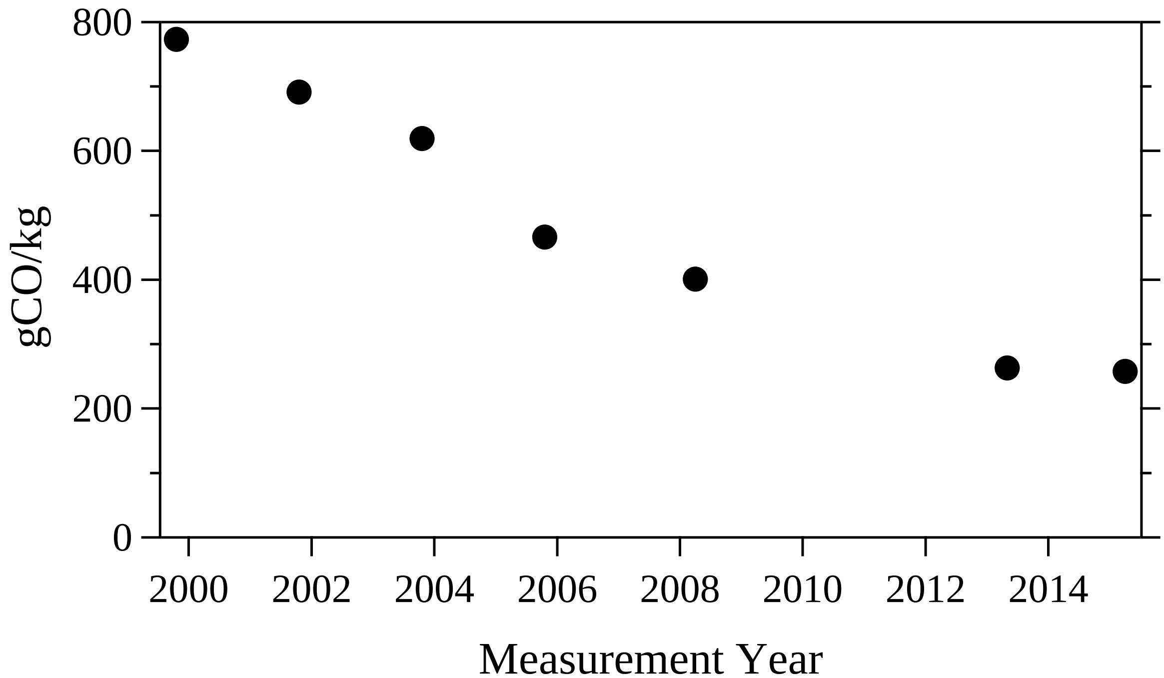

Figure E2. The gCO/kg of fuel 99th percentile for each of the West Los Angeles data sets plotted against measurement year.

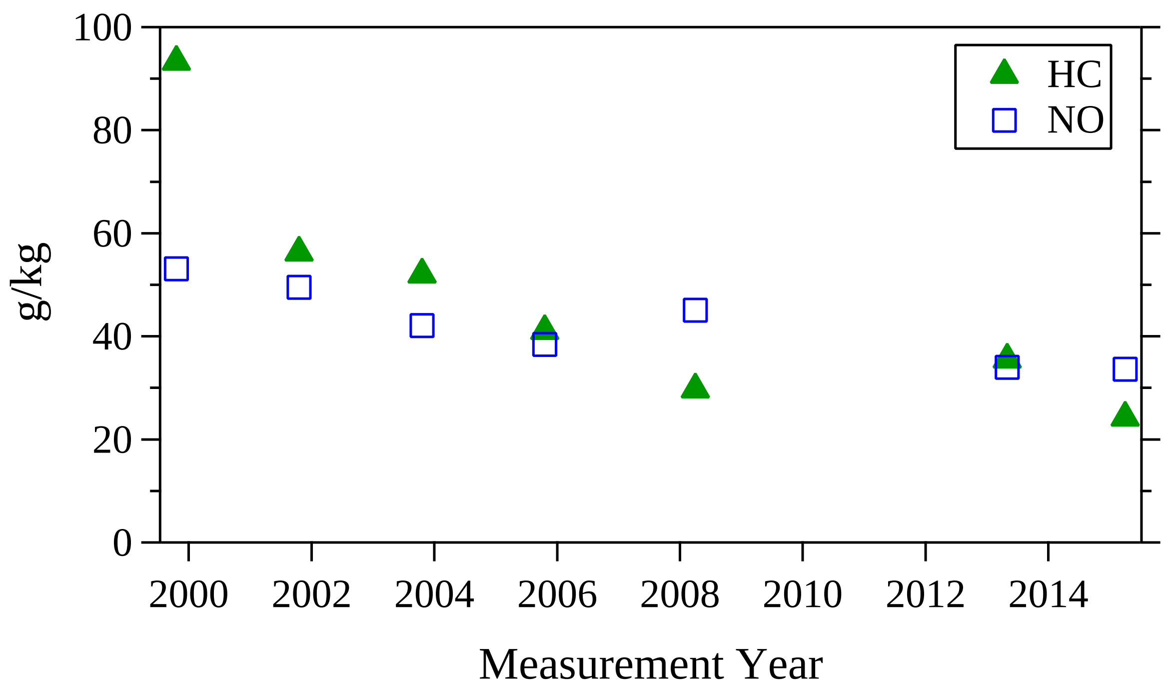

Figure E3. The gHC/kg of fuel and gNO/kg of fuel 99th percentiles for each of the West Los Angeles data sets plotted against measurement year.

A major change observed in 2013 was a dramatic increase in the age of the vehicle fleet. Since 1999 the vehicle fleet age at this site had been trending downward from 7.9 years old in 1999 to 7.4 years old in 2005 and 2008. The dramatic economic downturn that began in late 2008 and continued through 2010 increased the average age of the West LA fleet to 9.1 years old. California new vehicle registrations as reported by the National Automobile Dealers Association for 2009 were 45% lower than for 2007. For the 2013 West LA data there are 38% fewer 2009 model year vehicles than 2007 models but 2008 – 2011 model years also show the effects. Fleet age recovered slightly in 2015 with the observed fleet age decreasing slightly to 8.9 years old. Recovery from the 08-09 recession does not appear as if it will be very fast as at this rate it will take more than 20 years to return to the previous fleet age of 7.4 years measured in 2008.

The sudden increase in the fleet age has resulted in tailpipe emissions not decreasing at the same rate they had been before the downturn. When we age adjusted the 2013 data to the fleet age distribution seen in 2008 we find that CO, HC, NO and NH_3 emissions would have been 23% (3.8 g/kg), 10% (0.2 g/kg), 28% (0.6 g/kg) and 14% (0.08 g/kg) lower respectively than measured absent the downturn. These differences are statistically significant for all of these species but the HC emissions. The emissions which would have been eliminated by fleet turnover were concentrated in the 10 to 20 year old vehicles.

For the first time we collected emission measurements during the weekend at the West LA site. To our surprise Saturday had the highest traffic volumes of the week. As expected we see fewer diesel powered vehicles on the weekend days (2013 weekday average of 2.4%, Saturday 1.5% and Sunday 0.5% / 2015 weekday average of 2.0%, Saturday 0.8% and Sunday of 0.5%) although low exhaust, diesel powered vehicles in general are not a large segment of this fleet. Emission differences between the weekday and weekend days are very small with the fleet getting slightly newer on Sunday (2013 weekday and Saturday mean model year of 2004.7 and 2005 for Sunday / 2015 weekday and Saturday mean model year of 2006.9 and 2006.6 and 2007 for Sunday). Sunday emissions are the lowest for all of the species in both years except NO_2 but the differences are not statistically significant when compared to the weekday means.

Because diesel passenger vehicles are an insignificant fraction of the Los Angeles fleet we combined data collected in 2013 at the West Los Angeles site with measurements from Denver, CO and Tulsa, OK. Figure E4 is a graph of gNO_x/kg of fuel emissions (circles) versus model year for diesel passenger vehicles with engines that are 2L or smaller for the combined data sets. Due to the lack of a 50 state standard there were no diesel passenger vehicles manufactured in 2006 and 2007. The horizontal bars are the mean emissions for the model years that they span (2002 – 2006 and 2009 – 2013) and the triangles are the mean gNO_2/kg of fuel emissions for those same model years. The uncertainties plotted are the standard errors of the mean calculated from the daily means. There is no statistical difference between the fuel specific NO_x emissions from diesel passenger vehicles built prior to 2007 and those manufactured to Tier II/LEV II standards beginning with the 2009 models. However, there is an approximately 23% increase in the Tier II vehicles NO_2 emissions (7.8 ± 1.6 to 10.1 ± 1.3) and the NO_2/NO_x ratio increased from 0.33 to 0.57. For the 2013 West LA data set mean gNO_x/kg of fuel emissions for 2009 and newer Volkswagens (33 measurements) and Audis (8 measurements) averaged 18.4 and 30.6 gNO_x/kg of fuel respectively. Measurements collected concurrently from diesel passenger vehicles that were manufactured prior to 2007 showed their essentially uncontrolled mean

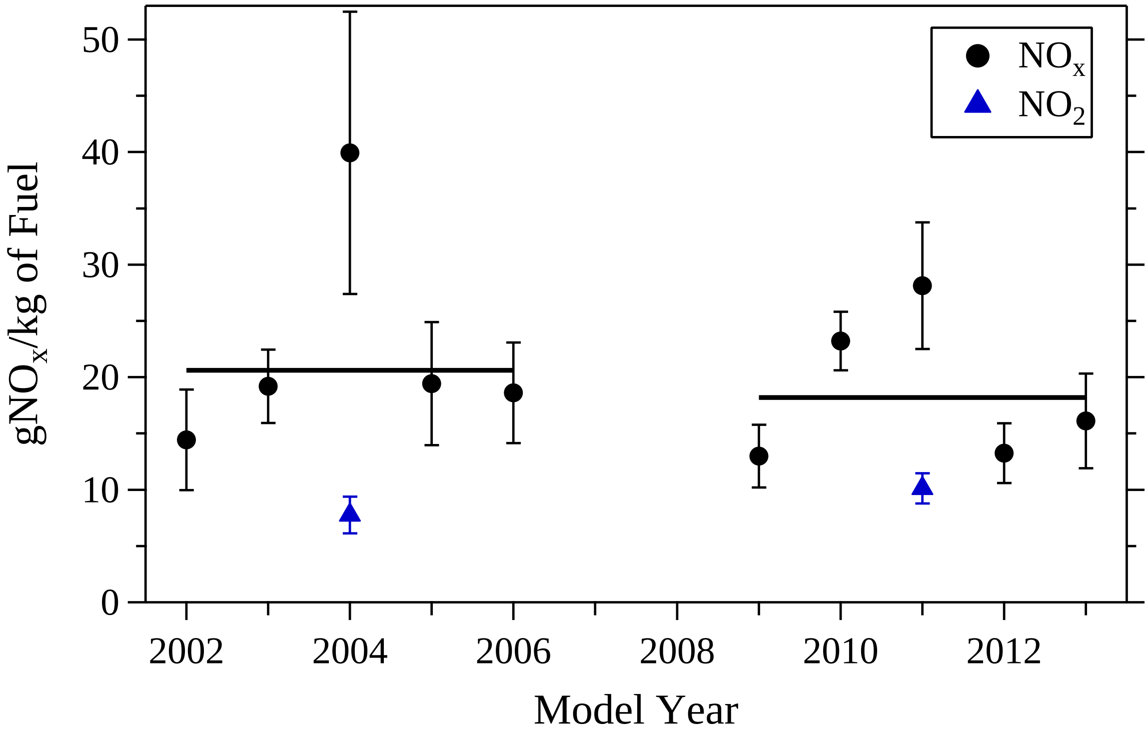

Figure E4. Diesel passenger vehicle gNO$_x$/kg of fuel emissions for passenger vehicles with engine sizes of 2L and smaller (circles) versus model year for data collected in 2013 in Denver CO, Los Angeles CA and Tulsa OK. The horizontal lines and triangles show the mean gNO$_x$/kg and gNO$_2$/kg of fuel emission levels for the 2002 – 2006 (left) and 2009 – 2013 (right) models. Uncertainties plotted are standard errors of the mean determined from the daily means.

gNO$_x$/kg of fuel emissions of 13.1. In addition the newer vehicles had a significantly higher proportion of their NO$_x$ emissions emitted as NO$_2$ (0.5 versus 0.2). FEAT's ability to unobtrusively monitor on-road emissions is one method that can be exploited to identify egregious emissions certification compliance.

Introduction

Since the early 1970's, many heavily populated U.S. cities have violated the National Air Quality Standards (NAAQS) established by the Environmental Protection Agency (EPA) pursuant to the requirements of the Federal Clean Air Act.[1, 2] Carbon monoxide (CO) levels become elevated primarily due to direct emissions of the gas, and ground-level ozone, a major component of urban smog, is produced by the photochemical reaction of nitrogen oxides (NO_x) and hydrocarbons (HC). Ambient levels of particulate emissions can result either from direct emissions of particles or semi-volatile species or from secondary reactions between gaseous species, such as ammonia (NH_3) and nitrogen dioxide (NO_2). Sulfur dioxides (SO_2) are emitted when the sulfur found in fuel is oxidized and emitted in the exhaust.

Transportation is a common source for all of these gases. While emissions of all of these species have dropped dramatically over the last two decades on-road vehicles still are a major source. As of 2010, the most recent trends report available from the EPA, on-road vehicles are estimated to contribute 44% of the CO, 34% of the volatile organic carbon (VOC), 8% of the NH_3 and 34% of the NO_x to the national emission inventory.[3] In California the State's Air Almanac for 2013 estimates that on-road light-duty passenger vehicle and light and medium duty gasoline trucks contribute 17% of the VOC's, 6.0% of the NH_3 and 15% of the NO_x to the statewide inventory.[4]

Properly operating modern vehicles with three-way catalysts are capable of partially (or completely) converting engine-out CO, HC and NO_x emissions to carbon dioxide (CO_2), water and nitrogen. If there is a reducing environment on the catalyst, NH_3 can be formed as a byproduct of the reduction of NO. For a complete description of the internal combustion engine and causes of pollutants in the exhaust see Heywood.[5]

NH_3, emitted from three-way catalyst equipped vehicles, is a growing concern because of the adverse health effects that have been attributed from its contribution to secondary particulate matter formation that is smaller than 2.5μm in diameter ($PM_{2.5}$).[6-9] Ammonium nitrate is known to be a dominate component of $PM_{2.5}$, though its NH_3 sources are commonly associated with livestock waste, fertilizer application, and sewage treatment.[10, 11] In urban areas these sources are less common and the contribution of ammonia from mobile sources is thought to be a significant and growing source.[10, 12] Its atmospheric levels are directly linked to the amount of free NH_3 in the atmosphere and with the recent reductions of sulfur from motor fuels this will have likely increased its availability.[10, 13]

A direct knowledge of fleet average on-road emission levels is a critical input for estimating inventories, evaluating emission control programs and planning strategies that can lead to attaining the NAAQS.[14] Many areas remain in non-attainment for the NAAQS, and with the 8 hour ozone standards introduced by the EPA in 1997 being further tightened in 2015, many more locations will likely violate these new standards and some will have great difficulty reaching attainment.[15, 16] Knowing how tailpipe emission levels and their ratios are changing in the on-road fleet requires monitoring programs that can collect enough measurements often enough to allow researchers to find and follow new trends.

The purpose of this report is to describe the two most recent on-road emission measurements collected at the West Los Angles E-23 site in the spring of 2013 and 2015, under Air Resources Board contract no. 12-303. Measurements were made on eight consecutive days, April 27 – May 4, 2013 and on seven consecutive days, March 28 – April 3, 2015 at the on-ramp from southbound La Brea Ave. to eastbound I-10E in West L.A. This site has a growing emission measurement history and was first used for the Inspection and Maintenance Review Committee measurements in 1999, for all of the Coordinating Research Council sponsored E-23 measurements in 2001, 2003, and 2005 and in 2008 for an Air Resources Board project.[17] The 2008 measurements were the first to take advantage of the University's added spectrophotometer instrument with measurements for NH_3, SO_2 and NO_2.[18] That same equipment was used for these measurements with the only change being that while SO_2 measurements were collected they were not calibrated for and will not be reported or discussed.

Materials and Methods

The remote sensor used in this study was developed at the University of Denver for measuring the pollutants in motor vehicle exhaust, and has previously been described in the literature.[19-21] The instrument consists of a non-dispersive infrared (NDIR) component for detecting CO, CO_2, and HC, and twin dispersive ultraviolet (UV) spectrometers for measuring oxides of nitrogen (NO and NO_2), SO_2 and NH_3 (0.26 nm/diode resolution). The source and detector units are positioned on opposite sides of the road in a bi-static arrangement. Collinear beams of infrared (IR) and UV light are passed across the roadway into the IR detection unit, and are then focused through a dichroic beam splitter, which serves to separate the beams into their IR and UV components. The IR light is then passed onto a spinning polygon mirror, which spreads the light across the four infrared detectors: CO, CO_2, HC and reference.

The UV light is reflected off of the surface of the dichroic mirror and is focused onto the end of a quartz fiber bundle that is mounted to a coaxial connector on the side of the detector unit. The quartz fiber bundle is split in order to carry the UV signal to two separate spectrometers. The first spectrometer was adapted to expand its UV range down to 200nm in order to measure the peaks from SO_2 and NH_3 and continue to measure the 227nm peak from NO. The absorbance from each respective UV spectrum of SO_2, NH_3, and NO is compared to a calibration spectrum using a classical least squares fitting routine in the same region in order to obtain the vehicle emissions. The second spectrometer measures only NO_2 by measuring an absorbance band at 438nm in the UV spectrum and comparing it to a calibration spectrum in the same region.[22]

The exhaust plume path length and density of the observed plume are highly variable from vehicle to vehicle, and are dependent upon, among other things, the height of the vehicle's exhaust pipe, wind, and turbulence behind the vehicle. For these reasons, the remote sensor only directly measures ratios of CO, HC, NO, NH_3 or NO_2 to CO_2. The molar ratios of CO, HC, NO, NH_3 or NO_2 to CO_2, termed Q^{CO}, Q^{HC}, Q^{NO}, Q^{NH3} and Q^{NO2} respectively, are constant for a given exhaust plume, and on their own are useful parameters for describing a hydrocarbon combustion system. This study reports measured emissions as molar %CO, %HC, %NO, $\%NH_3$ and $\%NO_2$ in the exhaust gas, corrected for water and excess air not used in combustion. The HC measurement is calibrated with propane, a C_3 hydrocarbon. But based on measurements using flame ionization detection (FID) of gasoline vehicle exhaust, the remote sensor is only half as sensitive to exhaust hydrocarbons on a per carbon atom basis as it is to propane on a per carbon atom basis.[23] Thus, in order to calculate mass emissions as described below, the %HC values reported will first be multiplied by 2.0 as shown below, assuming that the fuel used is regular gasoline. These percent emissions can be directly converted into mass emissions by the equations shown below.

$$\text{gm CO/gallon} = 5506 \cdot \%CO / (15 + 0.285 \cdot \%CO + 2(2.87 \cdot \%HC)) \quad (1a)$$
$$\text{gm HC/gallon} = 2(8644 \cdot \%HC) / (15 + 0.285 \cdot \%CO + 2(2.87 \cdot \%HC)) \quad (1b)$$
$$\text{gm NO/gallon} = 5900 \cdot \%NO / (15 + 0.285 \cdot \%CO + 2(2.87 \cdot \%HC)) \quad (1c)$$
$$\text{gm } NH_3\text{/gallon} = 3343 \cdot \%NH_3 / (15 + 0.285 \cdot \%CO + 2(2.87 \cdot \%HC)) \quad (1d)$$
$$\text{gm } NO_2\text{/gallon} = 9045 \cdot \%NO_2 / (15 + 0.285 \cdot \%CO + 2(2.87 \cdot \%HC)) \quad (1e)$$

These equations indicate that the relationship between concentrations of emissions to mass of emissions is linear, especially for CO and NO and at low concentrations for HC. Thus, the percent difference in emissions calculated from the concentrations of pollutants reported here is equivalent to a difference calculated from masses. Note that NO is reported as grams of NO, while vehicle emission factors for NO_x are normally reported as grams of NO_2, even when the actual compound is NO.

Another useful conversion is from percent emissions to grams of pollutant per kilogram (g/kg) of fuel. This conversion is achieved directly by first converting the pollutant ratio readings to moles of pollutant per mole of carbon in the exhaust using the following equation:

$$\frac{\text{moles pollutant}}{\text{moles C}} = \frac{\text{pollutant}}{CO + CO_2 + 6HC} = \frac{(\text{pollutant}/CO_2)}{(CO/CO_2) + 1 + 6(HC/CO_2)} = \frac{(Q^{CO}, 2Q^{HC}, Q^{NO} ...)}{Q^{CO} + 1 + 6Q^{HC}} \quad (2)$$

Next, moles of pollutant are converted to grams by multiplying by molecular weight (e.g., 44 g/mole for HC since propane is measured), and the moles of carbon in the exhaust are converted to kilograms by multiplying (the denominator) by 0.014 kg of fuel per mole of carbon in fuel, assuming gasoline is stoichiometrically CH_2. Again, the HC/CO_2 ratio must use two times the reported HC (see above) because the equation depends upon carbon mass balance and the NDIR HC reading is about half a total carbon FID reading.[23]

$$\text{gm CO/kg} = (28Q^{CO} / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \quad (3a)$$
$$\text{gm HC/kg} = (2(44Q^{HC}) / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \quad (3b)$$
$$\text{gm NO/kg} = (30Q^{NO} / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \quad (3c)$$
$$\text{gm } NH_3\text{/kg} = (17Q^{NH3} / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \quad (3d)$$
$$\text{gm } NO_2\text{/kg} = (46Q^{NO2} / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \quad (3e)$$

Quality assurance calibrations are performed at least twice daily in the field unless observed voltage readings or meteorological changes are judged to warrant additional calibrations. For the multi-species instrument three calibration cylinders are needed. The first contains CO, CO_2, propane and NO, the second contains NH_3 and propane and the final cylinder contains NO_2 and CO_2. A puff of gas is released into the instrument's path, and the measured ratios from the instrument are then compared to those certified by the cylinder manufacturer (Air Liquide). These calibrations account for day-to-day variations in instrument sensitivity and variations in ambient CO_2 levels caused by local sources, atmospheric pressure and instrument path length. Since propane is used to calibrate the instrument, all hydrocarbon measurements reported by the remote sensor are reported as propane equivalents.

Studies sponsored by the California Air Resources Board and General Motors Research Laboratories have shown that the remote sensor is capable of CO measurements that are accurate to within ±5% of the values reported by an on-board gas analyzer, and within ±15% for HC.[24, 25] The NO channel used in this study has been extensively tested by the University of Denver, but we are still awaiting the opportunity to participate in an extensive blind study and instrument intercomparison to have it independently validated. Tests involving a late-model low-emitting vehicle indicate a detection limit (3σ) of 25 ppm for NO, with an error measurement of ±5% of the reading at higher concentrations.[20] Appendix A gives a list of criteria for determining valid or invalid data. Comparison of fleet average emission by model year versus IM240 fleet average emissions by model year show correlations between 0.75 and 0.98 for data from Denver, Phoenix and Chicago.[26]

The remote sensor is accompanied by a video system to record a freeze-frame image of the license plate of each vehicle measured. The emissions information for the vehicle, as well as a time and date stamp, is also recorded on the video image. The images are stored digitally, so that license plate information may be incorporated into the emissions database during post-processing. A device to measure the speed and acceleration of vehicles driving past the remote sensor was also used in this study. The system consists of a pair of infrared emitters and detectors (Banner Industries) which generate a pair of infrared beams passing across the road, six feet apart and approximately two feet above the surface. Vehicle speed is calculated (reported to 0.1mph) from the time that passes between the front of the vehicle blocking the first and then the second beam. To measure vehicle acceleration, a second speed is determined from the time that passes between the rear of the vehicle unblocking the first and the second beam. From these two speeds, and the time difference between the two speed measurements, acceleration is calculated (reported to 0.001 mph/sec). Appendix B defines the database format used for these data sets.

2013 Results and Discussion

Measurements were made on eight consecutive days, from Saturday, April 27, to Saturday, May 4, between the hours of 6:30 and 19:00 on the uphill ramp just west of where La Brea Ave. passes under I-10. The instrument was located as far up the ramp as possible, this is the same location used for all of the previous measurement campaigns. A schematic of the measurement setup is shown in Figure 1 and a photograph of the ramp is shown in Figure 2. From the picture one can see that this is a traffic light metered on-ramp, unfortunately the metering lights were not operational for the 2013 measurements. This significantly changed the sites driving mode and emission characteristics previously observed at this location. The uphill grade at the

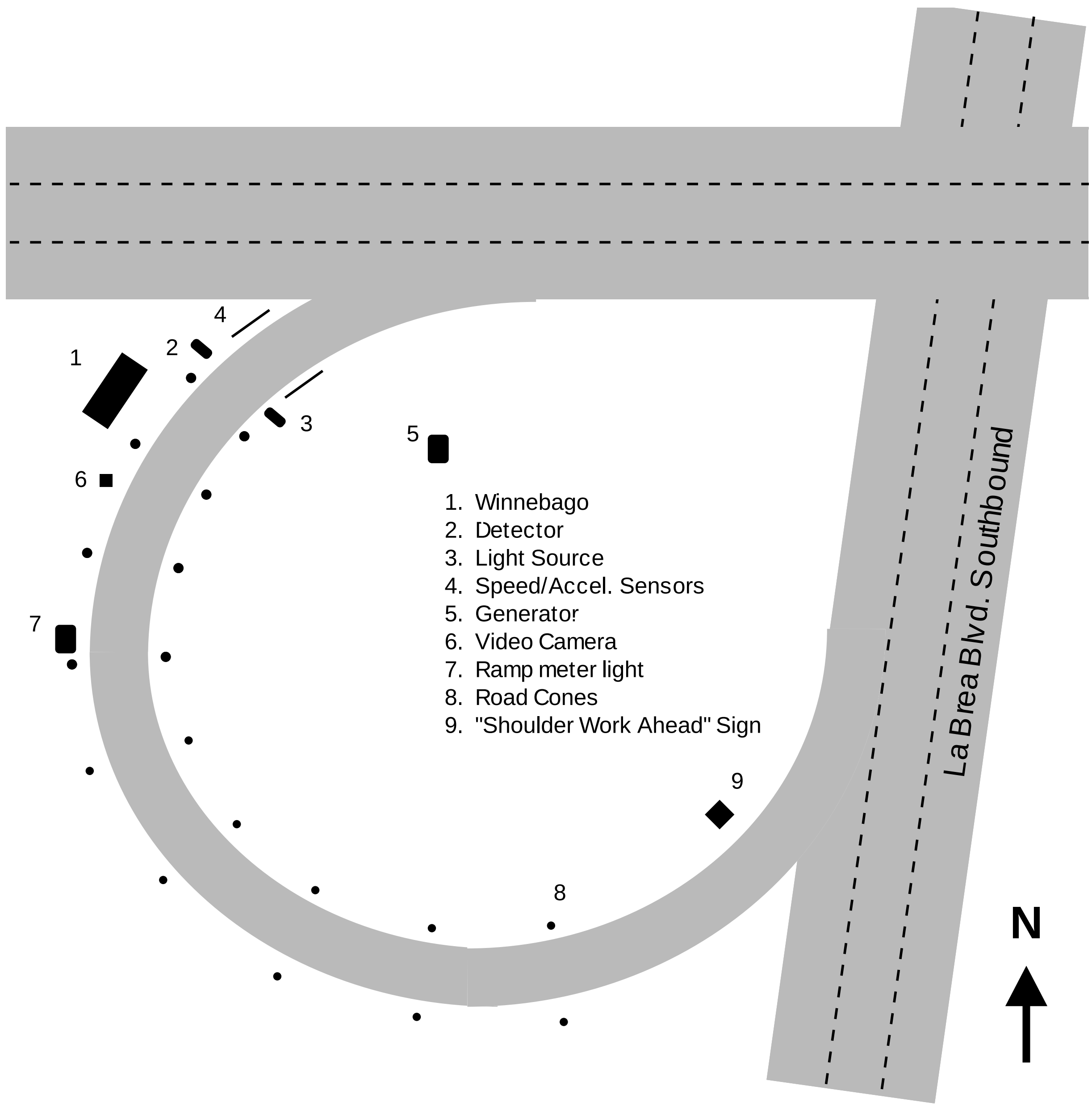

Figure 1. A schematic drawing of the on-ramp from southbound La Brea Ave. to eastbound I-10. The location and safety equipment configuration was the same for all measurement days.

measurement location is 2°. Appendix C gives temperature and humidity data for the 1999, 2001, 2003, 2005, 2008 and 2013 studies from Los Angeles International Airport, approximately eight miles southwest of the measurement site. Following the eight days of data collection the vehicle images were read for license plate identification. Plates that appeared to be in state and readable were sent to the State of California to have the vehicle make and model year determined. The resulting database contained 27,247 records with make and model year information and valid measurements for at least CO and CO_2. The database and all previous databases compiled for all of the previous measurement campaigns can be found at www.feat.biochem.du.edu. Most of these records also contain valid measurements for the other species as well. The validity of the

Figure 2. The West LA monitoring site with the measurement beam located at the end of the guardrail, to the right of the motor home. The vehicle stopped at the light is 84ft. from the measurement location. Note that for the 2013 measurements the ramp metering lights were unfortunately not functioning and the vehicles did not stop as they had in all previous studies.

Table 1. 2013 Validity Summary.

	CO	HC	NO	NH_3	NO_2
Attempted Measurements	33,807				
Valid Measurements	31,805	31,703	31,797	31,711	30,677
Percent of Attempts	94.1%	93.8%	94.1%	93.8%	90.7%
Submitted Plates	27,808	27,725	27,800	27,727	26,833
Percent of Attempts	82.3%	82.0%	82.2%	82.0%	79.4%
Percent of Valid Measurements	87.4%	87.5%	87.4%	87.4%	87.5%
Matched Plates	27,247	27,168	27,240	27,170	26,288
Percent of Attempts	80.6%	80.4%	80.6%	80.4%	77.8%
Percent of Valid Measurements	85.7%	85.7%	85.7%	85.7%	85.7%
Percent of Submitted Plates	98.0%	98.0%	98.0%	98.0%	98.0%

attempted measurements is summarized in Table 1. The table describes the data reduction process beginning with the number of attempted measurements and ending with the number of records containing both valid emissions measurements and vehicle registration information. An attempted measurement is defined as a beam block followed by a half second of data collection. If the data collection period is interrupted by another beam block from a close following vehicle, the measurement attempt is aborted and an attempt is made at measuring the second vehicle. In this case, the beam block from the first vehicle is not recorded as an attempted measurement. Invalid measurement attempts arise when the vehicle plume is highly diluted, or the reported measurement error in the ratio of the pollutant to CO_2 exceeds a preset limit (see Appendix A). The greatest loss of data in this process occurs during the plate reading process, when out-of-state vehicles and vehicles with unreadable plates (obscured, missing, temporary, dealer, out of camera field of view) are omitted from the database.

Table 2 provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured. Of the 27,249 records used in this fleet analysis, 16,654 (61.1%) were contributed by vehicles measured only once, while the remaining 10,595 (38.9%) records were from vehicles measured at least twice.

Table 2. Number of measurements of repeat vehicles in 2013.

Number of Times Measured	Number of Vehicles	Number of Measurements	Percent of Measurements
1	16,654	16,654	61.1%
2	2,080	4,160	15.3%
3	889	2,667	9.8%
4	507	2,028	7.4%
5	235	1,175	4.3%
6	58	348	1.3%
7	8	56	0.2%
>7	17	161	0.6%

Table 3 is the data summary and includes summaries of all the previous remote sensing databases collected by the University of Denver at the West LA site. The previous measurements were conducted in November of 1999, October 2001, 2003, 2005 and March of 2008.

Mean fleet emissions continue to decrease at the La Brea site in much the same manner as they are at other sites across the country. The mean model year in La Brea has not kept pace with the measurement schedule with the last recession in 2008-2009 leading to a significant increase in the age of the on-road fleet. The percentage of emissions from the highest emitting 10% of the measurements increased for all species except CO. The changes in driving mode are evident in the large reductions in mean acceleration and vehicle specific power (VSP).

The average HC values here have been adjusted to remove an artificial offset in the measurements. This offset, restricted to the HC channel, has been reported in earlier CRC E-23-4

Table 3. West Los Angeles Site Historic Data Summary.

Study Year	1999	2001	2003	2005	2008	2013
Mean CO (%) (g/kg of fuel)	0.58 (70.3)	0.44 (56.2)	0.34 (42.4)	0.22 (27.3)	0.17 (21.4)	0.13 (16.4)
Median CO (%)	0.09	0.06	0.06	0.03	0.02	0.03
Percent of Total CO from Dirtiest 10% of the Fleet	67.4%	72.4%	72.2%	77.0%	80.7%	76.7%
Mean HC (ppm)[a] (g/kg of fuel)[a] Offset (ppm)	195 (7.0) -60	125 (4.6) -21	121 (4.5) -35	84 (3.2) 65/0[b]	50 (1.8) 10	56 (2.2) 47
Median HC (ppm)[a]	70	39	45	40	10	27
Percent of Total HC from Dirtiest 10% of the Fleet	57%	61.6%	60.3%	78.0%	81%	99.3%
Mean NO (ppm) (g/kg of fuel)	477 (6.6)	411 (5.6)	323 (4.5)	242 (3.4)	265 (3.75)	153 (2.16)
Median NO (ppm)	116	72	48	24	11	5
Percent of Total NO from Dirtiest 10% of the Fleet	51.6%	54.9%	59.3%	66.9%	71%	83%
Mean NH_3 (ppm) (g/kg of fuel)	NA	NA	NA	NA	99 (0.79)	72 (0.58)
Median NH_3 (ppm)	NA	NA	NA	NA	34	24
Percent of Total NH_3 from Dirtiest 10% of the Fleet	NA	NA	NA	NA	50.8%	52.8%
Mean NO_2 (ppm) (g/kg of fuel)	NA	NA	NA	NA	4 (0.08)	7 (0.16)
Median NO_2 (ppm)	NA	NA	NA	NA	2	3.5
Percent of Total NO_2 from Dirtiest 10% of the Fleet	NA	NA	NA	NA	61.8%	85.7%
Mean Model Year	1992.4	1994.4	1996.5	1998.9	2001.2	2004.7
Mean Fleet Age[c]	7.9	7.8	7.8	7.4	7.4	9.1
Mean Speed (mph)	17.6	18.3	17.0	17.7	17.6	21.9
Mean Acceleration (mph/s)	1.4	1.4	1.9	1.7	1.9	-0.2
Mean VSP (kw/tonne) Slope (degrees)	9.0 2.0°	10.3 2.0°	11.6 2.0°	11.4 2.0°	12.2 2.0°	4.6 2.0°

[a]Indicates values that have been HC offset adjusted as described in text.
[b]Only the October 17th data was offset adjusted, the remaining days had a zero offset.
[c]Assumes new vehicle model year starts September 1.

reports. Calculation of the offset is accomplished by computing the mode and means of the newest model year vehicles, and assuming that these vehicles emit negligible levels of hydrocarbons, using the lowest of either of these values as the offset. The offset adjustment subtracts or adds this value from all of the hydrocarbon data. Since we assume the cleanest vehicles to emit little if any hydrocarbons, such an approximation will only err slightly towards clean because the true offset will be a value somewhat less than the average of the cleanest model year and make. This adjustment facilitates comparisons with the other E-23 sites and/or different collection years for the same site. The offset has been performed where indicated in the analyses in this report, but has not been applied to the archived database.

The inverse relationship between vehicle emissions and model year is shown in Figure 3, for data collected for all of the years sampled. The HC data have been offset adjusted here for comparison. The increase in HC emissions beginning with the 2009 model year is very noticeable in this graph but further investigation of that increase, which will be discussed later, will show that it is not statistically significant. In general all of the 2013 HC emissions have increased slightly which is a likely result of the change in driving mode. The slight increase in speed and dramatic drop in acceleration (see Table 3) leads to more vehicles being measured during foot-off-the-accelerator declarations that will greatly reduce fuel consumption and will exaggerate the HC/CO_2 emission ratios observed. The CO and NO emissions have likely been influenced by this change as well.

As originally shown by Ashbaugh et al.,[27] vehicle emissions by model year, with each model year divided into emission quintiles, were plotted for data collected in 2013. This resulted in the plots shown in Figures 4 - 6. The bars in the top plot represent the mean emissions for each quintile by model year, but do not account for the number of vehicles in each model year. The middle graph shows the fleet fraction by model year for the first 19 model years, model years older than 1995 account for ~5.8% of the measurements and about a third of the emissions. The bottom graph for each species is the combination of the top and middle figures. These figures illustrates that the cleanest 60% of the vehicles, regardless of model year, make an essentially negligible contribution to the overall fleet emissions. The accumulations of negative emissions in the first two quintiles are the result of ever decreasing emission levels. Our instrument is designed such that when measuring a true zero emission plume, half of the readings will be negative and half will be positive. As the lowest emitting segments of the fleets continue to dive toward zero emissions, the negative emission readings will continue to grow toward half of the measurements.

Figures 4 - 6 can also be used to get a picture of federal compliance standards. The on-road data are measured as mass emissions per kg of fuel. It is not possible to determine mass emissions per mile for each vehicle because the instantaneous gasoline consumption (kg/mile) is not known. An approximate comparison with the fleet average emissions shown in Figures 4-6 can, however, be carried out. To make this comparison, we assume a fuel density of 0.75 kg/L and an average gas mileage for all model years of 23mpg. The LEV II (LEV), 120,000 mile standards for CO, HC, and NO are 4.2, 0.09, and 0.07 gm/mi, respectively. With the above assumptions, these correspond to 34, 0.7, and 0.6 gm/kg, respectively. Inspection of Figures 4-6 shows that

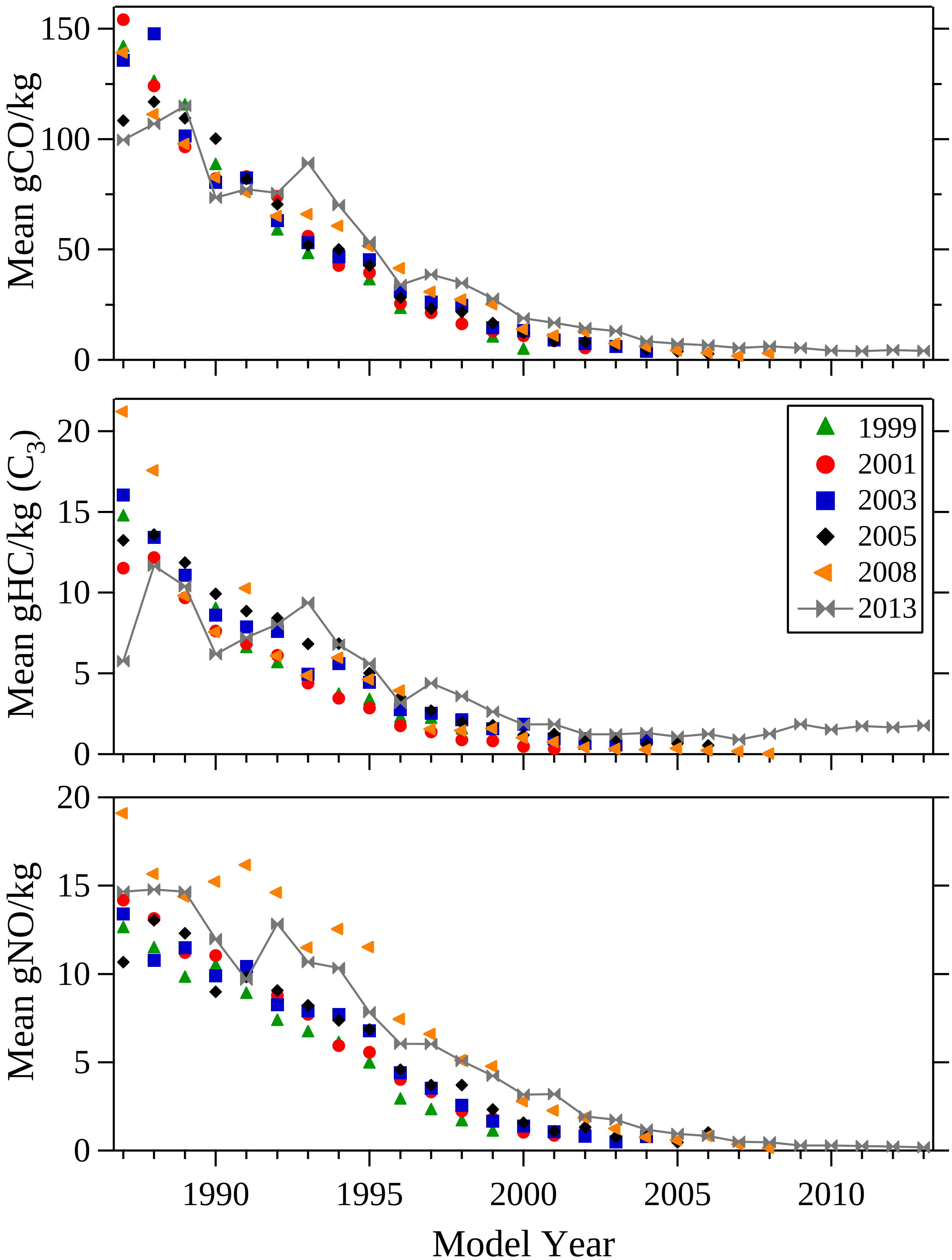

Figure 3. Mean fuel specific vehicle emissions illustrated as a function of model year for all of the West Los Angeles data sets. HC data have been offset adjusted as described in the text.

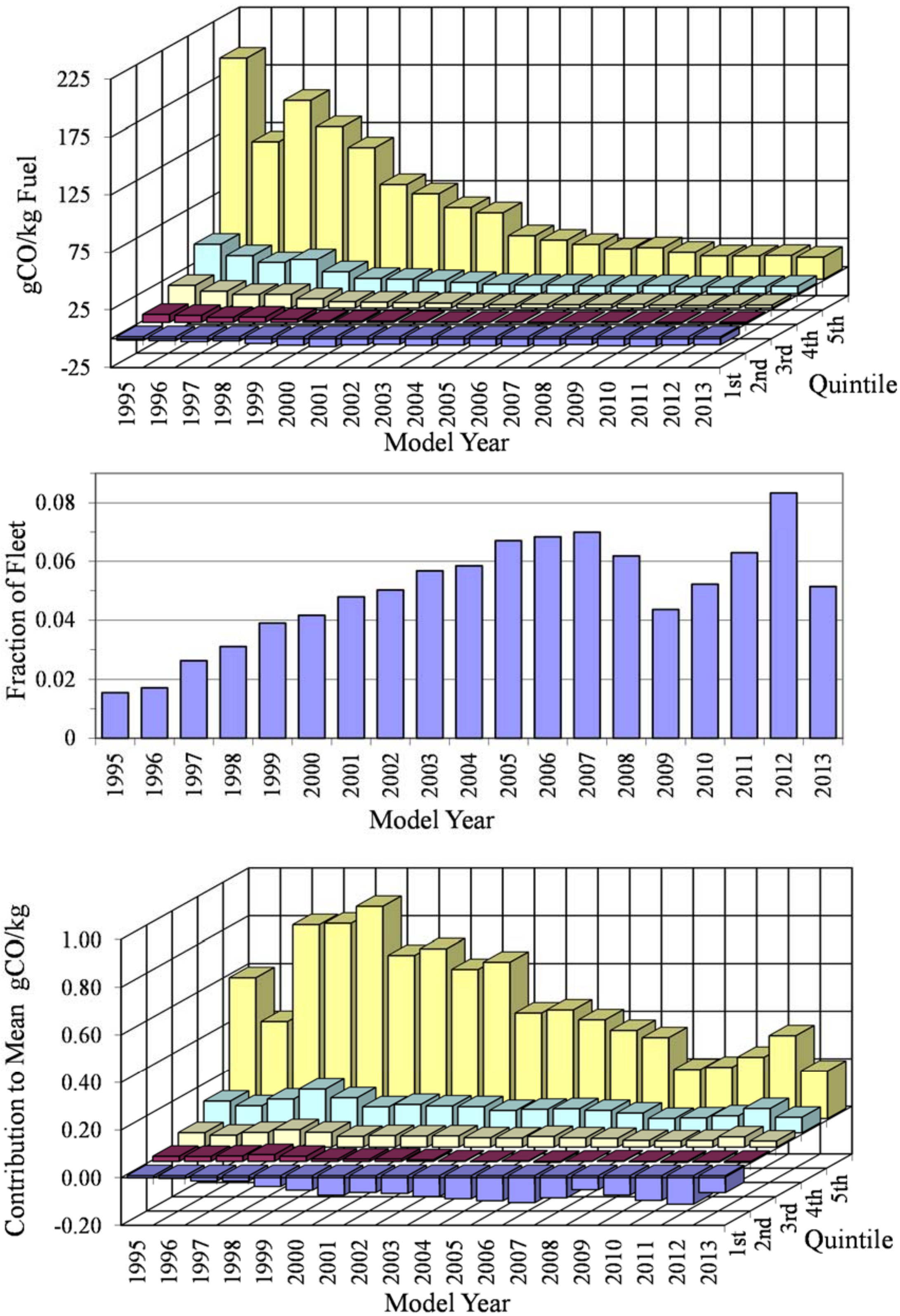

Figure 4. Mean gCO/kg emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gCO/kg emissions by model year and quintile (bottom).

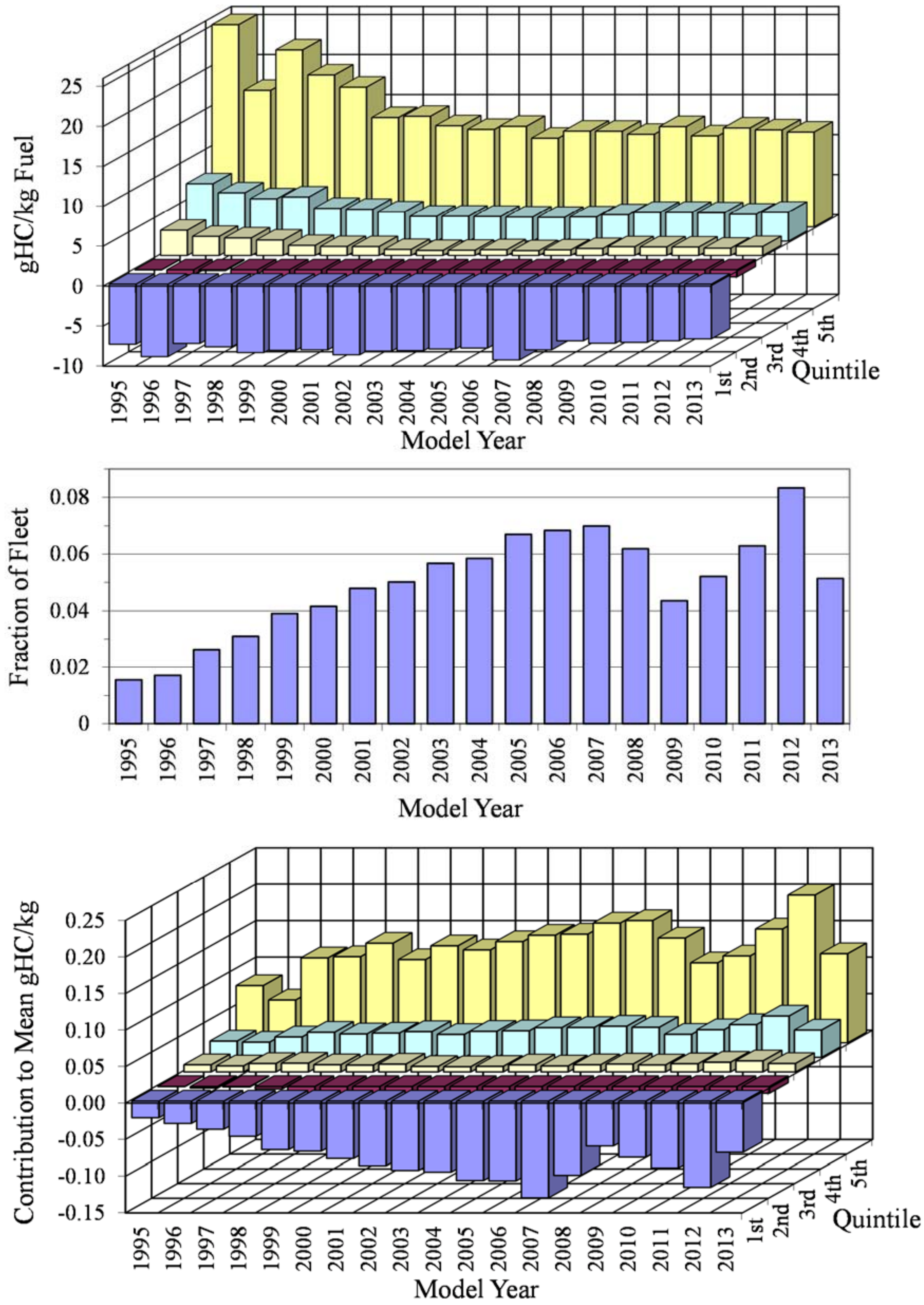

Figure 5. Mean gHC/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gHC emissions by model year and quintile (bottom).

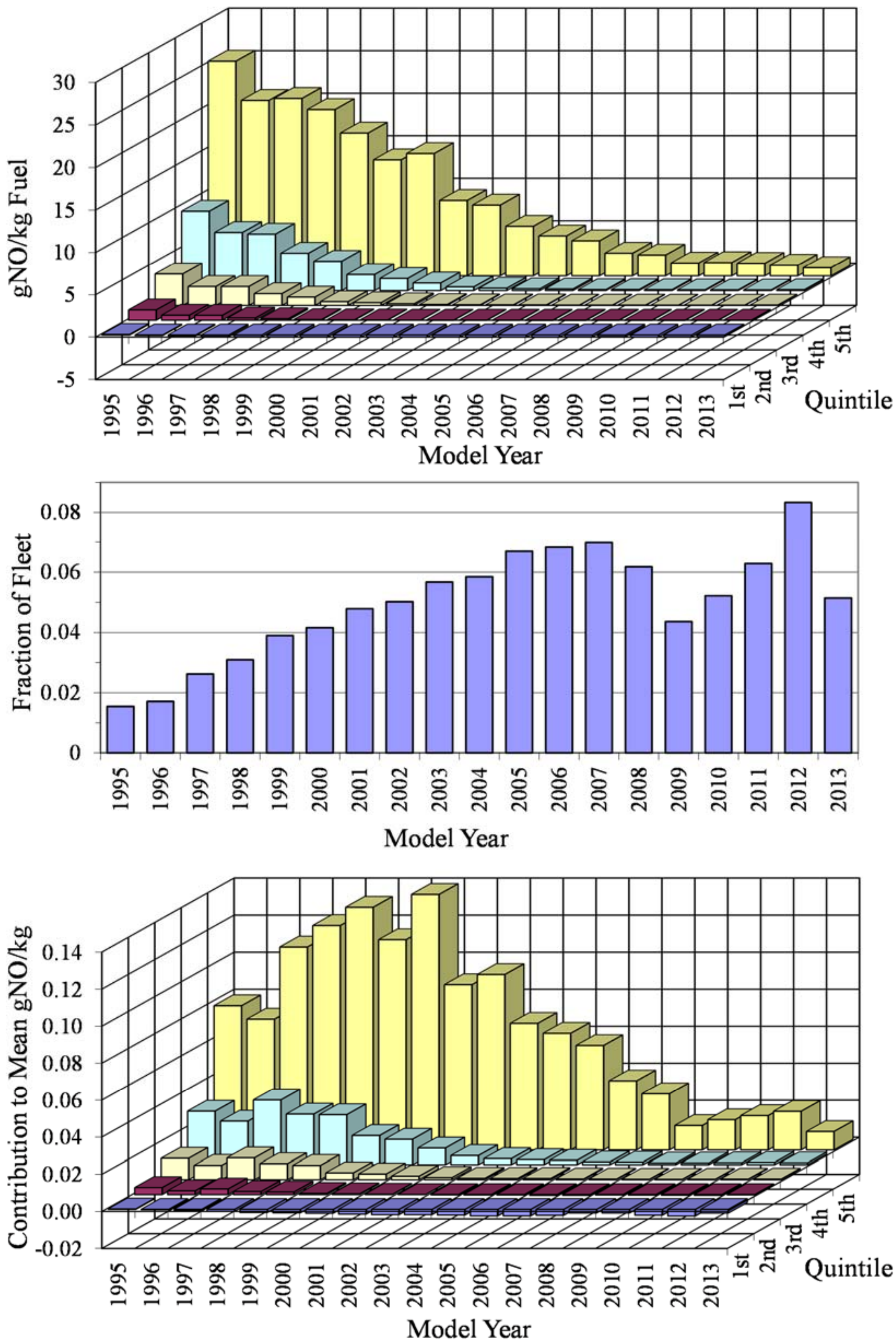

Figure 6. Mean gNO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gNO/kg emissions by model year and quintile (bottom).

significant fractions, especially of the newer vehicles, are measured with on-road emissions well below these standards.

Emissions and Vehicle Specific Power. An equation for determining the instantaneous power of an on-road vehicle has been proposed by Jimenez,[28] which takes the form

$$\text{VSP} = 4.39 \bullet \sin(\mathit{slope}) \bullet v + 0.22 \bullet v \bullet a + 0.0954 \bullet v + 0.0000272 \bullet v^3$$

where VSP is the vehicle specific power in kW/metric tonne, *slope* is the slope of the roadway (in degrees), v is vehicle speed in mph, and a is vehicle acceleration in mph/s. Derived from dynamometer studies, and necessarily an approximation, the first term represents the work required to climb the gradient, the second term is the $f = ma$ work to accelerate the vehicle, the third is an estimated friction term, and the fourth term represents aerodynamic resistance. Using this equation, VSP was calculated for the 2013 measurements and for all of the previous years' databases. This equation, in common with all dynamometer studies, does not include any load effects arising from road curvature. The emissions data were binned according to vehicle specific power, and illustrated in Figure 7. All of the specific power bins contain at least 100 measurements except for VSP's of 30 in 1999, 2001 and 2005 which contain 77, 69 and 90 measurements and VSP's of -10 in 2013 which contain 85 measurements. The HC data have been offset adjusted for this comparison.

The difference in driving mode is readily apparent with a significant shift to lower VSP values for the majority of the measurements in 2013 (bottom panel). In addition the spread of measurements increased in 2013 as the repeatability of the metered onramp was eliminated. All of the emissions continue to decrease with each successive data set. All of the species measured in 2013 show a negative dependence on specific power which was not readily observable in prior data sets. The error bars included in the plot are standard errors of the mean calculated from the daily averages. These uncertainties were generated for these γ-distributed data sets by applying the central limit theorem. Each day's average emissions for a given VSP bin were assumed an independent measurement of the emissions at that VSP. Normal statistics were then applied to these daily averages.

Using VSP, it is possible to reduce the influence of driving behavior in the mean vehicle emissions. Table 4 shows the measured mean emissions for all of the databases (HC data not offset adjusted) for vehicles with only vehicle specific powers between –5 and 20 kw/tonne. Note that these emissions do not vary considerably from the mean emissions for the entire databases, as shown in Table 3. Also shown in Table 4 are the mean emissions for all the databases adjusted (all years of HC data include an offset adjustment) for vehicle specific power to exactly match the 1999 VSP distribution.

This correction is accomplished by applying the mean vehicle emissions for each VSP bin (between –5 and 20 kw/tonne) from a future year's measurements to the 1999 vehicle distribution, for each vehicle specific power bin. A sample calculation, for the vehicle specific powers adjusted mean NO emissions, is shown in Appendix D.

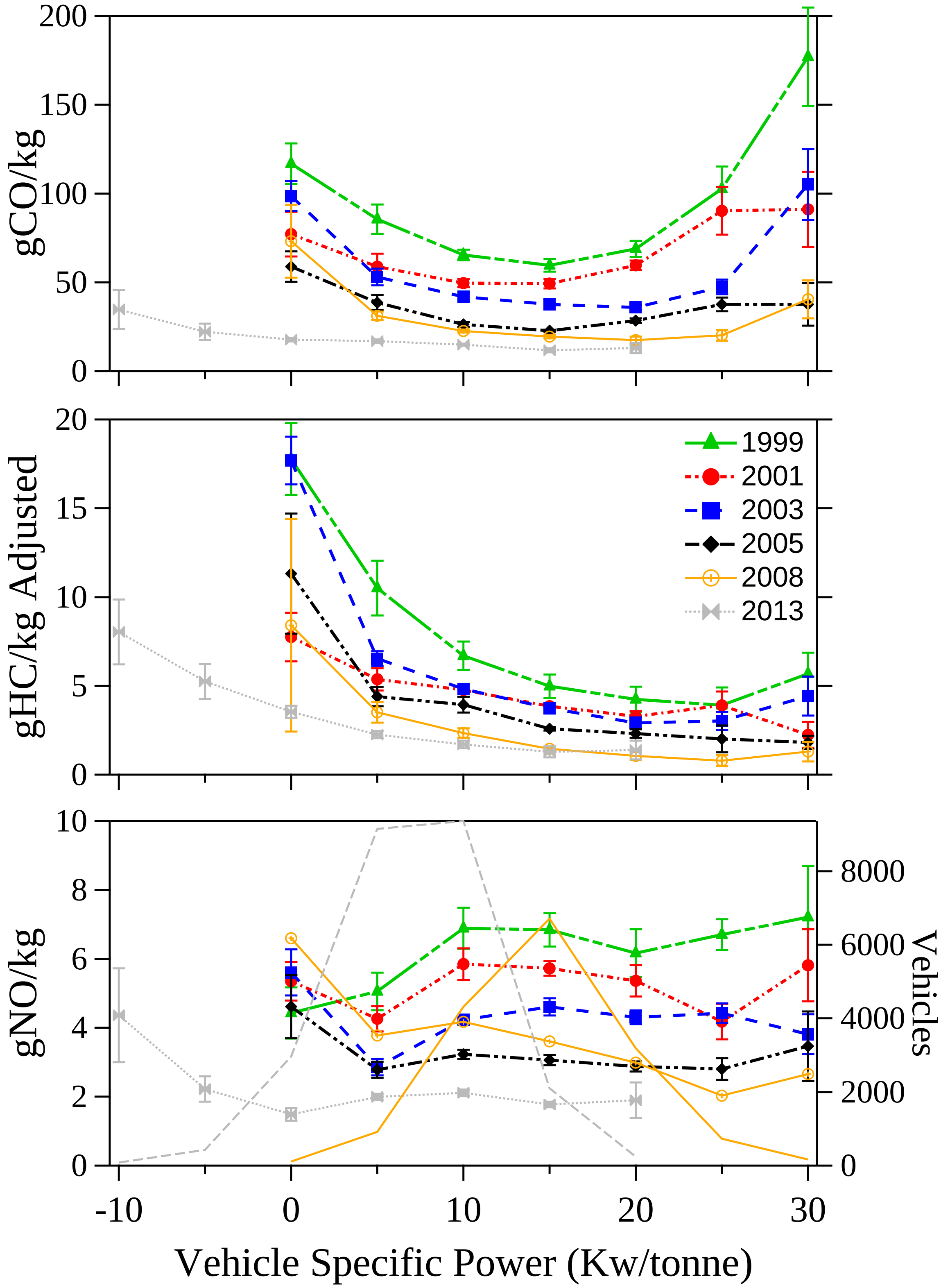

Figure 7. Fuel specific vehicle emissions (left axis) as a function of vehicle specific power for all of the West LA data sets. Error bars are standard errors of the mean calculated from daily samples. The dashed and solid lines without markers (bottom panel) are the vehicle count (right axis) profiles for the 2013 and 2008 data sets respectively.

Table 4. Vehicle specific power emissions adjusted to match the 1999 fleet VSP distribution (-5 to 20 kw/tonne only) with standard error of the means calculated using daily averages.

Species	1999 measured (adjusted)	2001 measured (adjusted)	2003 measured (adjusted)	2005 measured (adjusted)	2008 measured (adjusted)	2013 measured (adjusted)
Mean gCO/kg	68.1 ± 2.1 (68.1 ± 2.1)	52.5 ± 2.5 (52.9 ± 2.6)	40.3 ± 1.0 (43.7 ± 1.0)	26.1 ± 0.6 (28.0 ± 0.7)	21.1 ± 0.5 (23.8 ± 0.6)	15.8 ± 0.7 (13.9 ± 0.6)
Mean gHC/kg[a]	9.1 ± 0.7 (6.7 ± 0.7)	5.2 ± 0.2 (4.5 ± 0.2)	5.7 ± 0.3 (4.9 ± 0.3)	2.8 ± 0.7 (3.5 ± 0.1)	2.2 ± 0.1 (2.5 ± 0.1)	4.1 ± 0.2 (1.7 ± 0.2)
Mean gNO/kg	6.4 ± 0.5 (6.4 ± 0.5)	5.6 ± 0.3 (5.5 ± 0.3)	4.3 ± 0.2 (4.2 ± 0.2)	3.1 ± 0.1 (3.1 ± 0.1)	3.7 ± 0.3 (3.8 ± 0.3)	2.0 ± 0.2 (1.9 ± 0.1)

[a]HC emissions are offset adjusted for all of the years' adjusted data.

The measured and adjusted values of all three of the primary pollutants show large reductions since 1999 with the adjusted values of CO dropping by almost a factor of 5 while the HC and NO adjusted means have dropped by a factor of 4. These rates of reduction are consistent with those reported by other researchers using ambient, airborne and tunnel measurements.[29-31] By controlling for the driving mode first observed in 1999 at the West LA site the HC means are lower than the overall mean observed and reported in Table 3. This again is evidence of the change in driving mode for the 2013 data set caused by the ramp metering lights not being operational.

Historical Fleet Emissions Deterioration. A similar normalization can be used to create a fleet of specific model year vehicles to track deterioration, provided we use as a baseline with only the model years first measured in 1999. A sample calculation, for the model year adjusted mean NO emissions, is shown in Appendix E. Table 5 shows the mean emissions for all vehicles from model year 1984 to 2000, as measured in each of the six measurement years (HC data not offset adjusted). Applying the vehicle frequency distribution by model year from 1999 to the mean emissions by model year from the later studies yields the model year adjusted fleet emissions (all adjusted years of HC data include an offset adjustment). The calculation indicates that, although some of the measured decrease in fleet average emissions is due to fleet turnover, the emissions of even the older model years (1984-2000) measured previously has not increased significantly. The slow growth in emissions deterioration over a growing period of time (now 13 years) is likely the result of a large number of factors and not just the imposition of reformulated fuels, as discussed in previous CRC reports, and as observed on-road by Kirchstetter et al.[32] The measurements in 2013 included monitoring on the weekend for the first time and as such the number of vehicles for the 1984 -2000 model year fleet is enlarged and does not give the true picture of the shrinkage from the previous years. If we only count the number of 1984 – 2000 model year vehicles that we measured between Monday and Friday that number is 4,519 and represents shrinkage of about 75% from 1999. The mean emissions presented here include not only vehicle fleet emission deterioration, but all the mechanisms which result in vehicles being

Table 5. Model year adjusted fleet emissions (MY 1984-2000 only). Errors are standard error of the means calculated from the daily means.

Species	1999 measured (adjusted)	2001 measured (adjusted)	2003 measured (adjusted)	2005 measured (adjusted)	2008 measured (adjusted)	2013 measured (adjusted)
Mean gCO/kg	60.6 ± 2.0 (60.6 ± 2.0)	52.1 ± 2.3 (61.1 ± 2.7)	51.5 ± 1.6 (65.6 ± 2.0)	43.0 ± 0.7 (61.4 ± 0.9)	46.2 ± 0.9 (68.1 ± 1.3)	44.8 ± 1.8 (71.0 ± 2.9)
Mean gHC/kg[a]	8.3 ± 0.6 (5.9 ± 0.6)	5.2 ± 0.2 (5.2 ± 0.2)	6.8 ± 0.3 (6.7 ± 0.3)	4.5 ± 0.6 (6.9 ± 0.2)	4.2 ± 0.3 (6.8 ± 0.5)	4.4 ± 0.3 (6.7 ± 0.5)
Mean gNO/kg	6.2 ± 0.4 (6.2 ± 0.4)	6.1 ± 0.4 (7.0 ± 0.4)	5.8 ± 0.2 (7.0 ± 0.3)	5.5 ± 0.2 (7.3 ± 0.3)	8.3 ± 0.6 (11.0 ± 0.8)	6.5 ± 0.1 (9.3 ± 0.2)
Vehicles[b]	17,903 17,798 17,798	17,304 17,194 17,194	13,827 13,786 13,786	10,125 10,111 10,111	6498 6481 6488	6069 6049 6064

[a]HC emissions are offset adjusted for all of the years measured and adjusted data.

[b]Number of vehicles in the CO, HC and NO means.

permanently removed from the fleet. The slowly increasing fleet mean emissions with time suggest that vehicle retirement is positively correlated with higher emissions, i.e. high emitting vehicles on average die sooner.

Another way to measure vehicle deterioration is to look at the mean emissions changes over time by model year. This type of analysis is only possible with the long historical record of emission measurements we have at the West LA site. Figure 8 is a plot of emissions deterioration rates for CO, HC and NO calculated with the assumption that vehicle emissions deterioration can be modeled as a linear process. The mean emissions for each individual model year from each measurement campaign are plotted against that model year's age at the time of the measurements and a line is fit using a linear least squares method. The resulting slope of that line is an emissions deteriorations rate in grams of emissions per kilogram of fuel used per year. A minimum of three measurement points are needed and as of the 2013 measurements we are only able to calculate these statistics for 2006 and older model year vehicles. This then covers an age range from 8 to 30 year old vehicles.

All of the species experience emissions deterioration during the first 20+ years of life when smaller measurement numbers introduce more variability and larger errors. The shape of the NO emissions plot (bottom panel) can at least be rationalized by combining the notion that as the 3-way catalyst ages it loses its efficiency at reducing NO emissions allowing them to rise until the fleet reaches a point where factors from engine age limit NO production leading to its decrease. For CO and HC the deterioration rates are remarkably consistent until the early 90's where again the rates appear to decrease but the increase in noise makes that impossible to statistically prove. If the presence of the OBDII check engine light (in 1996 and newer vehicles) has increased or improved emission related repairs for vehicles then we might expect to see a decrease in emission deterioration rates after 1996. Figure 8 shows there is no significant statistical

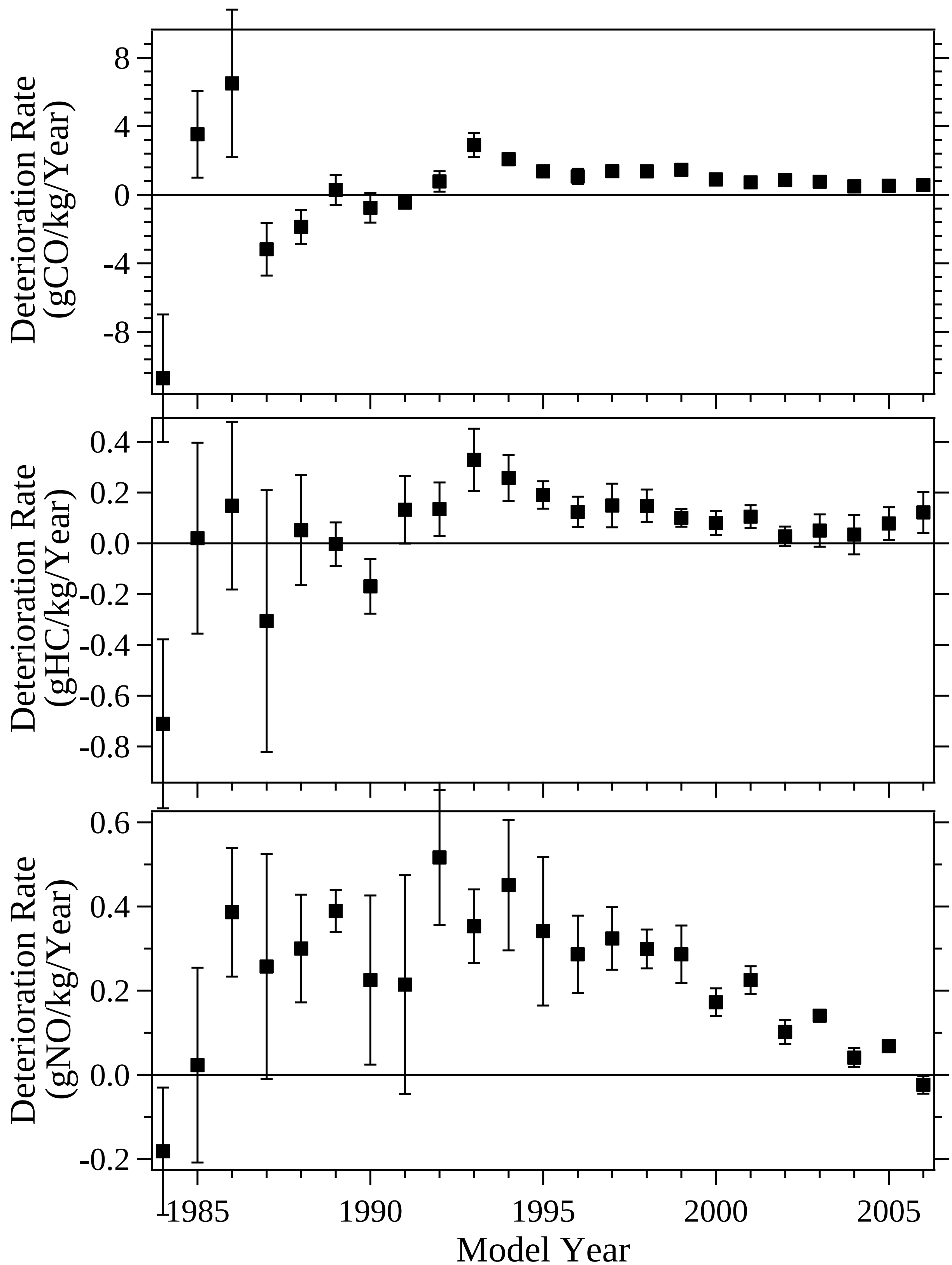

Figure 8. On-road fuel specific emissions deterioration rates vs. model year for the West LA sampling location incorporating the 2013 data. The uncertainty bars plotted are the standard error of the slope for the least-squares fit.

difference in the emissions deterioration rates between the 1995 and 1996 model years, even though there is a statistical difference in emission levels (see Figure 3). Figure 8 does lend support to the idea that vehicle attrition has a hand in keeping deterioration rates low for such long periods of time as it represents one of the largest distinguishing factors between newer and older model years. It is difficult to explain negative emissions deterioration rates among the oldest models without vehicle attrition being a major piece of that explanation. It is possible that the remaining oldest model vehicles either have had their engines reconditioned, or have been very well maintained, or have had exceptionally low mileage, hence the very low or even negative deterioration rates.

We previously discussed the emissions by model year for CO, HC and NO and pointed out that the 2013 HC emissions appear to decrease in models older than 2009 model year vehicles. Figure 9 is a plot of adjusted gHC/kg of fuel emissions by model year and includes standard error of the mean uncertainty estimates for each model year. The uncertainties have been calculated by assuming that each daily gHC/kg mean is a random sample and that those daily means will be normally distributed and a standard error of the mean can be estimated. With the errors plotted it is easy to see that while the 2002 – 2008 model years are lower than the following newer models the uncertainties in the measurement means make those differences statistically similar. Vehicle speeds, accelerations and therefore VSP all increase linearly from the 2000 models with the newest models having the highest values for all of those parameters. However, as shown in Figure 7 increasing VSP leads to lower mean gHC/kg of fuel values and so that is unlikely a major issue.

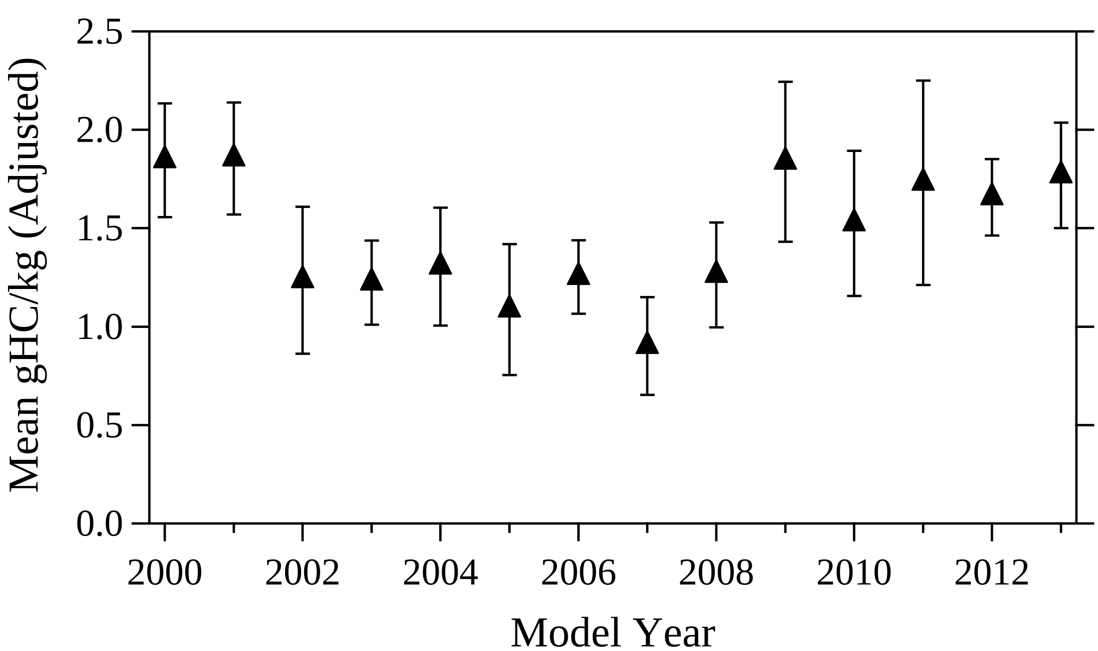

Figure 9. Mean gHC/kg of fuel emissions as a function of model year. The uncertainty bars plotted are the standard error of the mean determined from the daily samples. The data have been offset adjusted as described in the text.

2008 Recession Effects. The middle graph in Figures 4 – 6 previously showed the fleet fractions by model year for the 2013 West LA database. The dramatic drop in new car sales beginning in late 2008 and continuing through the 2011 model year is clearly evident. The previous recession that occurred in 2001 is not noticeable in this data set though we have previously reported that data collected in San Jose and Fresno clearly showed its effects.[18] Nationwide new car sales, as reported by the National Automobile Dealers Association, for 2009 were the lowest per capita since World War II.[33] California new vehicle registrations for 2009 were 45% lower than for 2007. For the 2013 West LA data there are 38% fewer 2009 model year vehicles than 2007 models. We have one other data set collected in Van Nuys in August of 2010 to compare with. Figure 10 shows the fleet fractions for the 2013 West LA data set compared to the 2010 Van Nuys data. Both data sets show nearly identical reductions for 2008 and 2009 model year vehicles. Because of the lag in new vehicle registrations the 2010 model year data from Van Nuys would not have been fully populated by the time that these measurement were collected. It should be noted that model year 2012 has more vehicles than 2007 to negate some of the previous years' losses.

The direct result is that both fleets have gotten significantly older on average. Table 3 summarized the mean fleet ages for all of the previous data sets collected at the West LA site since 1999 highlighting a slight decrease in the average age from 7.8 to 7.4 years. Data sets collected near Riverside CA between 1999 and 2001 had similar mean fleet ages of 7.4, 7.5 and 7.3 years.[29] The age increase to 9.1 years at the West LA site is significant and it will be

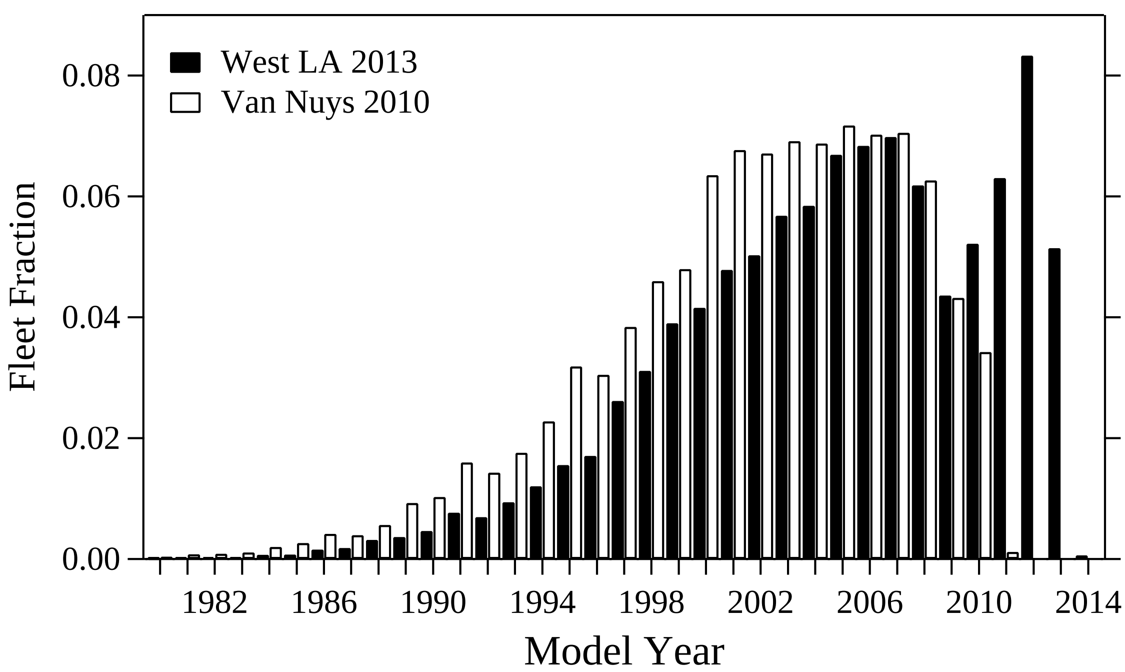

Figure 10. Fleet fractions by model year for the 2013 West LA data (filled bars) and a data set collected in Van Nuys in August of 2010 (open bars). Keep in mind that these data sets were collected more than 2.5 years apart and that similar model years at West LA have 2.5 years of attrition included.

interesting to see if future model year's sales increase to help to recover some of this lost ground as we see with the 2012 models.

We can estimate where those changes have taken place by comparing the fleet fractions between the 2013 and 2008 distributions. We cannot directly map model years between the two data sets because they were collected five years apart so we have mapped all model years to vehicle age ignoring the 5 to 6 weeks difference between sampling dates. Figure 11 is a bar chart which compares the fleet fraction distribution for the 2013 and 2008 West LA data sets. The vehicle age has been estimated assuming that a vehicle model year starts in September. As expected the large reduction in early model year vehicles did not exist in the 2008 sample and that in turn has created an excess of ~10 to 25 year old vehicles. These changes are not uniformly distributed across vehicle types either. The VIN data for the 2008 and 2013 data sets were decoded for vehicle type by Polk tagging each vehicle as a passenger vehicle or truck. Figure 12 is a bar chart that compares the fleet fraction distribution for the 2013 and 2008 West LA data sets for passenger vehicles and trucks. Truck sales suffered a larger percentage drop than the passenger vehicles during the recession and the increase in the number of 10 to 25 year old vehicles has a larger contribution from the truck segment as well.

While a recession cannot cause an increase in tailpipe emissions it can forestall reductions that would have occurred had the mean fleet age remained similar to the 2008 data set. To estimate the magnitude of these lost reductions we used the fleet model year fractions from the 2008 data set to make the 2013 fleet have the same age as the 2008 fleet. Figure 13 is a bar chart of the 2013 measured fleet average emissions (solid bars) and the "modeled" emissions (hatched bars)

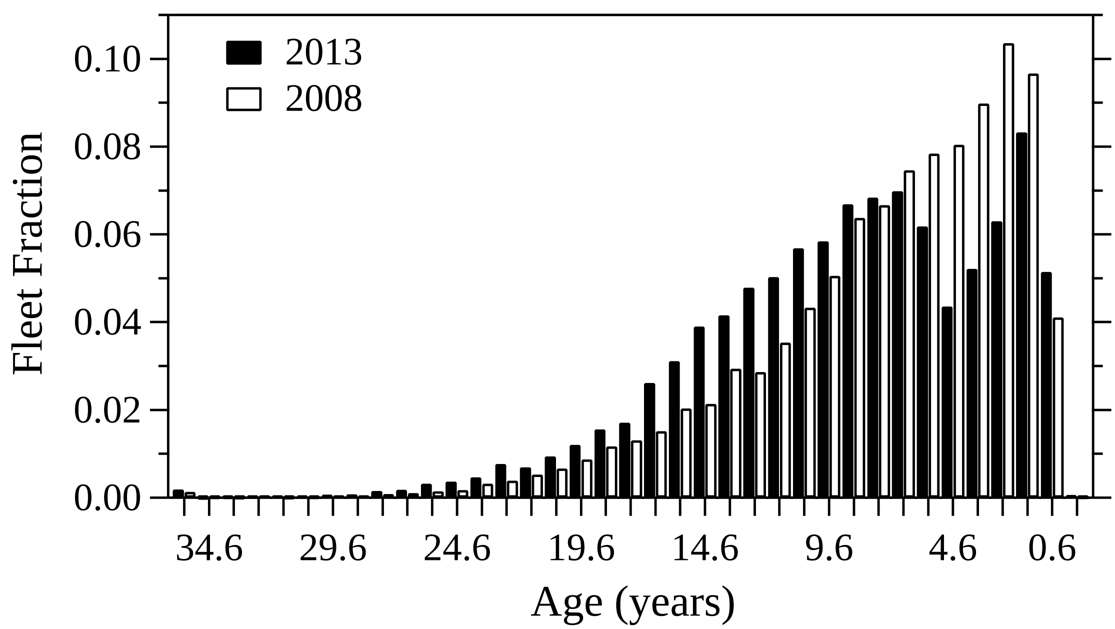

Figure 11. Fleet fraction plotted by vehicle age for the 2013 (filled bars) and 2008 (open bars) West LA data sets. The vehicle age calculation assumes a September 1 date for each new model year.

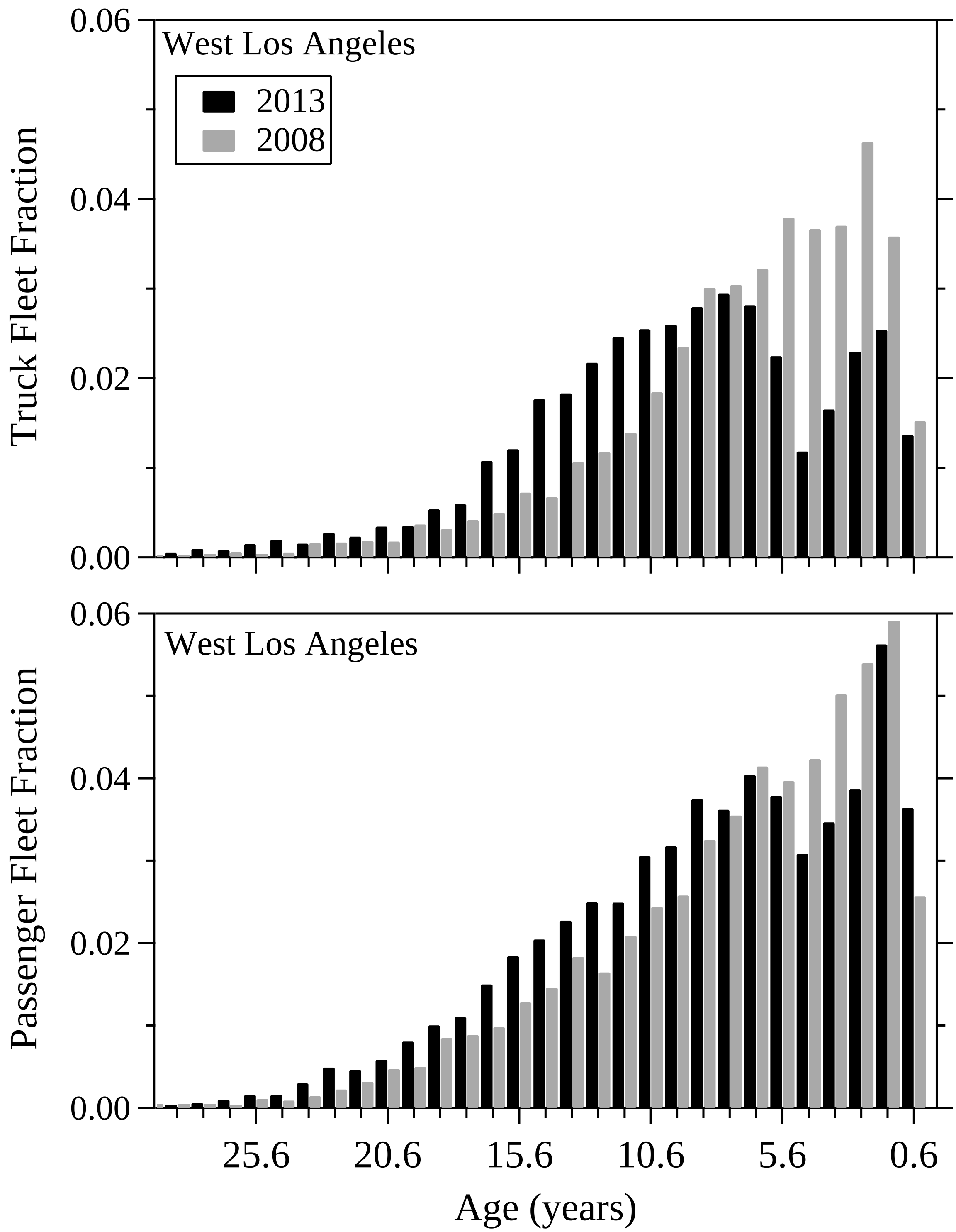

Figure 12. Fleet fractions plotted by vehicle age comparing the 2013 (black bars) and 2008 (grey bars) West LA data sets by vehicle type. The top panel shows the fractions by age for vehicles labeled as a truck by the Polk VIN decoder. The bottom panel shows the fractions by age for the passenger fleet.

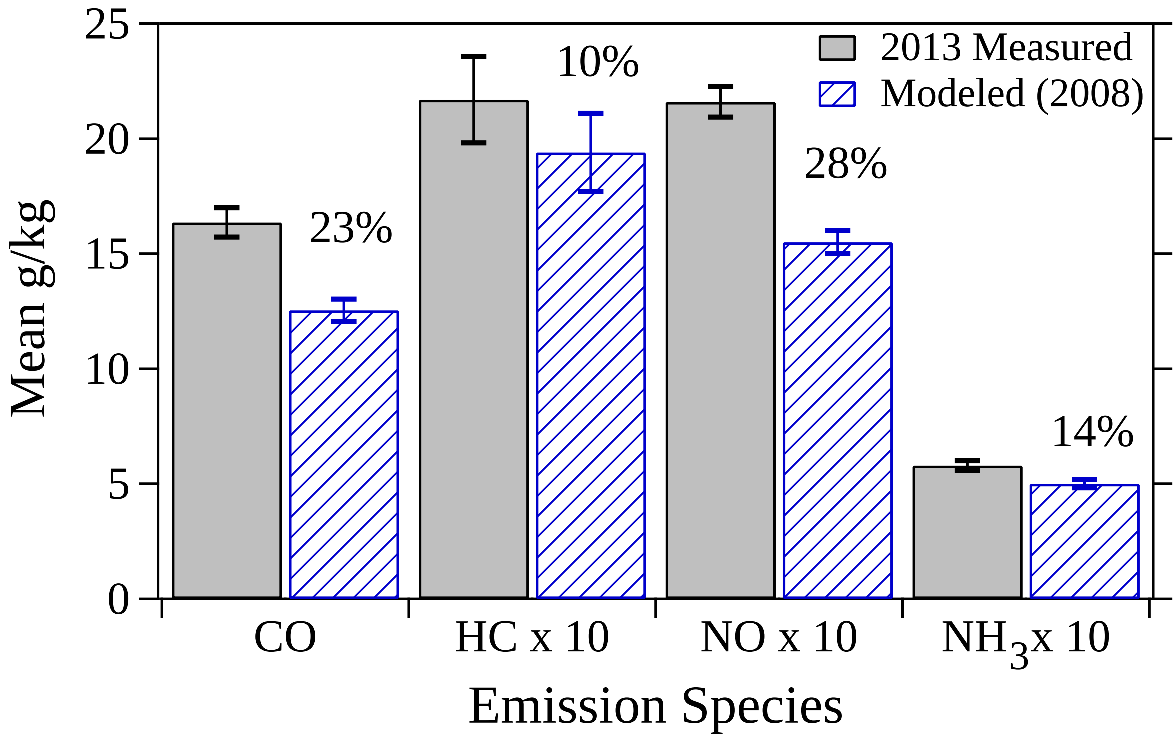

Figure 13. Fleet mean emissions comparison for the 2013 West LA data set as measured (solid bars) and when modeled (hatched bars) to match the 2008 fleet age (7.4 yrs old). Uncertainties are standard errors of the mean calculated from the daily means for the original data and are the same for each species measured and modeled mean. HC, NO and NH_3 emissions values are multiplied by 10 for easier viewing. Percentages are the differences between measured and modeled means.

that would have been observed if the 2013 fleet had the same age (7.4 years old) distribution as the 2008 data set. The 2013 modeled data set has 23% lower CO (3.8 g/kg), 10% lower HC (0.2 g/kg), 28% lower NO (0.6 g/kg) and 14% lower NH_3 (0.08 g/kg) emissions. All the emission differences except HC are statistically significant. A similar calculation for the Van Nuys data set (mean fleet age ~9.5 yrs) resulted in generally larger differences of 29%, 28%, 25% and 11% for CO, HC, NO and NH_3 respectively. The increases likely reflect the fact that the data were collected closer to the actual recessionary period while the West LA site has benefited by some rebound in recent vehicle purchases.

We can take the differences between the measured and modeled emissions and distribute them across the 2013 model years to see which age groups were affected the most by the lack of new car purchases. Figures 14 and 15 graph the 2013 measured minus the modeled emission differences in grams per kilogram of fuel by model years for gCO/kg (3.8g/kg of fuel difference), gHC/kg (0.2 g/kg of fuel difference), gNO/kg (0.6 g/kg of fuel difference) and gNH_3/kg (0.08 g/kg of fuel difference). The 1983 model year bar includes not only the 1983 model year vehicles but any older models as well. It is also important to point out that these emission differences are independent of the changes in driving mode previously discussed since

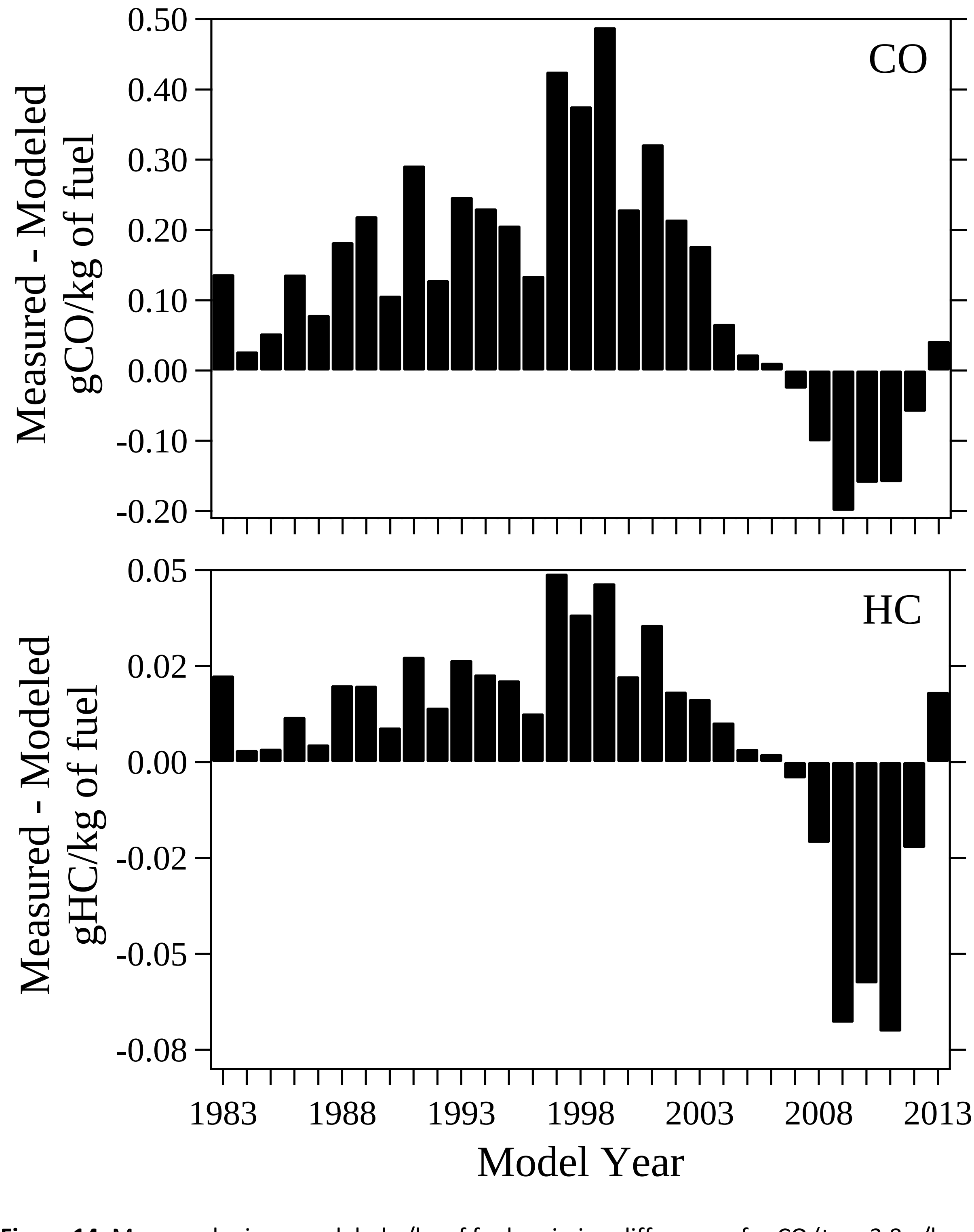

Figure 14. Measured minus modeled g/kg of fuel emission differences for CO (top, 3.8 g/kg of fuel) and HC (bottom, 0.2 g/kg of fuel) versus model year for the 2013 West LA site. Positive values indicate 2013 emissions that would not be present if the rate of fleet turnover had not been slowed by the recession, and the 2013 fleet's age distribution was as measured in 2008. Negative values are model years where emissions are lacking due to fewer vehicles.

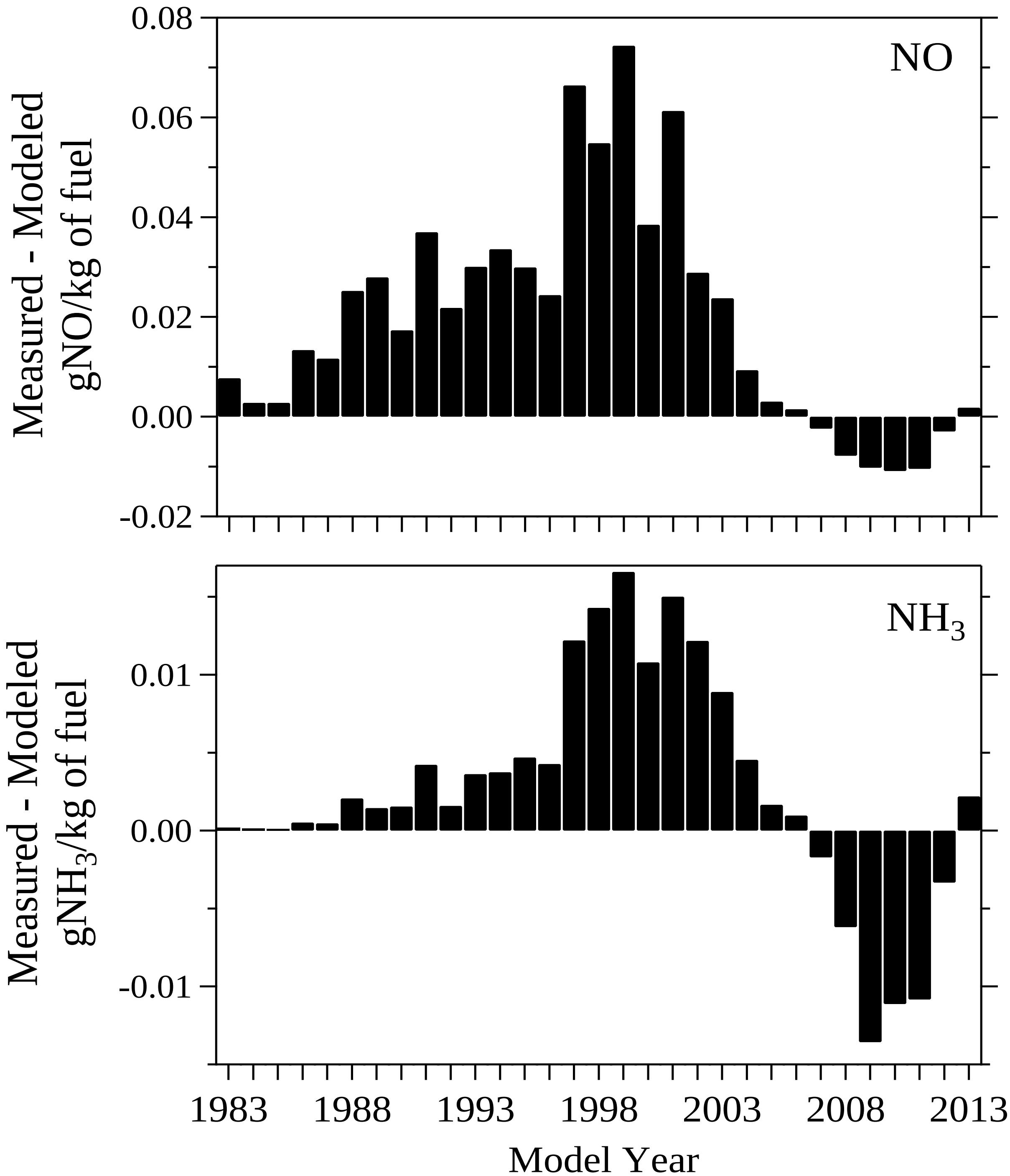

Figure 15. Measured minus modeled g/kg of fuel emission differences for NO (top, 0.6 g/kg of fuel) and NH_3 (bottom, 0.08 g/kg of fuel) versus model year for the 2013 West LA site. Positive values indicate 2013 emissions that would not be present if the rate of fleet turnover had not been slowed by the recession, and the 2013 fleet's age distribution was as measured in 2008. Negative values are model years where emissions are lacking due to fewer vehicles.

these calculations only depend on the changes in the emissions distribution of the 2013 fleet. Positive values indicate 2013 emissions that would not be present if the rate of fleet turnover had not been slowed by the recession, and the 2013 fleet's age distribution was as measured in 2008. Negative values are model years where emissions are lacking due to fewer vehicles. As expected from the fleet fraction differences shown in Figure 11 the measured minus modeled emissions for all of the species starts to accumulate around 10 year old vehicles (2003 to 2004 models) peaks around 15 year old vehicles (1998 to 1999 models) and then tails off. The measured minus modeled differences observed for the first fifteen model years is largely driven by the differences in the fleet fractions while during the later fifteen years the emissions distribution appears to play a more important role. For example the NH_3 emissions have a narrower peak and very short tail compared to the other species as a gasoline vehicle loses its ability to reduce NO to NH_3 as its catalyst ages. The lost reduction in emissions is only part of the overall emission picture at the West LA site. The recession also resulted in a reduction in fuel sales. The state wide survey of yearly gasoline sales for California reports a 4 to 7.5% reduction in gallons sold since 2007.[34] When combined with the estimated emission reductions lost there will still be significant amounts of CO and NO and to a lesser extent NH_3 reductions that the recession has forestalled.

Weekday versus Weekend Comparison. Because weekday and weekend traffic differences have been implicated in many metropolitan areas as being a driver for differences in resulting ozone precursor levels as part of this study we measured differences in the light-duty fleet during both periods for the first time at the West LA site.[35-37] Table 6 is an emissions comparison table that groups the data into weekday (Monday - Friday) and weekend (Saturday and Sunday) sets. The HC data are offset adjusted and the uncertainties reported are standard errors of the mean calculated from the daily averages. Saturday and Sunday standard errors of the mean use the same uncertainties calculated for the weekend data. The only statistically significant difference observed is the Sunday gHC/kg of fuel emission being the lowest reported value for the comparison. Mean model year differences are also insignificant with Sunday having the newest fleet. The fraction of diesel vehicles is higher for weekdays (~2.4%) than on the weekend days 1.5% on Saturday and 0.5% on Sunday). Traffic volumes in 2013 did not decrease on Saturday and were actually slightly higher than the weekdays. While the hourly rates on Sunday were the highest the measurements were only collected in the afternoon (13:00 – 18:30) as equipment that was damaged on Saturday took most of Sunday morning to replace.

Hybrid Vehicle Emissions. The matched data provided by the California DMV generally includes fuel type with a special designation (Q) for hybrid drive train vehicles. We have previously discussed the observation that hybrid drive train vehicles have significantly lower NO emissions; however that has not been the case for HC emissions. Initially we were concerned that this differences might be the result of a water interference as the original data sets collected at the West LA site were collected in the late fall with cooler temperatures and higher humidity. Since then we have collected two data sets at the West La site during the spring and one data set from Van Nuys in 2010.[29] The amount of hybrid drive train vehicles have grown from zero in the early 2000's to more than 3.3% of the measurements in the 2013 data set. This number will likely underrepresent the fleet makeup at the West LA site as our measurement method requires

Table 6. 2013 Comparison of Mean Emissions for the Weekday and Weekend Data.

Period (Hourly Rate)	Mean gCO/kg (counts)	Mean gHC[a]/kg (counts)	Mean gNO[b]/kg (counts)	Mean gNO_2^c/kg (counts)	Mean gNH_3/kg (counts)	Mean gNO_x^c/kg (counts)	Mean Model Year	Diesel Fraction
Weekday (354)	16.4±0.6 (20045)	2.2±0.2 (19988)	2.2±0.1 (20038)	0.17±0.03	0.58±0.03	3.5±0.1	2004.7	0.024
Weekend (363)	16.1±1.6 (7202)	2.2±0.5 (7180)	2.1±0.2 (7202)	0.14±0.03	0.58±0.03	3.3±0.3	2004.8	0.012
Saturday (360)	16.6±1.6 (5161)	2.5±0.5 (5150)	2.1±0.2 (5161)	0.11±0.03	0.59±0.03	3.3±0.3	2004.7	0.015
Sunday[d] (371)	14.9±1.6 (2041)	1.2±0.5 (2030)	1.9±0.2 (2041)	0.20±0.03	0.56±0.03	3.1±0.3	2005	0.005

[a] HC data is offset adjusted as described in the text
[b] moles of NO
[c] moles of NO_2
[d] Because of equipment problems Sunday measurements do not include the morning hours.

a minimum amount of CO_2 emissions before we can measure a vehicle and some fraction of hybrid attempts will register below this minimum and we will thus be unable to register a reading and undercount. However, this process should be random and our hybrid data set is large enough (921 records) that mean emission rates for these vehicles will not be underrepresented. Table 7 contains a summary for all of these data sets and includes the mean emissions for the hybrid vehicles and the age-adjusted composite emissions for the remaining vehicles identified as being fueled by either gasoline or natural gas. The age adjustment is constructed by using the mean emissions by model year for the other vehicles and then weighting those means according to the age distribution of the hybrid vehicles. The uncertainties reported are standard errors of the mean calculated using the daily means. The HC emissions for the 2013 West LA data set are still higher for the hybrid vehicles; however, the differences are not statistically significant as the standard error of the means for the hybrid measurements are still too large. There still are not enough hybrid vehicles in operation to say with certainty that their on-road fuel specific HC emissions are higher than conventional vehicles.

<u>Ammonia Emissions.</u> While NH_3 is not a regulated pollutant it is a necessary precursor for the production of ammonium nitrate which is often a significant component of secondary aerosols and $PM_{2.5}$ found in urban areas such as LA.[38] Ammonia is most often associated with farming and livestock operations but it can also be produced by 3-way catalyst equipped vehicles.[39] The production of NH_3 emissions is contingent upon the vehicles ability to produce NO in the presence of a catalytic convertor that has enough stored hydrogen to reduce that NO to NH_3. Without either of these species the formation of exhaust NH_3 is precluded. Dynamometer studies have shown that these conditions can be met when acceleration events are preceded by a deceleration event though not necessarily back to back.[40] Previous on-road ammonia emissions have been reported by Baum *et al.* for a Los Angeles site in 1999, by Burgard *et al.* in 2005 from gasoline-powered vehicles for sites in Denver and Tulsa and by Kean et al in 1999 and 2006 from the Caldecott tunnel near Oakland.[41-44] In 2008 the University of Denver collected NH_3 measurements at three sites in California San Jose, Fresno and the West LA site and from a Van

Table 7. Comparison between Hybrid and Age Adjusted Gasoline Vehicle Emissions.

Fleet Site Year	Mean gCO/kg	Mean gHC^{a}/kg	Mean gNO^{b}/kg	Mean gNO_2^{c}/kg	Mean gNH_3/kg	Mean gNO_X^{c}/kg	Mean Model Year	Counts
Hybrids West LA 2005	3.5 ± 1.8	2.7 ± 0.2	0.24±0.07	N.A.	N.A.	N.A.	2004.3	82
Gasoline West LA 2005	4.3 ± 0.2	0.6 ± 0.1	0.31±0.03	N.A.	N.A.	N.A.	2004.3	8928
Hybrids Van Nuys 2010	-0.8 ± 0.5	0.8 ± 0.9	0.2 ± 0.1	0.02 ± 0.02	0.21 ± 0.04	0.4 ± 0.1	2007.3	143
Gasoline Van Nuys 2010	2.5 ± 0.2	0.29 ± 0.03	0.3 ± 0.01	0.04 ± 0.01	0.36 ± 0.01	0.53 ± 0.02	2007.3	7861
Hybrids West LA 2013	5.3 ± 0.7	2.4 ± 0.6	0.16 ± 0.3	0.06 ± 0.02	0.35 ± 0.03	0.30 ± 0.05	2009.1	921
Gasoline West LA 2013	5.4 ± 0.7	2.2 ± 0.2	2.0 ± 0.1	0.09 ± 0.01	0.60 ± 0.02	0.53 ± 0.02	2009.1	20800

[a] HC data is offset adjusted as described in the text
[b] moles of NO
[c] moles of NO_2

Nuys site in 2010.[18, 29] In addition air borne measurements of ammonia were collected in 2010 over the South Coast Air Basin as part of the CalNex campaign.[12]

Figure 16 compares gNH_3/kg of fuel emissions collected at the West LA site for the 2013 and 2008 measurement campaigns by model year. The uncertainty bars plotted are the standard errors of the mean determined from the daily samples for each model year. The data show the characteristic shape with NH_3 emissions increasing with age until vehicles get about 20 years old when the emissions start decreasing until they are indistinguishable from zero. Because NH_3 emissions are sensitive to vehicle age, and these data were collected five years apart, it gives the viewer an incorrect impression that these two data sets have similar means. Figure 17 compares the same two data sets but plots them against vehicle age. This better shows the influence of the ramp metering lights, which were functioning properly in 2008, had on our previous NH_3 measurements. The NH_3 mean emissions observed in 2008 were 0.79 ± 0.02 g/kg and the mean measured for the 2013 data were 0.58 ± 0.02 g/kg with the change in driving mode between the two data sets likely responsible for the much of the difference. The mean observed for this data set are identical to the mean observed at a Van Nuys location (0.59 ± 0.02) in August of 2010.[29]

One research interest for this data set was to estimate the rate of change, if any, for NH_3 emissions from light-duty vehicles. To make this comparison we would need to adjust for the

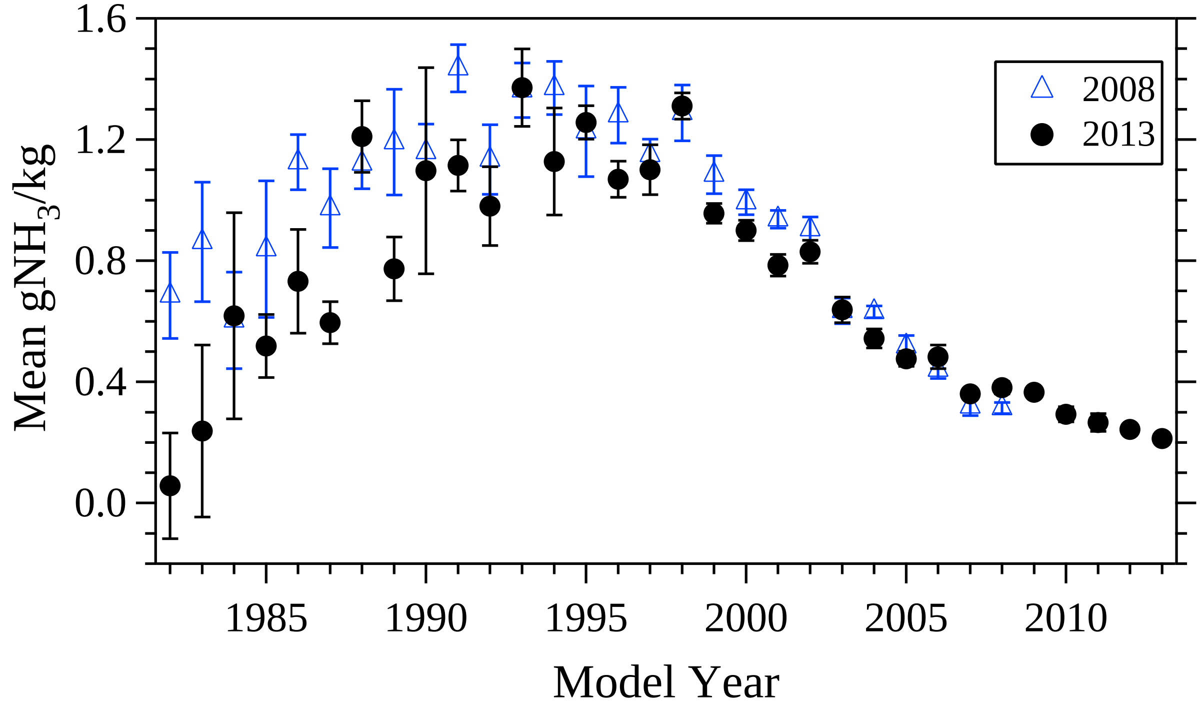

Figure 16. Mean gNH_3/kg of fuel emissions plotted against vehicle model year for the 2013 (circles) and 2008 (triangles) measurements at the West LA site. The uncertainty bars plotted are the standard error of the mean determined from the daily samples.

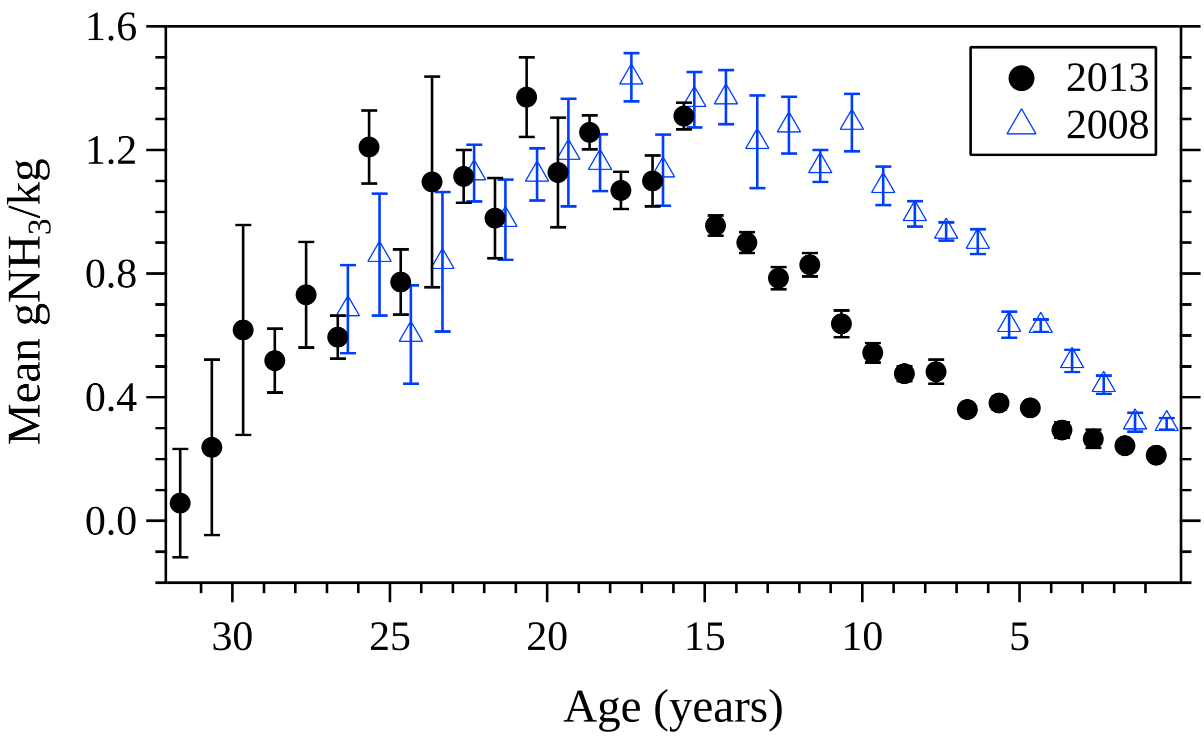

Figure 17. Mean gNH_3/kg of fuel emissions plotted against vehicle age for the 2013 (circles) and 2008 (triangles) measurements at the West LA site. The uncertainty bars plotted are the standard error of the mean determined from the daily samples.

changes in driving mode. If we adjust the 2013 data set to match the VSP driving mode of the 2008 data, to attempt to compensate for the driving mode change, we do increase mean emissions by about 10% (0.58 to 0.62) but there is still a large difference and it is unlikely that it is a true age difference. It looks as if this research question will have to be answered by the data collected in 2015 where we will have a driving mode which will match either the 2013 or 2008 data sets from which we can make a direct comparison.

Historical 99th Percentile Trends. Vehicle emissions distributions are most like a gamma distribution and the skewed nature of that distribution emphasizes the disproportional contribution of the minority of vehicles found in the tail of the distribution.[45] One useful metric for evaluating the changes in the tail of the distribution is to follow the 99th percentile over time. Figures 18 and 19 are plots of the CO, HC and NO 99th percentiles for all the West LA databases as a function of measurement year. The 99th percentile represents 31% of the total 2013 CO emissions, 29% of the 2013 HC emissions and 21% of the 2013 NO emissions. We have included all of the measurements in the database including the diesel fraction. We would expect this to have the largest effect on the NO distribution but at the extremes of the data set these differences are not a large as one might expect. The 99th percentile for NO is 34 g/kg for all of the 2013 data and 33.5 when the diesel fuel vehicles are excluded. Since 1999 the 99th percentile for CO has been reduced by more than a factor of 3 while the HC and NO 99th percentiles have been reduced by smaller amounts. Mean model years of the 99th percentiles vehicles have been reduced from 1984 to 1993 for CO, 1986 to 1999 for HC and 1987 to 1996 for NO. Only the CO distribution shows a significant jump in age to ~21 years old in this data set. For HC the mean model year for the 99th percentile increased by more than 6 years which might indicate some influence by the changes in driving mode as previously discussed.

Instrument Noise Evaluation. In the manner described in the Phoenix, Year 2 report,[46] instrument noise was measured using the slope of the negative portion of a plot of the natural log of the binned emission measurement frequency versus the emission level. Such plots were constructed for each pollutant. Linear regression gave best fit lines whose slopes correspond to the inverse of the Laplace factor, which describes the noise present in the measurements. This factor must be viewed in relation to the average measurement for the particular pollutant to obtain a description of noise. The Laplace factors for the 2013 data set were 4.5, 4.3, 0.18, 0.03 and 0.2 for CO, HC, NO, NH_3 and NO_2 respectively. These values indicate standard deviations of 6.4 g/kg (0.05%), 6.1 g/kg (134 ppm), 0.25 g/kg (21 ppm), 0.04 g/kg (6 ppm) and 0.3 g/kg (13 ppm) for individual measurements of CO, HC, NO, NH_3 and NO_2 respectively. In terms of uncertainty in average values reported here, the numbers are reduced by a factor of the square root of the number of measurements. For example, with averages of 100 measurements, which is often a low limit for the number of measurements per bin, the uncertainty reduces by a factor of 10. Thus, the uncertainties in the averages of 100 measurements reduce to 0.6 g/kg, 0.6 g/kg, 0.03 g/kg, 0.04 g/kg and 0.03 g/kg, respectively.

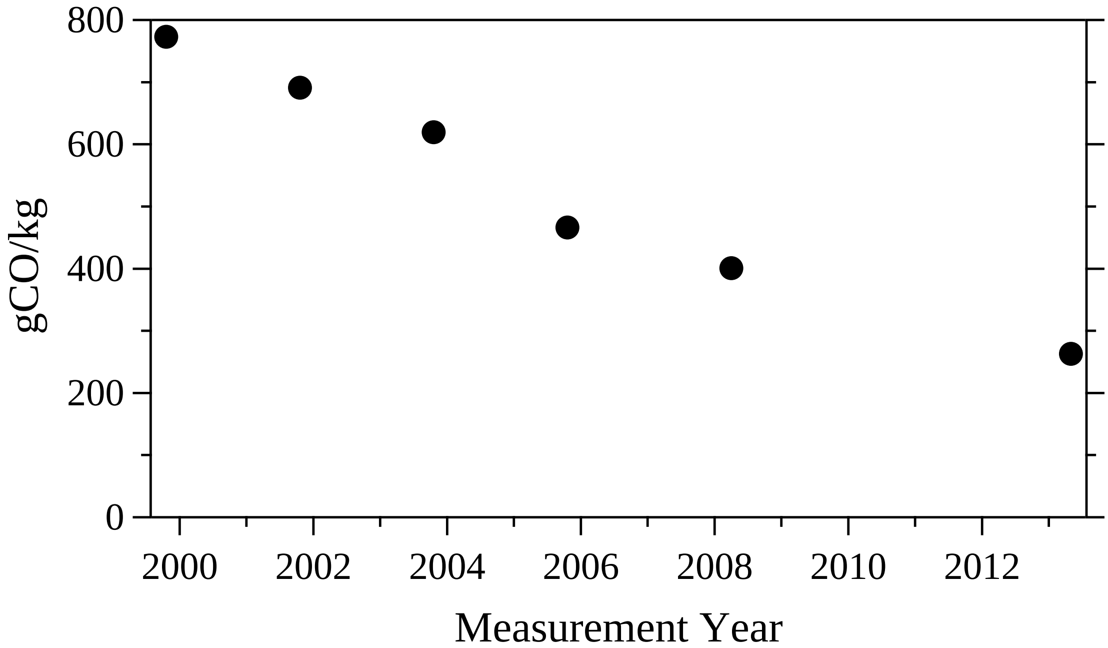

Figure 18. The gCO/kg of fuel 99th percentile for each of the West Los Angeles data sets plotted against measurement year.

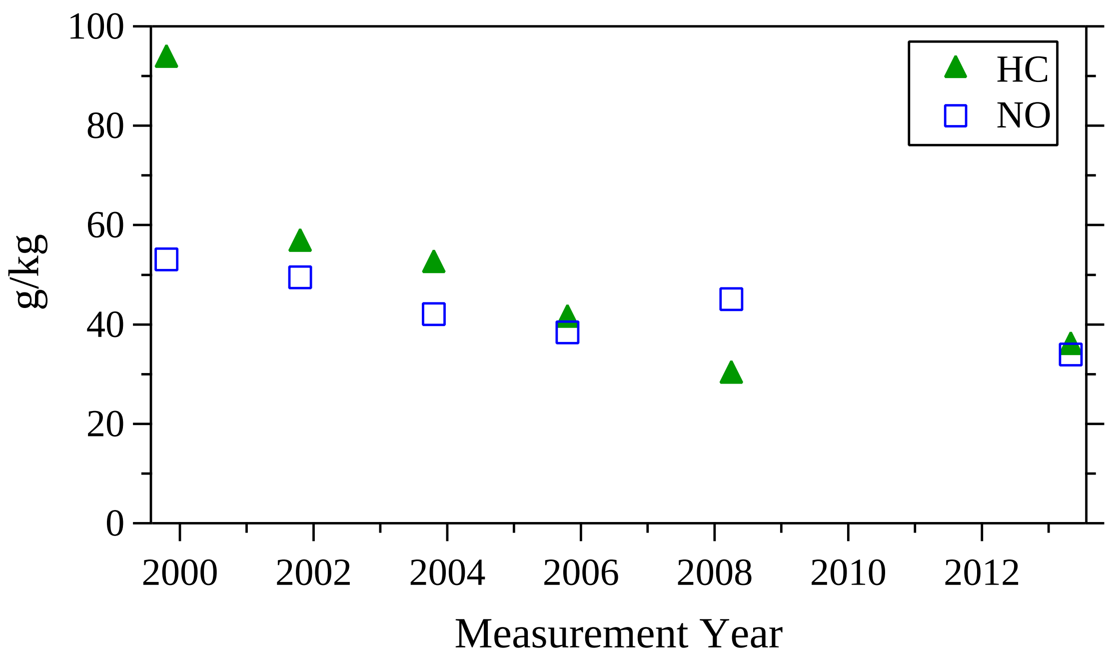

Figure 19. The gHC/kg of fuel and gNO/kg of fuel 99th percentiles for each of the West Los Angeles data sets plotted against measurement year.

2015 Results and Discussion

In 2015 measurements were made on seven consecutive days, from Saturday, March 28, to Friday, April 3, 2015 between the hours of 6:30 and 17:00 on the uphill ramp just west of where La Brea Ave. passes under I-10. In 2015 the ramp control light was functioning once again, however, whether because of less congestion on I-10 or other modifications it was not on constantly allowing periods of free flowing traffic and it did not operate at all on Sunday March 29. Appendix C gives temperature and humidity data for all of the data sets collected from Los Angeles International Airport, approximately eight miles southwest of the measurement site.

Following the seven days of data collection the vehicle images were read for license plate identification. Plates that appeared to be in state and readable were sent to the State of California to have the vehicle make and model year determined. The resulting database contained 22,124 records with make and model year information and valid measurements for at least CO and CO2. The database and all previous databases compiled for all of the previous measurement campaigns can be found at www.feat.biochem.du.edu. Most of these records also contain valid measurements for the other species as well. The validity of the attempted measurements is summarized in Table 8. The table describes the data reduction process beginning with the records containing both valid emissions measurements and vehicle registration information. An attempted measurement is defined as a beam block followed by a half second of data collection. If the data collection period is interrupted by another beam block from a close following vehicle, the measurement attempt is aborted and an attempt is made at measuring the second vehicle. In this case, the beam block from the first vehicle is not recorded as an attempted measurement.

Table 8. 2015 Validity Summary.

	CO	HC	NO	NH_3	NO_2
Attempted Measurements	27,414				
Valid Measurements	25,908	25,861	25,900	25,801	23,508
Percent of Attempts	94.5%	94.35	94.5%	94.1%	85.8%
Submitted Plates	23,624	23,572	23,596	23,509	21,463
Percent of Attempts	86.2%	86.0%	86.1%	85.8%	78.3%
Percent of Valid Measurements	91.2%	91.1%	91.1%	91.1%	91.3%
Matched Plates	22,124	22,093	22,118	22,033	20,105
Percent of Attempts	80.7%	80.6%	80.7%	80.4%	73.3%
Percent of Valid Measurements	85.4%	85.4%	85.4%	85.4%	85.5%
Percent of Submitted Plates	93.7%	93.7%	93.7%	93.7%	93.7%

Invalid measurement attempts arise when the vehicle plume is highly diluted, or the reported measurement error in the ratio of the pollutant to CO_2 exceeds a preset limit (see Appendix A). The greatest loss of data in this process occurs during the plate reading process, when out-of-state vehicles and vehicles with unreadable plates (obscured, missing, temporary, dealer, out of camera field of view) are omitted from the database.

Table 9 provides an analysis of the number of vehicles that were measured repeatedly in 2015, and the number of times they were measured. Of the 22,124 records used in this fleet analysis 14,666 (66.3%) were contributed by vehicles measured only once, and the remaining 7,458 (33.7%) records were from vehicles measured at least twice.

Table 9. Number of measurements of repeat vehicles in 2015.

Number of Times Measured	Number of Vehicles	Number of Measurements	Percent of Measurements
1	14,666	14,666	66.3%
2	1,519	3,038	6.9%
3	640	1,920	2.9%
4	349	1,396	1.6%
5	165	825	0.8%
6	31	186	0.1%
7	9	63	0.04%
>7	3	30	0.01%

Table 10 is the historical data summary including all of the previous remote sensing databases collected by the University of Denver at the West LA site. The previous measurements were conducted in November of 1999, October 2001, 2003, 2005, March of 2008 and April 2013. Mean fleet emissions measured in 2015 continue their reductions, the one exception being NH_3 emissions which increased to levels near those measured in 2008. This is undoubtedly a combination of factors including the driving mode reverting back to its previous traffic light controlled mode and the age increases of the fleet. The mean model year in 2015 only shows a slight rebound from the 2008-2009 recession of 0.2 model years newer. The percentage of emissions from the highest emitting 10% of the measurements increased for all species except NH_3. With the traffic light controlling freeway access for the majority of the time mean acceleration and VSP returned to be more like the values seen in the studies prior to 2013 though free flowing traffic on Sunday keeps average speeds a little higher and average accelerations a little lower. If we limit the 2015 dataset to just the weekdays average speed decreases an additional 2.6% to 18.3 mph, accelerations increase 16% to 1.4 mph/sec and VSP increases to 10.4 kw/tonne. These values are very similar to values reported for several campaigns prior to 2013. The average HC values in 2015 did not need any adjustment as the collected data set was within a few ppm of zero for the newest model year vehicles.

Figure 20 shows vehicle emissions versus model year for all of the data sets collected at the West LA site. The mean HC data have been calculated using the offset adjustment values found in Table 10 for the comparison. One will notice in the HC plot (middle) that with the return of the ramp metering light that the mysterious rise in HC emissions of the newest model year vehicles (newer than 2009 model years), which we discussed with the 2013 database, has disappeared. This is again an indication that the suspected cause was vehicle decelerations causing rapid

Table 10. West Los Angeles Site Historic Data Summary.

Study Year	1999	2001	2003	2005	2008	2013	2015
Mean CO (%) (g/kg of fuel)	0.58 (70.3)	0.44 (56.2)	0.34 (42.4)	0.22 (27.3)	0.17 (21.4)	0.13 (16.4)	0.1 (13.0)
Median CO (%)	0.09	0.06	0.06	0.03	0.02	0.03	(0.01)
Percent of Total CO from Dirtiest 10% of the Fleet	67.4%	72.4%	72.2%	77.0%	80.7%	76.7%	87.3%
Mean HC (ppm)[a] (g/kg of fuel)[a] Offset (ppm)	195 (7.0) -60	125 (4.6) -21	121 (4.5) -35	84 (3.2) 65/0[b]	50 (1.8) 10	56 (2.2) 47	34 (1.3) 0
Median HC (ppm)[a]	70	39	45	40	10	27	12
Percent of Total HC from Dirtiest 10% of the Fleet	57%	61.6%	60.3%	78.0%	81%	99.3%	100%
Mean NO (ppm) (g/kg of fuel)	477 (6.6)	411 (5.6)	323 (4.5)	242 (3.4)	265 (3.75)	153 (2.16)	136 (1.9)
Median NO (ppm)	116	72	48	24	11	5	2
Percent of Total NO from Dirtiest 10% of the Fleet	51.6%	54.9%	59.3%	66.9%	71%	83%	89%
Mean NH_3 (ppm) (g/kg of fuel)	NA	NA	NA	NA	99 (0.79)	72 (0.58)	88 (0.70)
Median NH_3 (ppm)	NA	NA	NA	NA	34	24	32
Percent of Total NH_3 from Dirtiest 10% of the Fleet	NA	NA	NA	NA	50.8%	52.8%	50.8%
Mean NO_2 (ppm) (g/kg of fuel)	NA	NA	NA	NA	4 (0.08)	7 (0.16)	0 (-0.01)
Median NO_2 (ppm)	NA	NA	NA	NA	2	3.5	-2
Percent of Total NO_2 from Dirtiest 10% of the Fleet	NA	NA	NA	NA	61.8%	85.7%	100%
Mean Model Year	1992.4	1994.4	1996.5	1998.9	2001.2	2004.7	2006.9
Mean Fleet Age[c]	7.9	7.8	7.8	7.4	7.4	9.1	8.9
Mean Speed (mph)	17.6	18.3	17.0	17.7	17.6	21.9	18.8
Mean Acceleration (mph/s)	1.4	1.4	1.9	1.7	1.9	-0.2	1.2
Mean VSP (kw/tonne) Slope (degrees)	9.0 2.0°	10.3 2.0°	11.6 2.0°	11.4 2.0°	12.2 2.0°	4.6 2.0°	9.8 2.0°

[a]Indicates values that have been HC offset adjusted as described in text.
[b]Only the October 17th data was offset adjusted, the remaining days had a zero offset.
[c]Assumes new vehicle model year starts September 1.

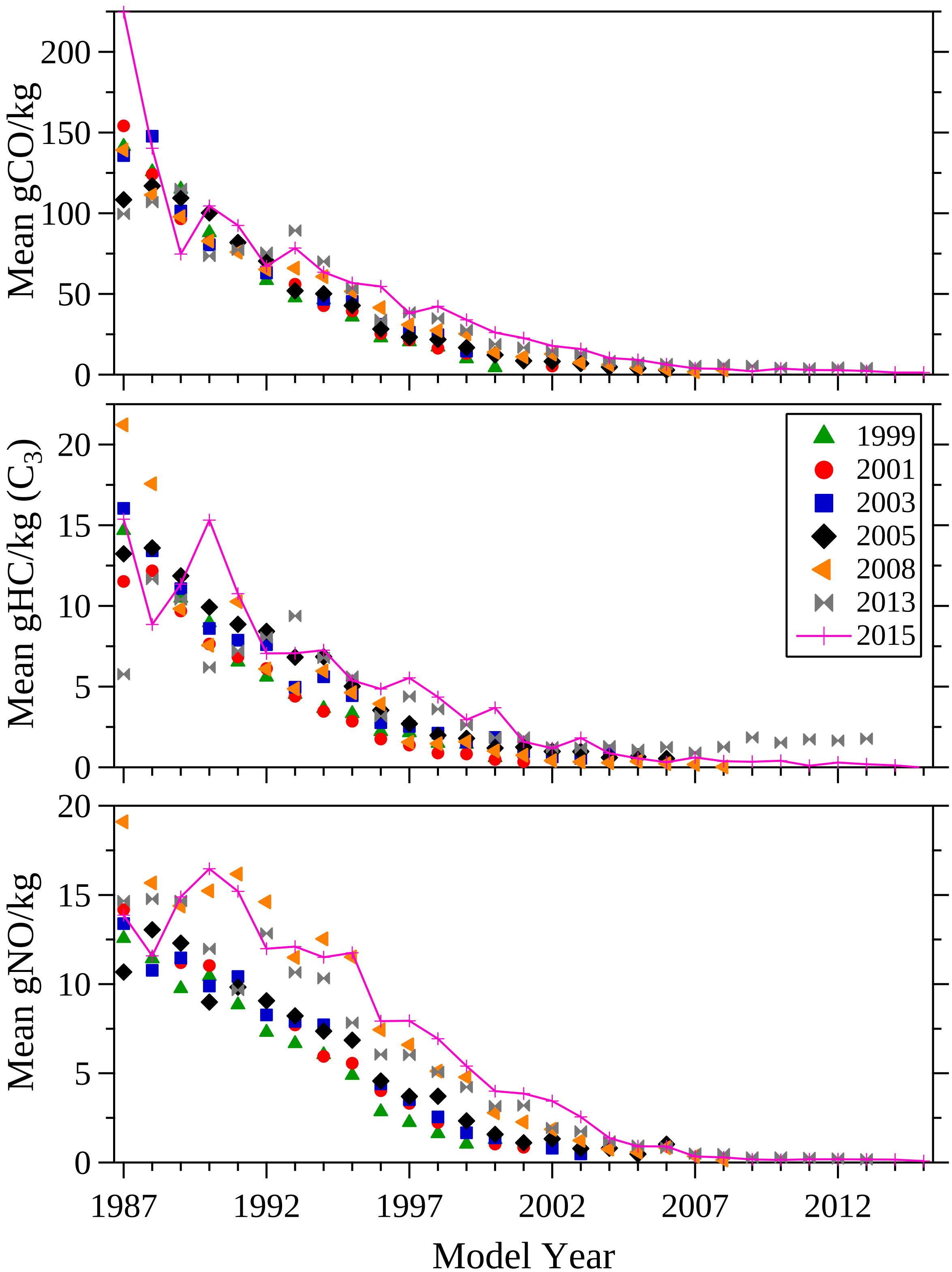

Figure 20. Mean fuel specific vehicle emissions illustrated as a function of model year for data collected between 1999 and 2015. HC data have been offset adjusted as described in the text.

increases in fuel specific HC emissions because of extremely low fuel usage rates.

The emission quintile plots for the 2015 data set are displayed in Figures 21 - 23. The bars in the top plot represent the mean emissions for each quintile by model year, but do not account for the number of vehicles in each model year. The middle graph shows the fleet fraction by model year for the first 19 model years, model years older than 1995 account for ~3.5% of the measurements and about a quarter of the emissions. The bottom graph for each species is the combination of the top and middle figures. These figures illustrates that the lowest emitting 60% of the vehicles, regardless of model year, make an essentially negligible contribution to the overall fleet emissions. The accumulations of negative emissions in the first two quintiles are the result of ever decreasing emission levels. Our instrument is designed such that when measuring a true zero emission plume, half of the readings will be negative and half will be positive. As the lowest emitting segments of the fleets continue to dive toward zero emissions, the negative emission readings will continue to grow toward half of the measurements.

Figures 21 - 23 can also be used to get a picture of federal compliance standards. The on-road data are measured as mass emissions per kg of fuel. It is not possible to determine mass emissions per mile for each vehicle because the instantaneous gasoline consumption (kg/mile) is not known. As previously discussed the LEV II, 120,000 mile standards for CO, HC, and NO correspond to 34, 0.7, and 0.6 gm/kg, respectively. An approximate comparison with the fleet average emissions shown in Figures 21 - 23 shows that significant fractions, especially of the newer vehicles, are measured with on-road emissions well below these standards.

Emissions and Vehicle Specific Power. Using the equation discussed previously VSP was calculated for all measurements in 2015 and all of the previous years' databases. This equation, in common with all dynamometer studies, does not include any load effects arising from road curvature. The emissions data were binned according to vehicle specific power, and illustrated in Figure 24. All of the specific power bins contain at least 100 measurements except for VSP's of 30 in 1999, 2001, 2005 and 2015 which contain 77, 69, 90 and 84 measurements and VSP's of -10 in 2013 which contain 85 measurements. The HC data have been offset adjusted for this comparison.

With the ramp metering light functioning once again the VSP measurement distribution has returned to a measurement profile observed prior to 2013. Comparison of Figures 7 and 24 shows a peak VSP value between 5 and 10 in 2013 and a peak between 10 and 15 for the 2015 data. All of the emissions continue to decrease with each successive data set to the point where there are few if any statistical differences across the entire range of VSPs. The uncertainties included in the plot are standard errors of the mean calculated from the daily averages. These uncertainties were generated for these γ-distributed data sets by applying the central limit theorem. Each day's average emissions for a given VSP bin were assumed an independent measurement of the emissions at that VSP. Normal statistics were then applied to these daily averages.

Using VSP, it is possible to reduce the influence of driving behavior in the mean vehicle emissions. Table 11 shows the measured mean emissions for all of the databases (HC data are

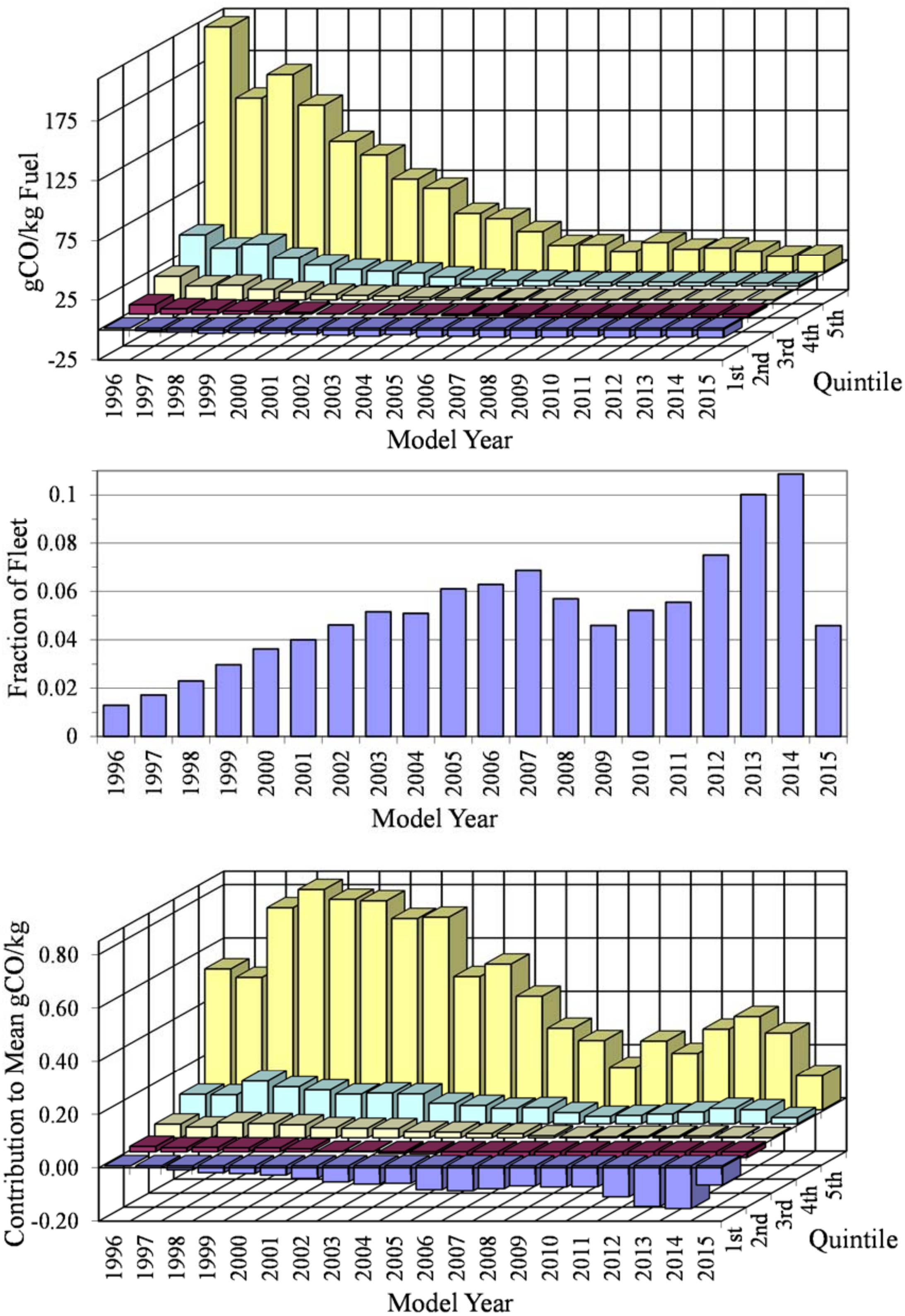

Figure 21. Mean gCO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gCO/kg emissions by model year and quintile (bottom).

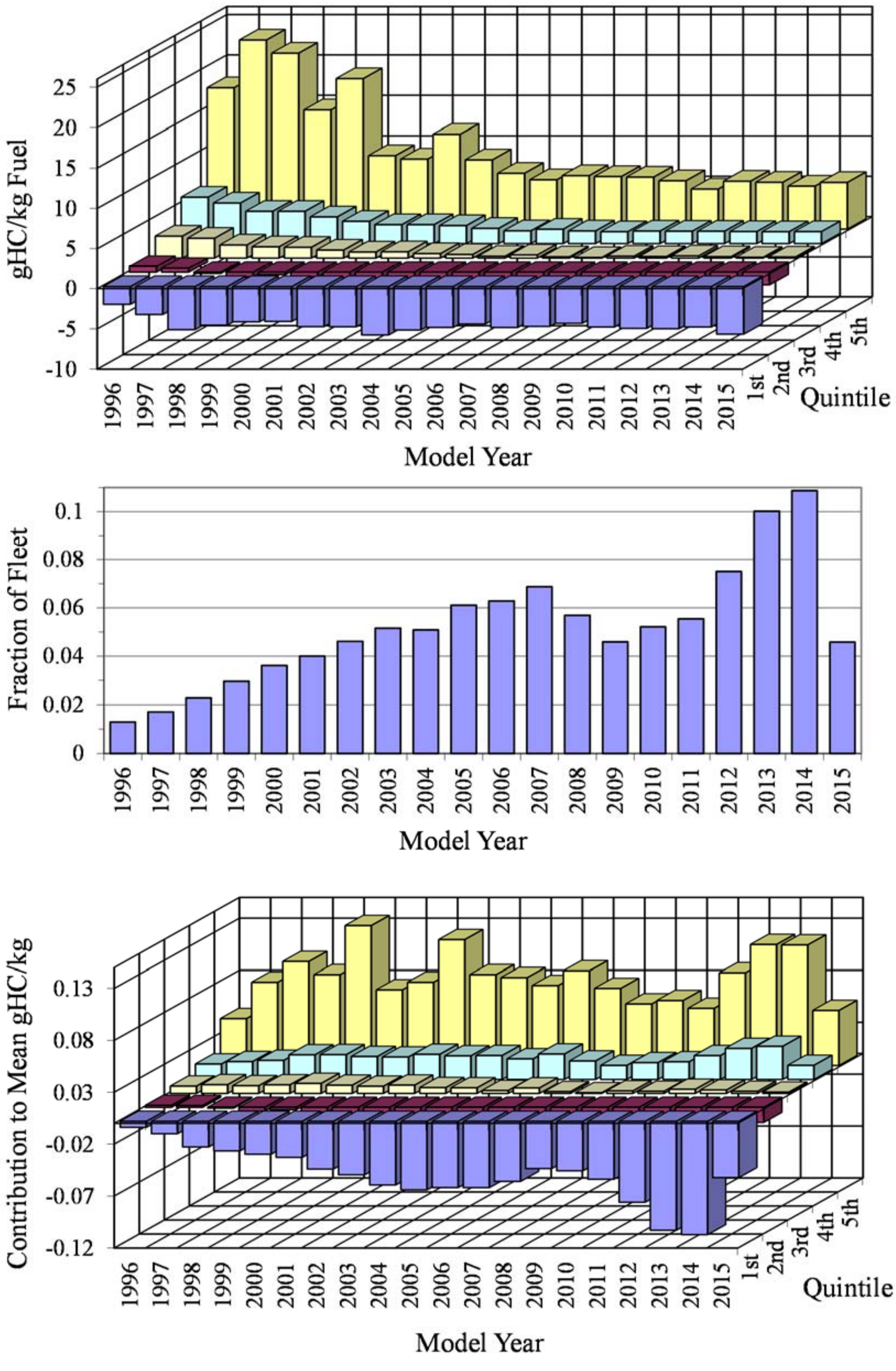

Figure 22. Mean gHC/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gHC emissions by model year and quintile (bottom).

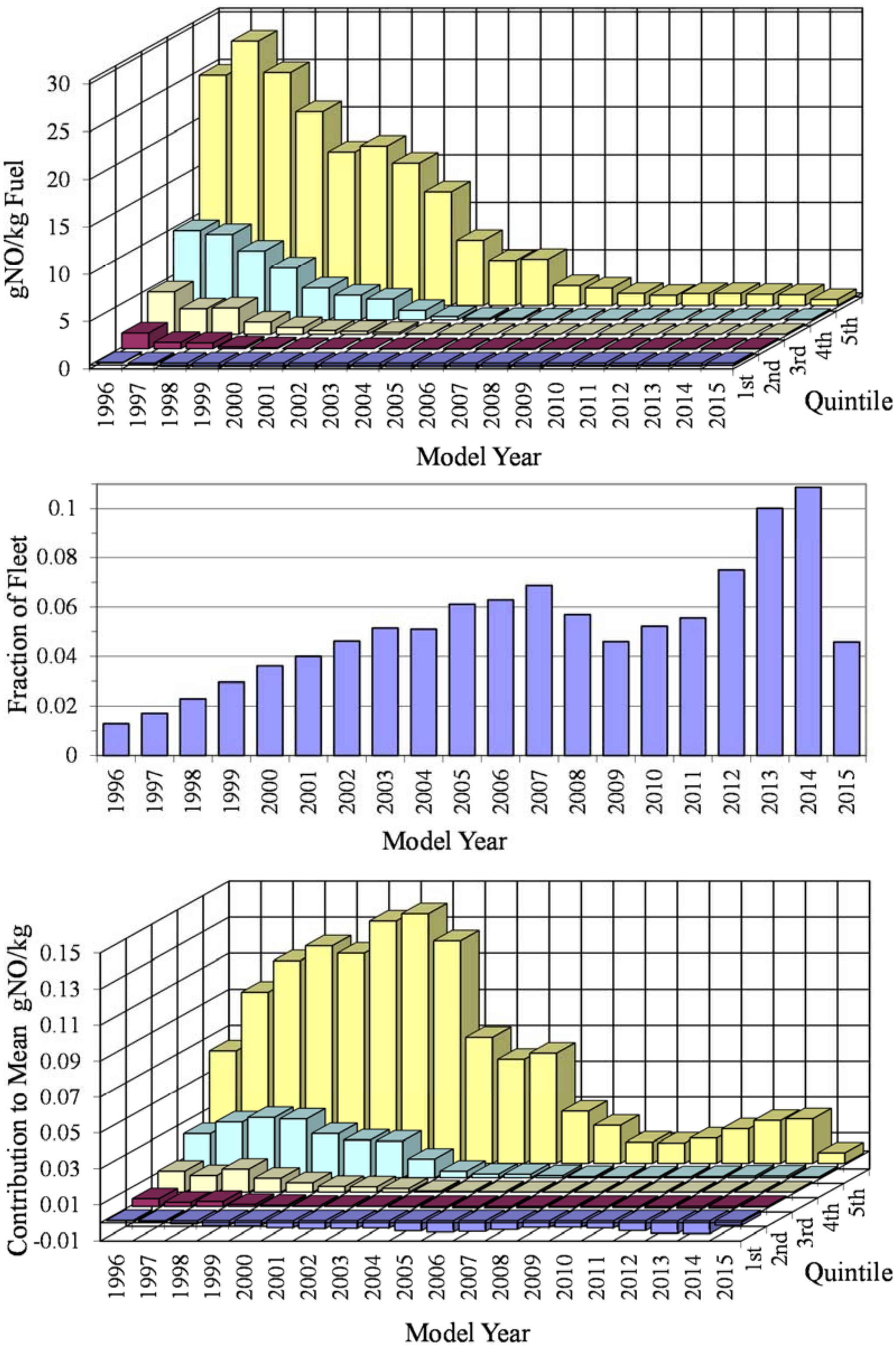

Figure 23. Mean gNO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gNO/kg emissions by model year and quintile (bottom).

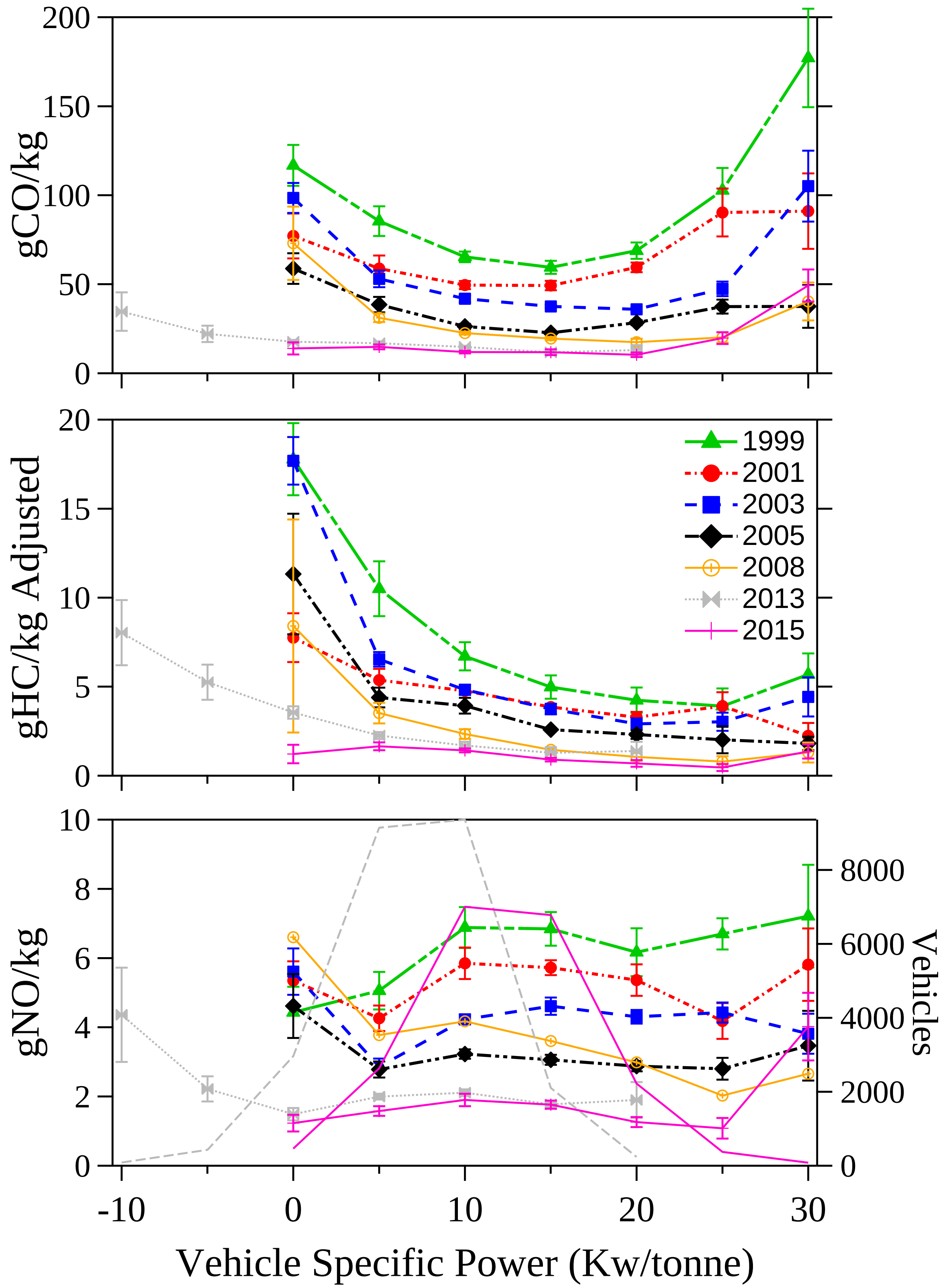

Figure 24. Fuel specific vehicle emissions (left axis) as a function of vehicle specific power for all of the West LA data sets. Uncertainties are standard errors of the mean calculated from daily samples. The dashed and solid lines without markers (bottom panel) are the vehicle count (right axis) profiles for the 2013 and 2015 data sets respectively.

Table 11. Vehicle specific power emissions adjusted to match the 1999 fleet VSP distribution (-5 to 20 kw/tonne only) with standard error of the means calculated using daily averages.

Species	1999 measured (adjusted)	2001 measured (adjusted)	2003 measured (adjusted)	2005 measured (adjusted)	2008 measured (adjusted)	2013 measured (adjusted)	2015 measured (adjusted)
Mean gCO/kg	68.1 ± 2.1 (68.1 ± 2.1)	52.5 ± 2.5 (52.9 ± 2.6)	40.3 ± 1.0 (43.7 ± 1.0)	26.1 ± 0.6 (28.0 ± 0.7)	21.1 ± 0.5 (23.8 ± 0.6)	15.8 ± 0.7 (13.9 ± 0.6)	12.1 ± 0.4 (12.2 ± 0.4)
Mean gHC/kg[a]	9.1 ± 0.7 (6.7 ± 0.7)	5.2 ± 0.2 (4.5 ± 0.2)	5.7 ± 0.3 (4.9 ± 0.3)	2.8 ± 0.7 (3.5 ± 0.1)	2.2 ± 0.1 (2.5 ± 0.1)	4.1 ± 0.2 (1.7 ± 0.2)	1.2 ± 0.1 (1.2 ± 0.1)
Mean gNO/kg	6.4 ± 0.5 (6.4 ± 0.5)	5.6 ± 0.3 (5.5 ± 0.3)	4.3 ± 0.2 (4.2 ± 0.2)	3.1 ± 0.1 (3.1 ± 0.1)	3.7 ± 0.3 (3.8 ± 0.3)	2.0 ± 0.2 (1.9 ± 0.1)	1.7 ± 0.1 (1.7 ± 0.1)

[a]HC emissions are offset adjusted for all of the years' adjusted data.

not offset adjusted) for vehicles with only vehicle specific powers between –5 and 20 kw/tonne. Note that these emissions do not vary considerably from the mean emissions for the entire databases, as shown in Table 10. Also shown in Table 11 are the mean emissions for all the databases adjusted (all years of HC data include an offset adjustment) for vehicle specific power to exactly match the 1999 VSP distribution.

This correction is accomplished by applying the mean vehicle emissions for each VSP bin (between –5 and 20 kw/tonne) from a future year's measurements to the 1999 vehicle distribution, for each vehicle specific power bin. A sample calculation, for the vehicle specific powers adjusted mean NO emissions, is shown in Appendix D. The measured and adjusted values of all three of the primary pollutants show large reductions since 1999 with the adjusted values of CO and HC dropping by more than a factor of 5 while the NO adjusted means have dropped by almost a factor of 4. These rates of reduction are consistent with those reported by other researchers using ambient, airborne and tunnel measurements.[29-31]

Historical Fleet Emissions Deterioration. A similar normalization can be used to create a fleet of specific model year vehicles to track deterioration, provided we use as a baseline only the model years first measured in 1999. A sample calculation, for the model year adjusted mean NO emissions, is shown in Appendix E. Table 12 shows the mean emissions for all vehicles from model year 1984 to 2000, as measured (HC data not offset adjusted) in each of the seven measurement years. Applying the vehicle frequency distribution by model year observed in 1999 to the mean emissions by model year from the later studies yields the model year adjusted fleet emissions (all adjusted years of HC data include an offset adjustment). The calculation indicates that, although some of the measured decrease in fleet average emissions is due to fleet turnover, the emissions of even the older model years (1984-2000) measured previously has not increased significantly. The slow growth in emissions deterioration over a growing period of time (now 16 years) is likely the result of a large number of factors and not just the imposition of reformulated fuels, as discussed in previous CRC reports, and as observed on-road by Kirchstetter et al.[32] The measurements in 2015 included monitoring on the weekend, as in 2013, and as such the number of vehicles for the 1984 -2000 model year fleet is slightly enlarged and may not give the true picture of the total shrinkage from the previous years. If we only count the number of 1984 –

Table 12. Model year adjusted fleet emissions (MY 1984-2000 only). Errors are standard error of the means calculated from the daily means.

Species	1999 measured (adjusted)	2001 measured (adjusted)	2003 measured (adjusted)	2005 measured (adjusted)	2008 measured (adjusted)	2013 measured (adjusted)	2015 measured (adjusted)
Mean gCO/kg	60.6 ± 2.0 (60.6 ± 2.0)	52.1 ± 2.3 (61.1 ± 2.7)	51.5 ± 1.6 (65.6 ± 2.0)	43.0 ± 0.7 (61.4 ± 0.9)	46.2 ± 0.9 (68.1 ± 1.3)	44.8 ± 1.8 (71.0 ± 2.9)	48.9 ± 1.7 (77.2 ± 2.7)
Mean gHC/kg[a]	8.3 ± 0.6 (5.9 ± 0.6)	5.2 ± 0.2 (5.2 ± 0.2)	6.8 ± 0.3 (6.7 ± 0.3)	4.5 ± 0.6 (6.9 ± 0.2)	4.2 ± 0.3 (6.8 ± 0.5)	4.4 ± 0.3 (6.7 ± 0.5)	5.3 ± 0.5 (8.0 ± 0.7)
Mean gNO/kg	6.2 ± 0.4 (6.2 ± 0.4)	6.1 ± 0.4 (7.0 ± 0.4)	5.8 ± 0.2 (7.0 ± 0.3)	5.5 ± 0.2 (7.3 ± 0.3)	8.3 ± 0.6 (11.0 ± 0.8)	6.5 ± 0.1 (9.3 ± 0.2)	7.9 ± 0.5 (10.9 ± 0.7)
Vehicles[b]	17,903 17,798 17,798	17,304 17,194 17,194	13,827 13,786 13,786	10,125 10,111 10,111	6498 6481 6488	6069 6049 6064	3368 3360 3366

[a]HC emissions are offset adjusted for all of the years measured and adjusted data.

[b]Number of vehicles in the CO, HC and NO means.

2000 model year vehicles that we measured between Monday and Friday that number is 2,516 and represents shrinkage of about 86% from 1999. The additional data set added in 2015 continues the trend found in 2013 that fleet averaged emission deterioration is increasing at a very slow rate.

Another way to look at vehicle deterioration is to look at the mean emissions changes over time by model year. This type of analysis is only possible with the long historical record of emission measurements we have at the west LA site. Figure 25 is a plot of emissions deterioration rates for CO, HC and NO calculated with the assumption that vehicle emissions deterioration can be modeled as a linear process. The mean emissions for each individual model year from each measurement campaign are plotted against that model year's age at the time of the measurements and a line is fit using a linear least squares method. The resulting slope of that line is an emissions deteriorations rate in grams of emissions per kilogram of fuel used per year. A minimum of three measurement points are needed and as of the 2015 measurements we are only able to calculate these statistics for 2008 and older model year vehicles. This then covers an age range from 7 to 31 year old vehicles.

All of the species experience emissions deterioration during the first 20+ years of life when smaller measurement numbers introduce more variability and larger errors. The shape of the NO emissions plot (bottom pane) can at least be rationalized by combining the notion that as the 3-way catalyst ages it loses its efficiency at reducing NO emissions allowing them to rise until the fleet reaches a point where factors from engine age limit NO production leading to its decrease. For CO and HC the deterioration rates are remarkably consistent until the early 90's where the increase in noise makes it difficult to statistically prove any specific trend.

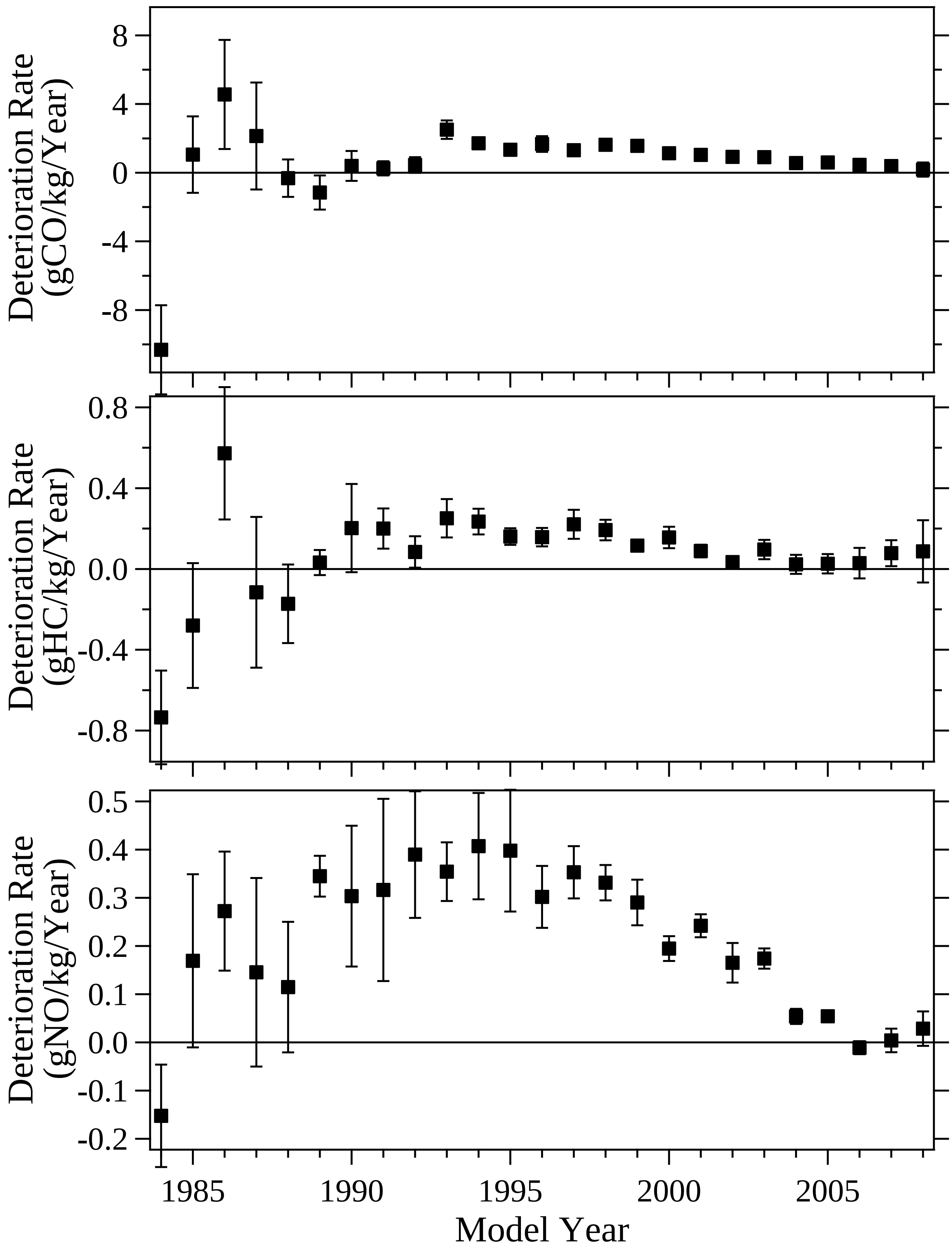

Figure 25. Fuel specific on-road emissions deterioration rates versus model year for the West LA sampling location incorporating the 2015 data. The uncertainty bars plotted are the standard error of the slope for the least-squares fit.

Using Figure 25 we again look for any emissions deterioration effect that corresponds with the introduction of the OBDII check engine light (in 1996 and newer vehicles). In past data sets there have been significant decreases in CO, HC and NO emissions between the 1995 and 1996 model year vehicles. In the 2015 data set those differences are no longer significant for CO and HC though for NO the emissions differences are still the single largest model year to model year change. However, Figure 25 shows that there is no significant statistical difference in the deterioration rates between the 1995 and 1996 model years for all three species.

2008 Recession Recovery. As previously discussed the recession of 2008 significantly increased the age of the vehicle fleet observed at the West LA site by reducing the number of 3 to 5 year old vehicles and increasing the number of 10 to 25 year old vehicles in 2013 (see Figure 11). With the passing of two years of time Figure 26 compares the fleet fractions by age for the 2013 and 2015 data sets. Since vehicles that are not built or purchased cannot rematerialize the lost 3 to 5 year old vehicles from 2013 are now missing 5 to 7 year old vehicles. There have been increased purchases of 1 to 4 year old vehicles, however, the 10 to 25 year old vehicles have remained fairly consistent which is the best explanation for why the age of the fleet has only gotten 0.2 model years newer since 2013 (see Table 10). At this pace it will take 20 years for this fleet to return to the previous 7 year old fleet age.

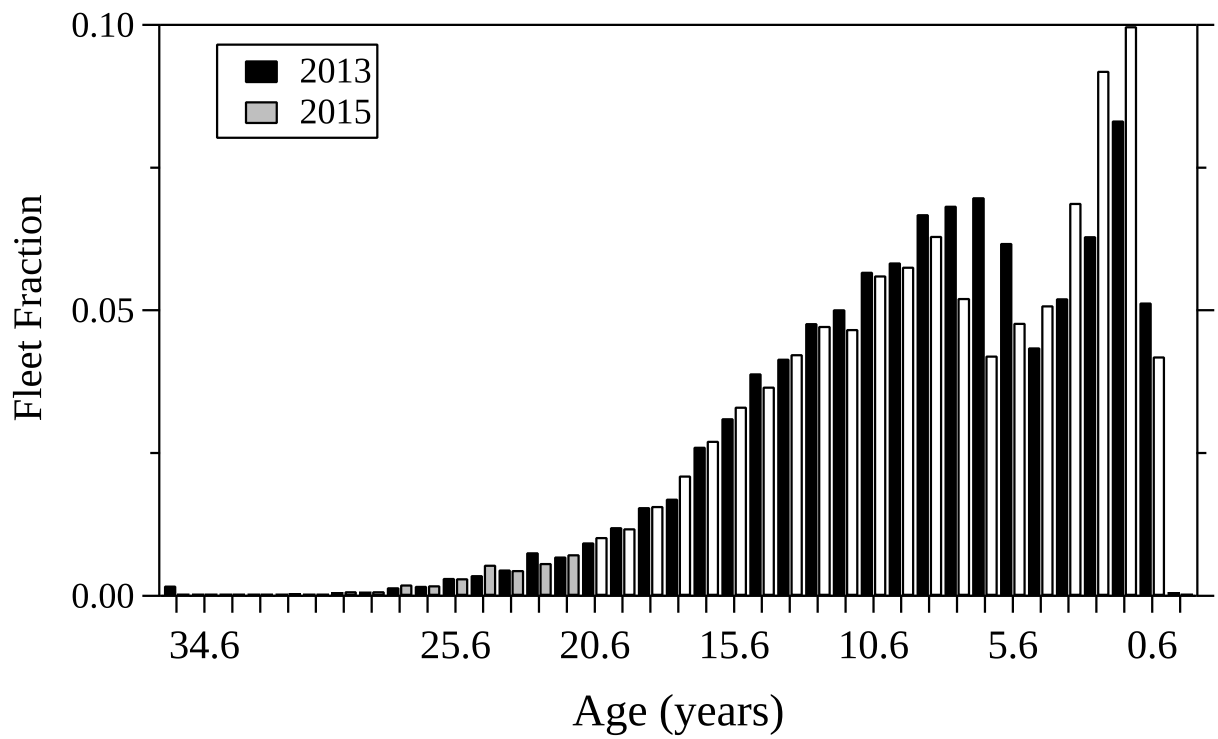

Figure 26. Fleet fraction plotted by vehicle age for the 2013 and 2015 West LA data sets. The vehicle age calculation assumes a September 1 date for each new model year.

Weekday versus Weekend Comparison. As with the 2013 database we investigated the weekday and weekend traffic differences observed during our seven days of measurements. Table 13 is the companion to Table 6 discussed previously comparing the traffic volumes, fleet age, fuel type and mean emissions grouping the data by week day (Monday - Friday) and weekend (Saturday and Sunday). The HC data are offset adjusted and the uncertainties reported are standard errors of the mean calculated from the daily averages. Saturday and Sunday standard errors of the mean use the same uncertainties calculated for the weekend data. The only statistically significant difference observed in 2015 are the Sunday gNH_3/kg of fuel, the gNO/kg of fuel and gNO_x/kg of fuel emissions being the lowest reported values for the comparison. This is likely more a reflection on the changes in driving mode as the ramp metering light did not function on Sunday. This opened up the driving mode with speeds increasing about 4 miles per hour and accelerations dropping to near zero levels much like the driving mode observed in 2013 which also showed lower levels for these species. Mean model year differences are also insignificant with Sunday having the newest fleet. The fraction of diesel vehicles are higher for weekdays (~2%) than on the weekend (0.8% on Saturday and 0.5% on Sunday). These fractions are also lower than observed in 2013.

Table 13. 2015 Comparison of Mean Emissions for the Weekday and Weekend Data.

Period (Hourly Rate)	Mean gCO/kg (counts)	Mean gHC[a]/kg (counts)	Mean gNO[b]/kg (counts)	Mean gNO_2^c/kg (counts)	Mean gNH_3/kg (counts)	Mean gNO_x^c/kg (counts)	Mean Model Year	Diesel Fraction
Weekday (330)	13.0±0.3 (16644)	1.3±0.1 (16618)	2.0±0.1 (16638)	-0.01±0.01 (15499)	0.73±0.02 (16564)	3.0±0.1 (15494)	2006.9	0.02
Weekend (359)	13.3±1.5 (5480)	1.3±0.1 (5475)	1.6±0.5 (5480)	0.003±0.01 (4606)	0.63±0.04 (5469)	2.2±0.7 (4606)	2006.8	0.007
Saturday (357)	14.8±1.5 (2589)	1.4±0.1 (2585)	2.1±0.5 (2589)	-0.01±0.01 (2279)	0.68±0.04 (2580)	2.9±0.7 (2279)	2006.6	0.008
Sunday[d] (361)	11.8±1.5 (2891)	1.2±0.1 (2890)	1.1±0.5 (2891)	0.01±0.01 (2327)	0.59±0.04 (2889	1.5±0.7 (2327)	2007	0.005

[a] HC data is offset adjusted as described in the text, offset is zero for 2015 data set.
[b] moles of NO
[c] moles of NO_2
[d] Ramp metering light turned off.

Traffic volumes did not decrease on the weekend with both Saturday and Sunday having slightly higher hourly rates than the weekdays. However, the hours of data collection on Saturday and Sunday were not the same as during the weekday sampling as the early morning hours on the weekend do have significantly less traffic. However, the hours sampled on the weekend did have higher hourly sampling rates than the similar hours during the weekdays.

Ammonia Emissions. Figure 27 compares 2015 gNH_3/kg of fuel emissions collected at the West LA site with the two previous measurement campaigns by model year. The uncertainty bars plotted are the standard error of the mean determined from the daily samples for each model year. The data show the characteristic shape with NH_3 emissions increasing with age until vehicles get about 20 years old when they start decreasing. Because NH_3 emissions are sensitive to vehicle age, and these data sets were collected at different times, Figure 28 compares the data sets by plotting them against vehicle age.

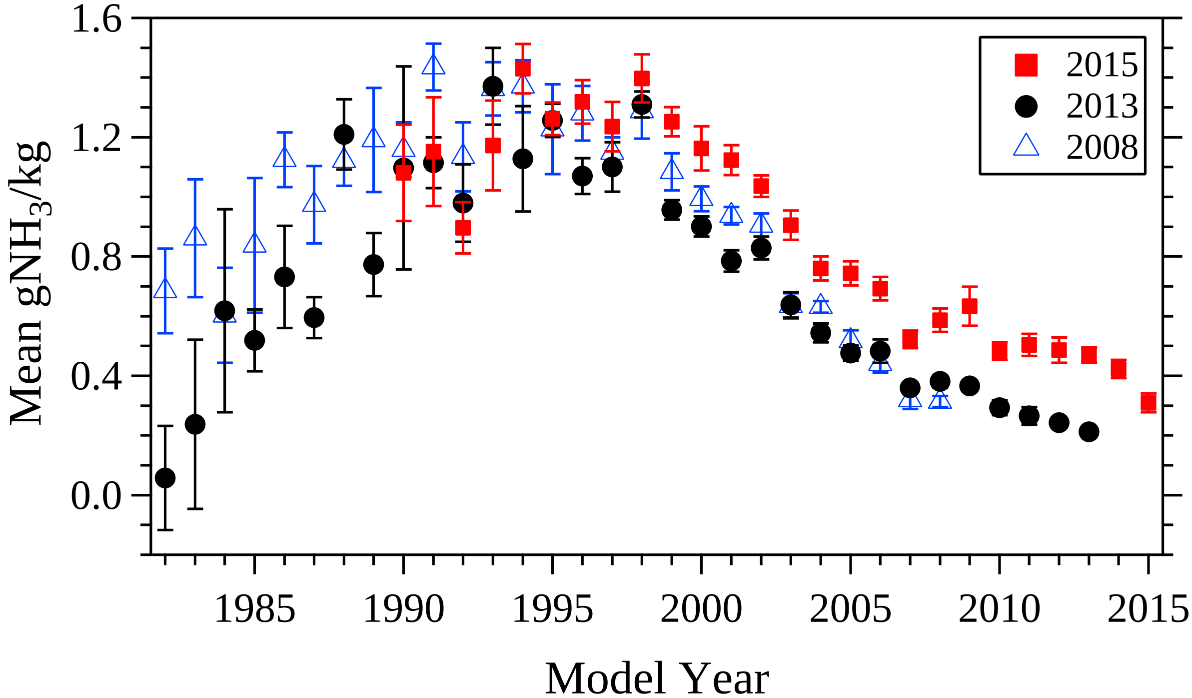

Figure 27. Mean gNH_3/kg of fuel emissions plotted against vehicle model year for the 2015 (squares), 2013 (circles) and 2008 (triangles) measurements at the West LA site. The uncertainty bars plotted are the standard error of the mean determined from the daily samples.

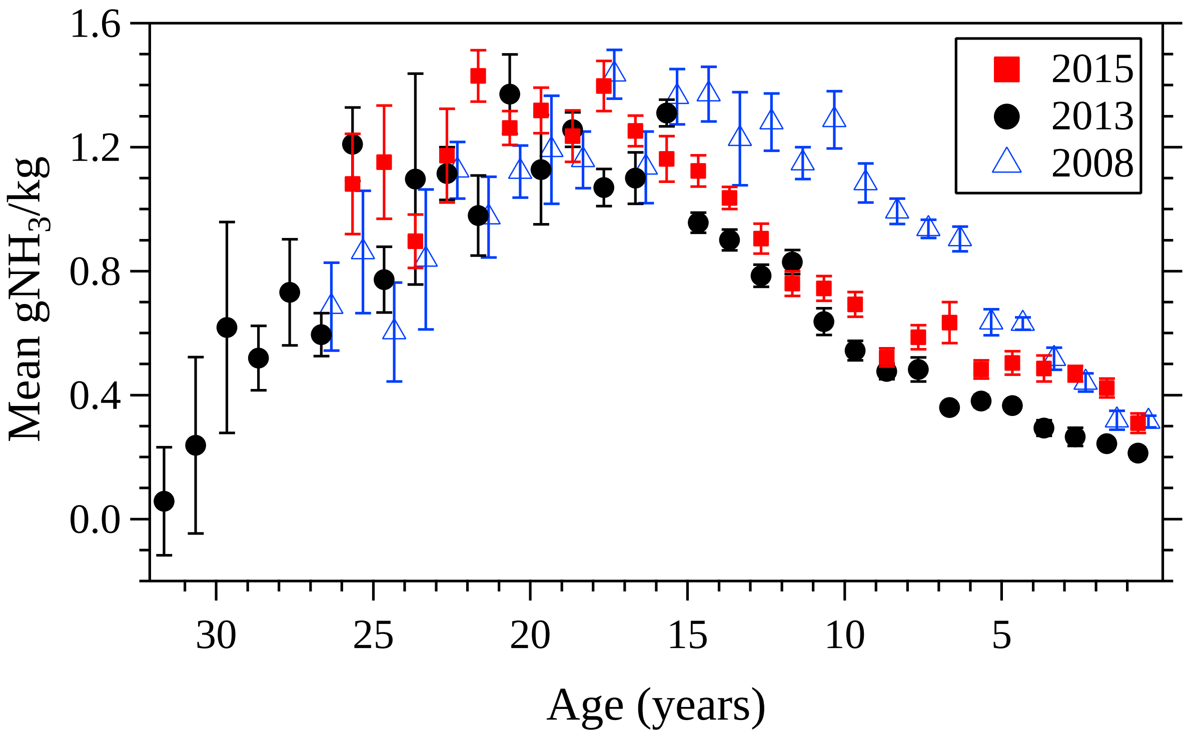

Figure 28. Mean gNH_3/kg of fuel emissions plotted against vehicle age for the 2015 (squares), 2013 (circles) and 2008 (triangles) measurements at the West LA site. The uncertainty bars plotted are the standard error of the mean determined from the daily samples.

The driving mode of the 2015 measurements is more like that observed in 2008. Comparing the mean differences between 2008 and 2015 results in only a slight reduction in ammonia emissions from 0.79 ± 0.05 to 0.7 ± 0.2 an 11% reduction in seven years. This is lower than the differences observed between 2008 and 2013. This reduction is more in line with the 8 year reduction observed in Tulsa OK (2005 to 2013) of 14%.[47]

Historical 99th Percentile Trends. Figures 29 and 30 are plots of the CO, HC and NO 99th percentiles including the 2015 database as a function of measurement year for the West LA site. The 99th percentile represents 35% of the total 2015 CO emissions, 46% of the 2015 HC emissions and 23% of the 2015 NO emissions. We have included all of the measurements in the database including the diesel fraction. We would expect this to have the largest effect on the NO distribution but at the extremes of the data set these differences are not a large as one might expect. The 99th percentile for NO is 33.6 g/kg for all of the data and the same value when the diesel fuel vehicles are excluded.

Since 1999 the 99th percentile for CO has been reduced by a factor of 3 and while the changes in driving mode caused by the inconsistent operation of the ramp control light have likely influenced the 2013 and 2015 values the 2015 value has not changed much since the 2013 measurements. Future measurements will have to be collected to see how significant this pause in the decline is. Mean model years for the 99th percentile CO vehicles have changed from 1984 models in the 1999 measurements to 1995 models for the 2015 measurements.

The HC 99th percentiles have been reduced by a similar factor as CO while NO has been reduced by a smaller amount. Mean model years of the 99th percentiles vehicles have increased from 1986 to 1997.8 models for HC and 1987 to 1996.1 models for NO. As discussed in the 2013 data set the HC mean model year for the 99th percentile has decreased by a couple of years as the driving mode reverted back to what was observed in data sets prior to 2013 with tailpipe HC emissions being minimized by the acceleration driving mode.

Instrument Noise Evaluation. Instrument noise was measured in 2015 using the slope of the negative portion of a plot of the natural log of the binned emission measurement frequency versus the emission level for all of the measured species. Linear regression gave best fit lines whose slopes correspond to the inverse of the Laplace factor, which describes the noise present in the measurements. This factor must be viewed in relation to the average measurement for the particular pollutant to obtain a description of noise. The Laplace factors for the 2015 data set were 3.7, 3.1, 0.18, 0.024 and 0.7 for CO, HC, NO, NH_3 and NO_2 respectively. These values indicate standard deviations of 5.2 g/kg (0.04%), 4.4 g/kg (95 ppm), 0.25 g/kg (22 ppm), 0.34 g/kg (5 ppm) and 1 g/kg (42 ppm) for individual measurements of CO, HC, NO, NH_3 and NO_2 respectively. In terms of uncertainty in average values reported here, the numbers are reduced by a factor of the square root of the number of measurements. For example, with averages of 100 measurements, which is often a low limit for number of measurements per bin, the uncertainty reduces by a factor of 10. Thus, the uncertainties in the averages of 100 measurements reduce to 0.5 g/kg, 0.4 g/kg, 0.03 g/kg, 0.03 g/kg and 0.1 g/kg, respectively. When compared with the 2013 measurements the 2015 data set has similar standard deviations for all of the species except the

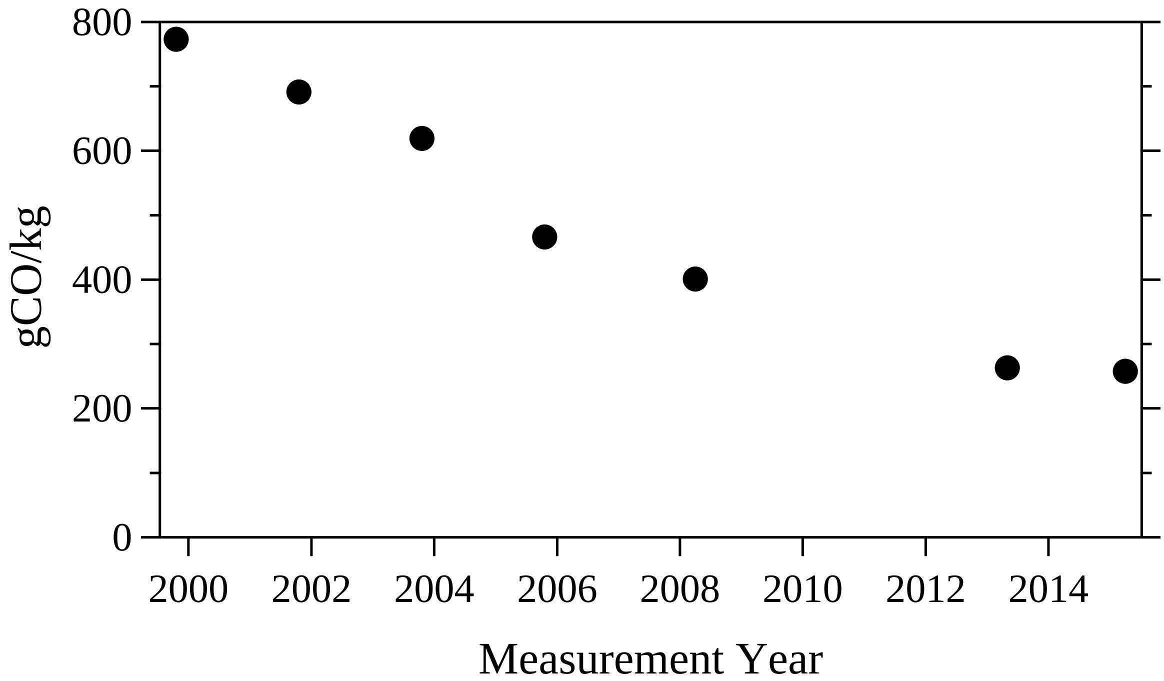

Figure 29. The gCO/kg of fuel 99th percentile for each of the West Los Angeles data sets plotted against measurement year.

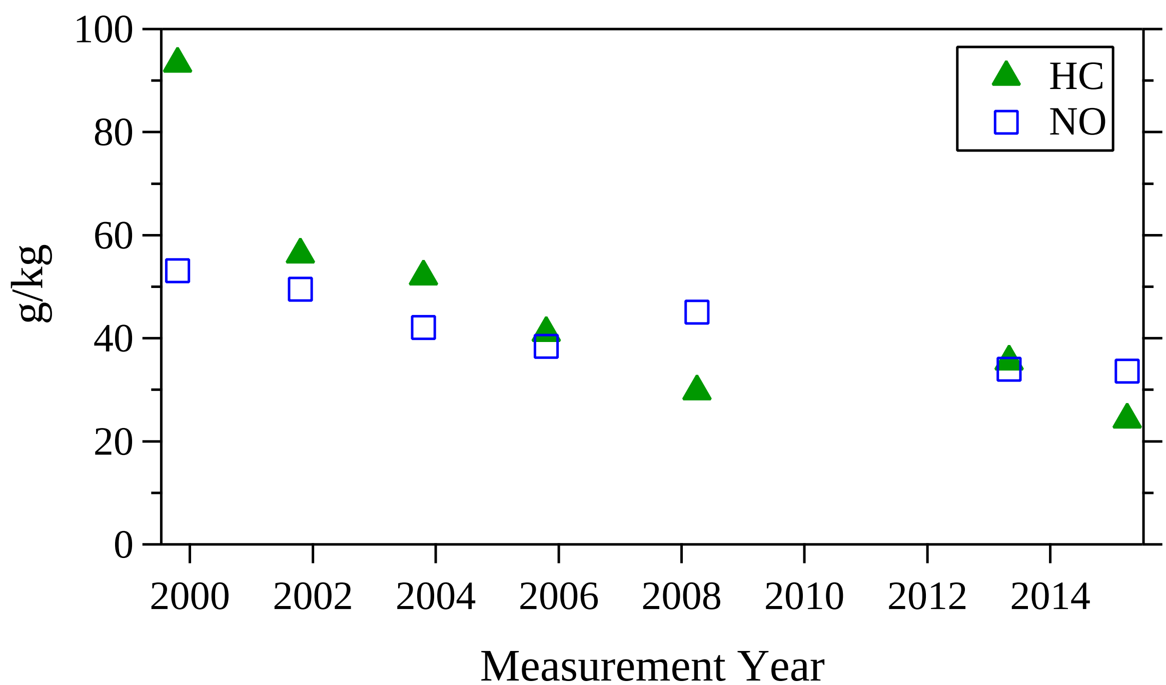

Figure 30. The gHC/kg of fuel and gNO/kg of fuel 99th percentiles for each of the West Los Angeles data sets plotted against measurement year.

HC measurements which have a lower standard deviation in 2015 (95ppm vs 134ppm) and NO_2 which has a much higher standard deviation in 2015 (42ppm vs 13ppm). The increased noise in the NO_2 also seems to be reflected in an increase in invalid readings (see Tables 1 and 8) of about 5% in 2015.

General Discussion

Historical Emissions Changes. Measurements have been collected at the West LA site since the fall of 1999 when data was collected for the State's Inspection and Maintenance Review committee. Since then data sets have been collected in the fall of 2001, 2003 and 2005 for CO, HC and NO. Beginning in the spring of 2008 we began collecting data with our multi-spectrophotometer instrument which added the species NH_3, SO_2 and NO_2. This report covers the two most recent data sets collected which now span 16 years since the first measurements. Figure 31 plots the g/kg of fuel emissions for CO, HC and NO for the 1999 and 2015 data sets against vehicle age. The zero year model years are 2000 for the 1999 data and 2015 for the 2015 data set. The uncertainties plotted are the standard errors of the mean calculated for each model year grouping using the daily means measured in each data set.

Figure 31 shows that in general 24 year old vehicles have seen an approximate 3 fold reduction in their CO and HC emissions while NO emissions have shown little change. NO emissions have only recently been a regulatory focus with LEV II, which dramatically lowered tailpipe NO_x levels, vehicles only being fully phased in by the 2009 models. We suspect that the very low NO means observed for 8 year old and newer vehicles will continue and that in the not so distant future the NO emissions plot will begin to look very similar to the CO and HC plots.

In both the CO and HC plots the 24 year old vehicles measured in 2015 (1991 models) have emissions that are very similar to that observed in 10 year old vehicles measured in 1999 (1990 models). Figure 25 shows that the CO and HC deterioration rates over the past 16 years are indistinguishable from zero for the 1990 models and for the 1991 model year vehicles only the HC emissions have a small positive deterioration rate. The lack of significant changes in the mean emissions for these model year vehicles may or may not be a true reflection of individual vehicles emission deterioration as there are several dynamic factors that contribute to the mean emissions of a fleet as it ages.

Mean emissions are dictated by the number and emissions level of the broken vehicles. The fraction of broken vehicles can be operationally defined by three rate constants as previously defined by Johnson and Pitchford.[48] These are the vehicle breakage rate, the repair rate and the retirement rate. Underlying these rate factors are of course a more extensive list of contributing factors such as vehicle durability for breakage rate and vehicle intrinsic value that factors into a retirement decision. Because of the length of time that has passed since we first observed the 1990 and 1991 model year vehicles the retirement rate is now likely the most important influence on the 2015 observed means. In 1999 the 1991 and 1990 model years accounted for 5.3% and 5.2% of the 1999 measurement fleet but only 0.6% (1991) 0.3% (1990) of the 2015 measurement fleet. These large changes are likely not completely random in nature meaning the survivors

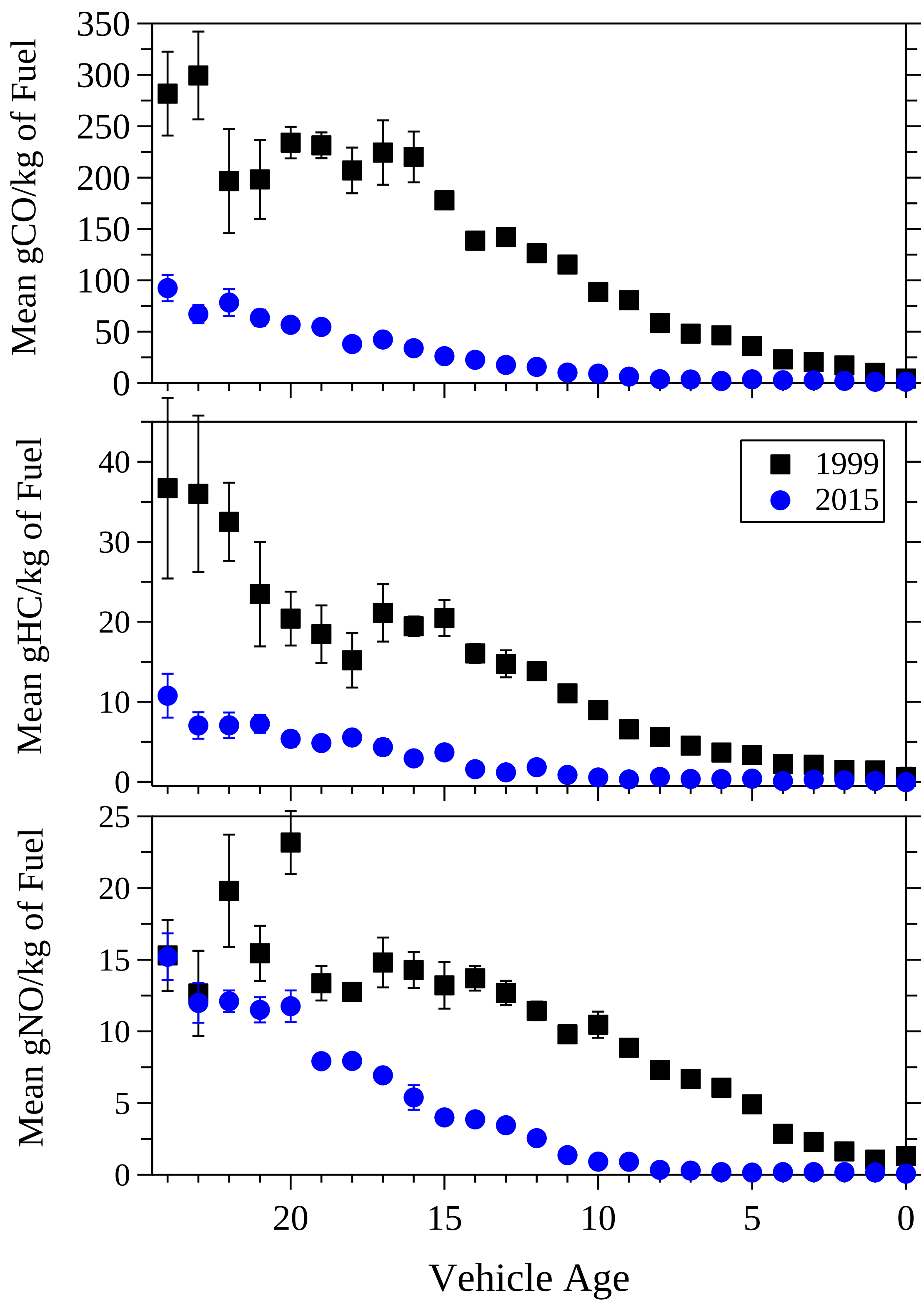

Figure 31. Fuel specific CO (top panel), HC (middle panel) and NO (bottom panel) emissions versus vehicle age for data sets collected at the West Los Angeles site in 1999 (squares) and 2015 (circles). The uncertainties plotted are standard errors of the mean estimated from the daily measurements. Zero model years are 2000 (1999 data) and 2015 (2015 data).

observed in 2015 may have very different rate constant characteristics than the fleet observed in 1999 making it difficult to separate out the specific influences on these models mean emissions.

As the fleet mean emissions have decreased since 1999 the emissions distribution has become increasingly skewed. Figure 32 are pie charts that represent the change in total CO and HC emissions between 1999 and 2015 and the percentage of those total emissions that the 99th percentile is responsible for. The 99th percentile for CO has increased by about a factor of 2.5 and for HC a factor of 2.7 times the percentage contribution found in 1999. If the reductions in the magnitude of the 99th percentile vehicles is in fact leveling out, as suggested in Figures 29 and 30, then the fractions of emissions that the 99th percentile is responsible for may increase at a faster rate than observed in the past.

Because of the 16 years difference between the 1999 and 2015 measurements at the West Los Angeles measurement site there is only about a decade of model years (1991 – 2000) that overlap with a sufficient number of measurements to compare. Figure 33 is a plot of the fuel specific 99th percentiles for CO (top panel), HC (middle panel) and NO (bottom panel) for the 1999 (squares) and 2015 (circles) data sets. Only model years with at least 100 measurements have been plotted. Many of the overlapping 2015 model years for CO and HC 99th percentiles show similar 99th percentiles for the mid-90 models. As previously seen in Figure 31 all three species have very low 99th percentile values for the first five (CO and NO) to 10 (HC) model years before the values begin to rise which is in contrast to the 1999 data which generally saw increasing percentile values after the first model year. NO percentiles are less straight forward to interpret due to the fact that diesel vehicles, if in sufficient quantity, may influence the upper percentiles. These plots are for the entire fleet and we have not tried to eliminate the diesel portion of the fleet.

Evaporative Emissions. For both the 2013 and 2015 West LA measurements we recorded and saved the high frequency data from each vehicle measurement. One motivation for this was to give the Air Resources Board an opportunity to use the high frequency data to identify high evaporative emission vehicles. FEAT takes advantage of the fact that all tailpipe emissions are emitted together and thus are correlated in time space. Evaporative hydrocarbons will likely originate from a location other than the tailpipe and will generally not be correlated with combustion emissions and while FEAT does not automatically look for these anti-correlations it may be possible to use the high frequency data to locate the anomalies and identify evaporative emitters. FEAT evaluates each species correlation to CO_2 and calculates the uncertainty on each best fit line and when these values exceed preset limits it will invalidate a measurement. High levels of evaporative HC emissions which are uncorrelated to CO_2 can be one reason for invalidated vehicle HC emissions and this knowledge led us to making notes to check the following vehicle that came by on April fool's day.

Figure 34 shows the half second of high frequency data recorded behind a 1967 Chrysler Newport whose original HC reading was invalidated by the software. If all of the gaseous emissions have been emitted from a common source they should all rise and fall together. It is apparent that the observed HC emissions started at elevated levels immediately after the vehicle cleared the beam and then moved in opposite directions from the tailpipe exhaust. The HC

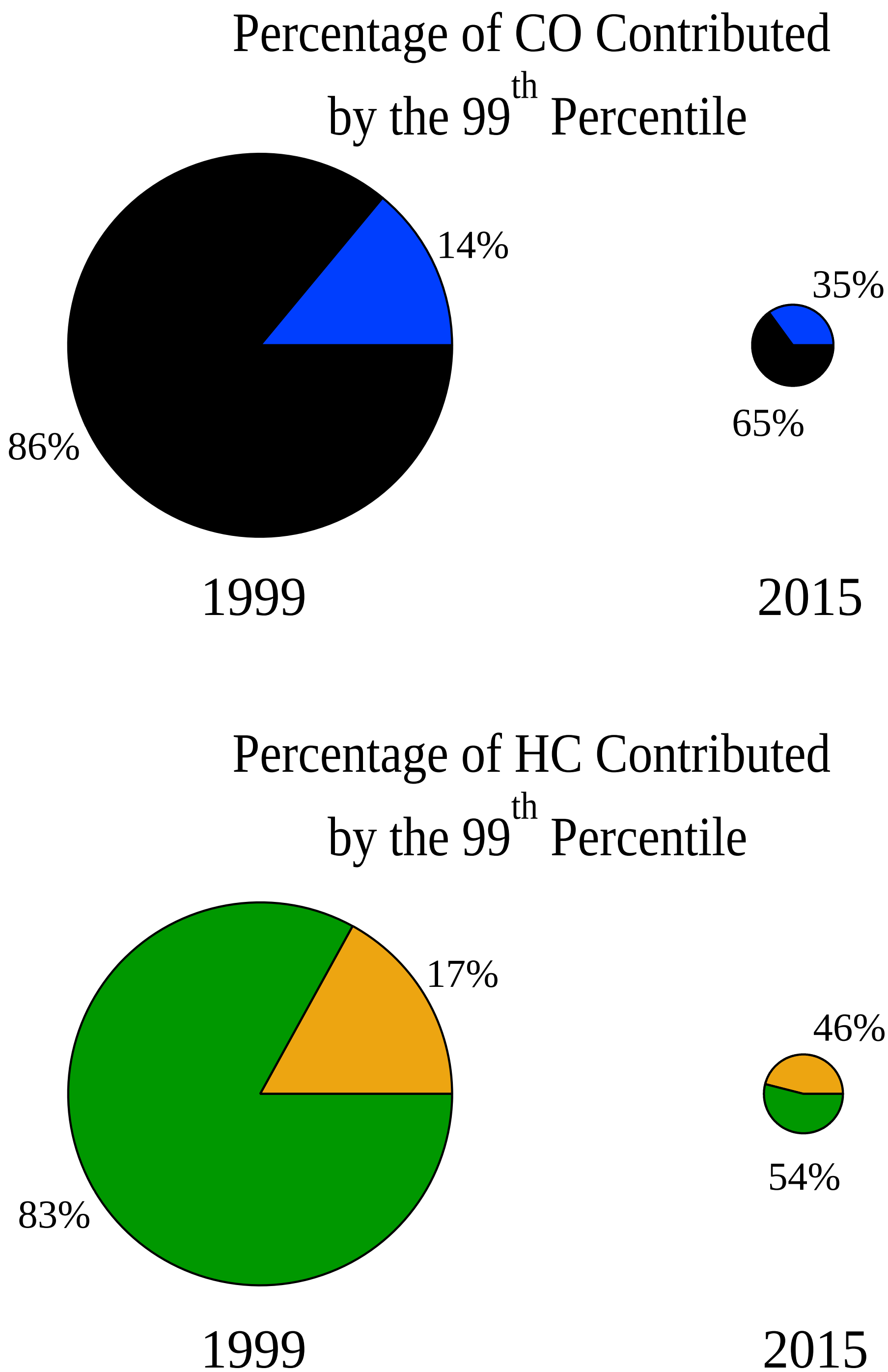

Figure 32. Pie charts representing the total fuel specific emissions for CO (top panel) and HC (bottom panel) for the data sets collected at the West Los Angeles site in 1999 and 2015. The minor slice in each pie is the percentage of fuel specific emissions that are contributed by the 99th percentile.

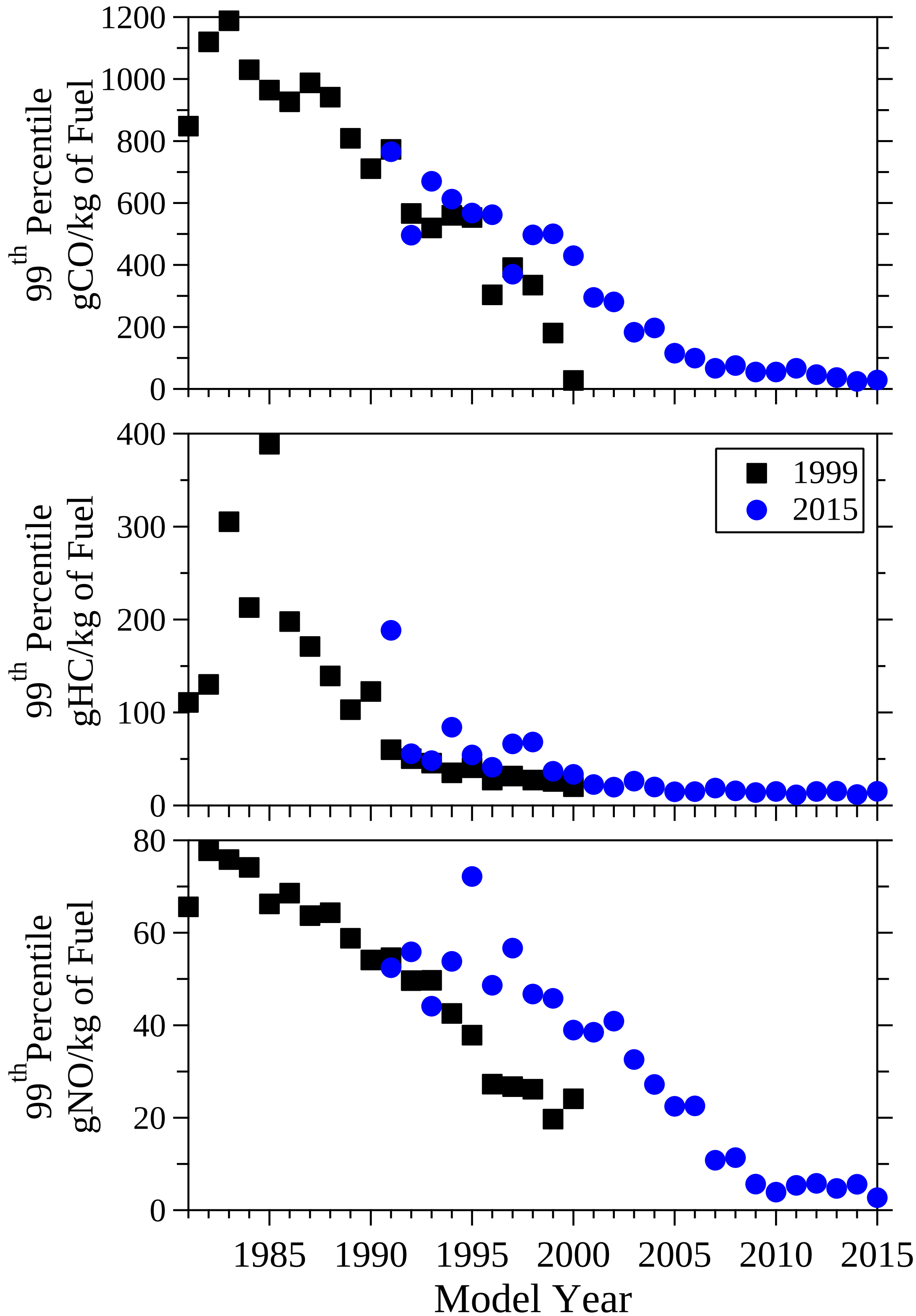

Figure 33. Fuel specific CO (top panel), HC (middle panel) and NO (bottom panel) 99th percentiles versus model year for data sets collected at the West Los Angeles site in 1999 (squares) and 2015 (circles).

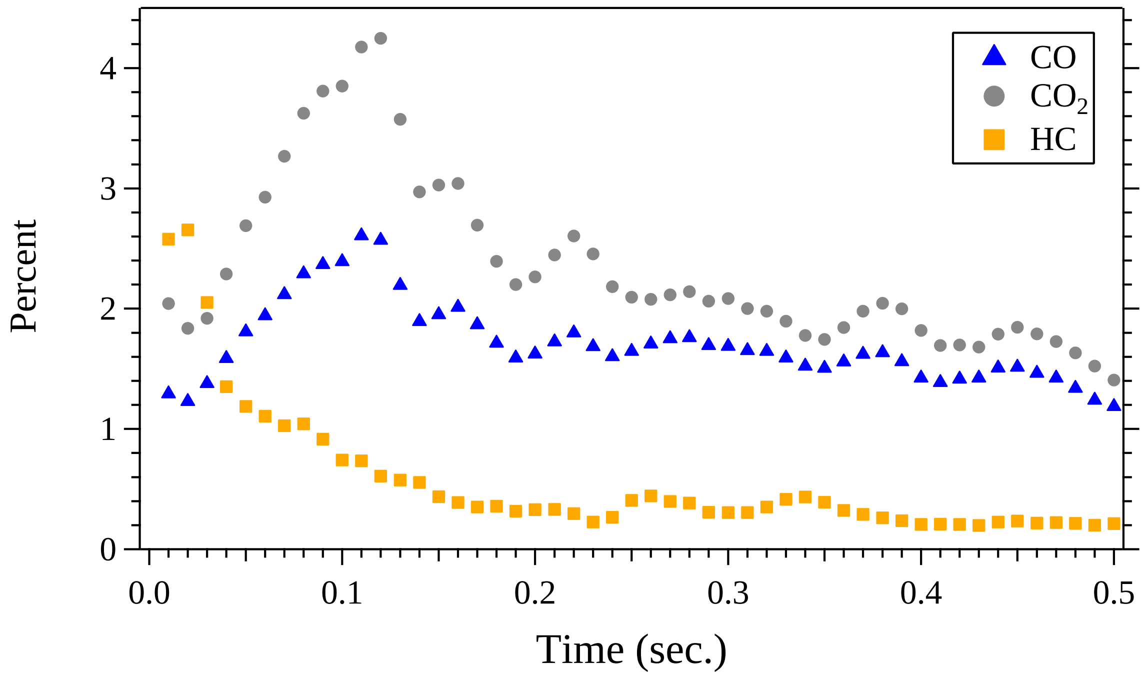

Figure 34. Percent emissions versus time for a 1967 Chrysler Newport measured at the West LA site on April 1, 2015. Percentages are calculated assuming that all of the exhaust has been compressed into an 8cm cell. HC emissions are not correlated with CO_2 emissions indicating a source other than the tailpipe.

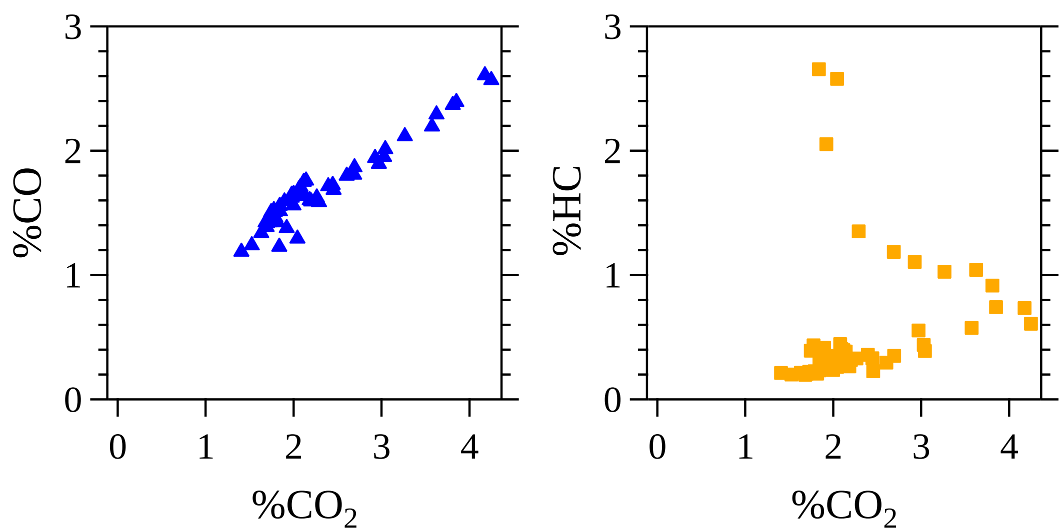

Figure 35. Correlation graphs for %CO versus %CO2 (left panel) and %HC versus %CO_2 (right panel) for the 1967 Chrysler Newport. The lack of correlation between the observed HC and CO_2 emissions resulted in this exhaust measurement being invalidated by the software.

emissions continued to exponentially decrease independently from the emissions that originated from the tailpipe. Figure 35 shows the plots that FEAT uses to measure the path length independent ratios for CO/CO_2 (left panel) and HC/CO_2 (right panel). The CO and CO_2 are well correlated and most of the points fall along a straight line. The HC emissions are poorly correlated to the tailpipe CO_2 suggesting that they were emitted from a separate source.

While pre-1970 vehicles would not be considered to have any significant evaporative emission controls it should be pointed out that none of the 10 additional measurements on pre-1970 vehicles in the 2015 database showed any indication of HC emissions other than from the tailpipe. The large magnitude of the HC emissions (> 1%HC which tailpipe levels rarely reach) from the 1967 Chrysler indicates a liquid leak of some kind and not simply evaporated fuel.

Diesel Vehicle Emissions. Remote vehicle exhaust sensing has a number of advantages over traditional testing methods such as costs, large volumes and unobtrusive testing which does not generally require consent from the vehicle owner or manufacturer. This last aspect makes remote sensing a useful tool in identifying egregious issues of on-road emission compliance with laboratory certification testing. Since most certification testing is performed by manufacturers, and the amount of policing is limited, it is important that there be some checks that can be used to alert regulators as to areas to focus that policing. Such is one use for the databases that we have collected at the West LA site.

The opportunity to VIN decode the 2013 database provided the ability to examine emissions as a function of vehicle type (car and truck), fuel type (gasoline or diesel) and engine size. Figure 36 is an example of the types of information that can be assembled from these data. In the top panel is plotted the gNO_x/kg of fuel emission by model year apportioned by gasoline and diesel powered cars and trucks. Car and truck designations are defined by the Polk VIN decoder and truck classifications have been restricted to weight classes 1 – 6. Gasoline vehicles include all hybrids, flex-fuel and natural gas vehicles as defined by the California DMV. The middle panel of Figure 36 shows the fleet percentages of each category with the gasoline fleet percentages on the left axis and the diesel fleet percentage on the right axis (note an order of magnitude reduction for the diesel percentages). The bottom panel combines the top and middle panel to show each categories percentage contribution to the 2015 databases total gNO_x/kg of fuel emissions.

As might be expected at this location gasoline passenger cars and trucks are responsible for the majority of the NO_x emissions, yet those emissions have been rapidly decreasing this century. Diesel truck emissions have also shown large reductions since 2005 (top panel). What was unexpected was that the percent contribution by 2009 and newer diesel passenger cars which were greater than the contribution by diesel trucks and on par with the contribution by gasoline trucks (bottom panel). This is in spite of the fact that the fleet percentage of diesel passenger cars is miniscule with individual model years never accounting for more than 0.025% of the total, well below both diesel and gasoline trucks (middle panel). Of course it is the emissions plotted in the top panel which are driving this increased contribution as 2009 diesel passenger vehicles have NO_x emissions that range between 10 and 30 gNO_x/kg of fuel not dissimilar from mean

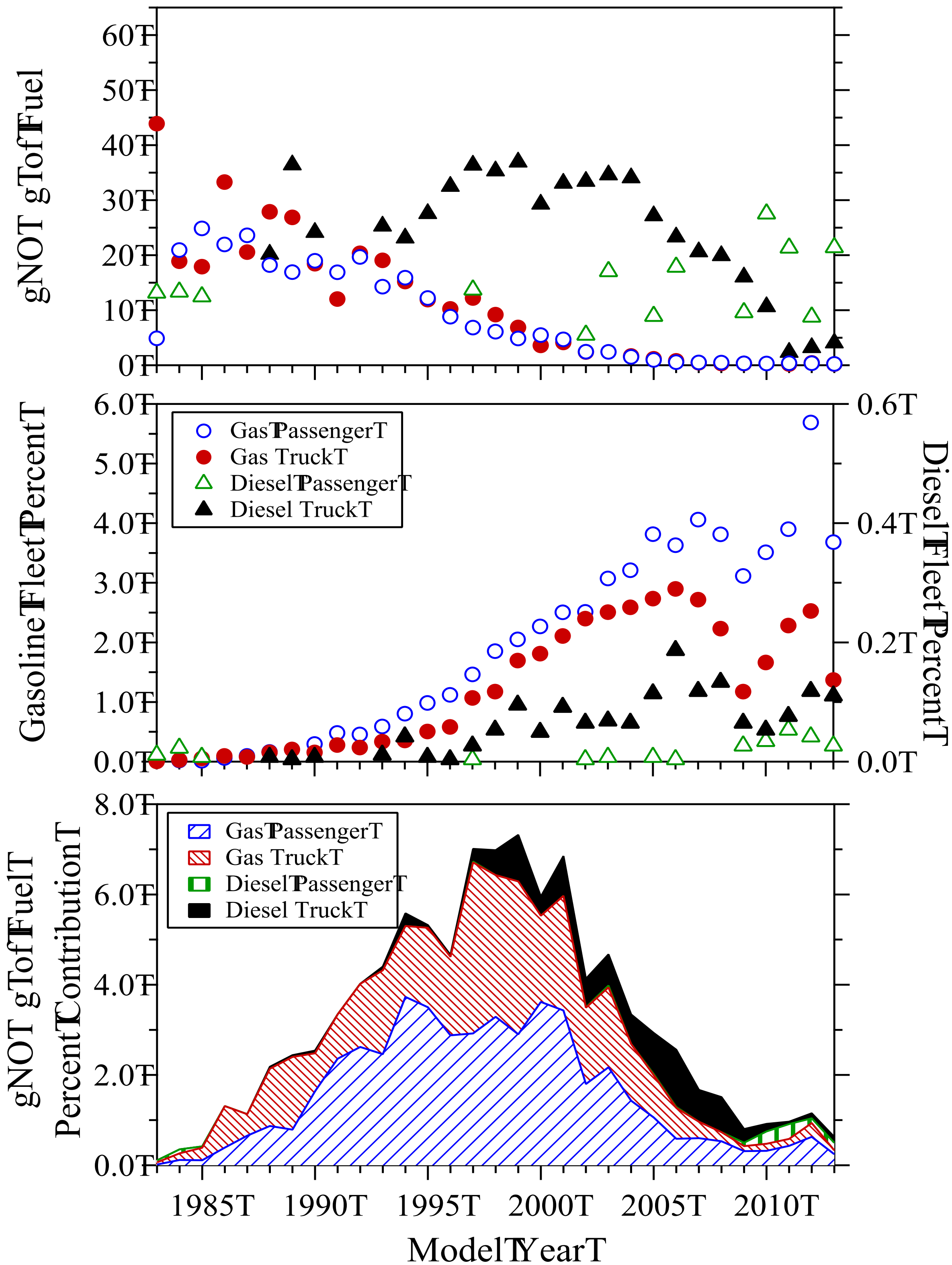

Figure 36. 2013 West LA grams of NO_x per kilogram of fuel emissions (top panel), fleet percentages (middle panel), and grams of NO_x per kilogram of fuel percent contributions (bottom panel) versus model year for gasoline and diesel passenger vehicles and trucks.

emissions of diesel passenger vehicles built prior to 2007. What makes this interesting is the fact that between 2007 and 2009 there was an order of magnitude reduction in the NO_x certification standards for diesel passenger cars. While no one assumes that laboratory certification standards translate 1:1 to emissions observed on-road such a large reduction should at least be observable in the on-road data. For example diesel trucks underwent a similar reduction in their NO_x certification standards and while those reduction do not fully show up in 2009 or 2010 models the 2011 and newer models show significant reductions in on-road NO_x emissions (top panel).

In the 2013 West LA database there are 4 different makes (Audi, BMV, Mercedes and Volkswagen) with 2009 and newer diesel passenger vehicle models totaling only 49 measurements. Volkswagen is the largest single make with 33 measurements or 67% of the total. Mean gNO_x/kg of fuel emissions for these 4 makes clearly show a high and low NO_x emissions mode with Volkswagen (33) and Audi (8) in the high mode (18.4 and 30.6 gNO_x/kg of fuel) and BMW (2) and Mercedes (5) in the lower mode (0.4 and 1.6 gNO_x/kg of fuel). There are only 20 measurements from diesel passenger vehicles that were manufactured before 2009 and their mean gNO_x/kg of fuel emissions are in the middle at 13.1. One additional major difference in the 2009 and newer vehicles is the increased fraction of NO_2 emissions in the total NO_x emissions. In the 2009 and newer VW and Audi's that fraction is 0.5, which is more than double that observed from the older passenger diesel vehicles of 0.2.

In 2013 the University of Denver also collected on-road measurements of light-duty vehicles in Denver, CO and Tulsa, OK where the diesel vehicle population is slightly larger than found in LA. The emission differences observed in Los Angeles were also observed in the data from Denver, CO and Tulsa, OK.[47] Figure 37 is a graph of gNO_x/kg of fuel emissions (circles) versus model year for diesel passenger vehicles with engines that are 2L or smaller for a combined database from the three cities. Due to the lack of a 50 state standard there were no diesel passenger vehicles sold in the US in 2006 and 2007. The horizontal bars are the mean emissions for the model years that they span and the triangles are the mean gNO_2/kg of fuel emissions for those same model year spans. The uncertainties plotted are the standard errors of the mean calculated from the daily means. There is no statistical difference between the fuel specific NO_x emissions from diesel passenger vehicles built prior to 2007 and those manufactured to Tier II/LEV II standards beginning with the 2009 models. However, there is an approximately 23% increase in the Tier II/LEV II vehicles NO_2 emissions (7.8 ± 1.6 to 10.1 ± 1.3) and the NO_2/NO_x ratio increased from 0.33 to 0.57.

Figure 38 compares the gNO_x/kg of fuel emissions by model year from the 2015 database for diesel Volkswagen and Audi models (62 measurements) with diesel pickup trucks manufactured by Ford, Chevrolet, Dodge and GMC (23 measurements). On a fuel specific basis the VW and Audi models have four times the fuel specific NO_x emissions of the pickup trucks. On a gram per mile basis this difference will probably be approximately halved as the fuel economy of the smaller engine sedans is probably about double that of the pickup trucks. As previously discussed with the 2013 database the Volkswagen and Audi models emit a majority of their NO_x emissions as the more toxic NO_2.

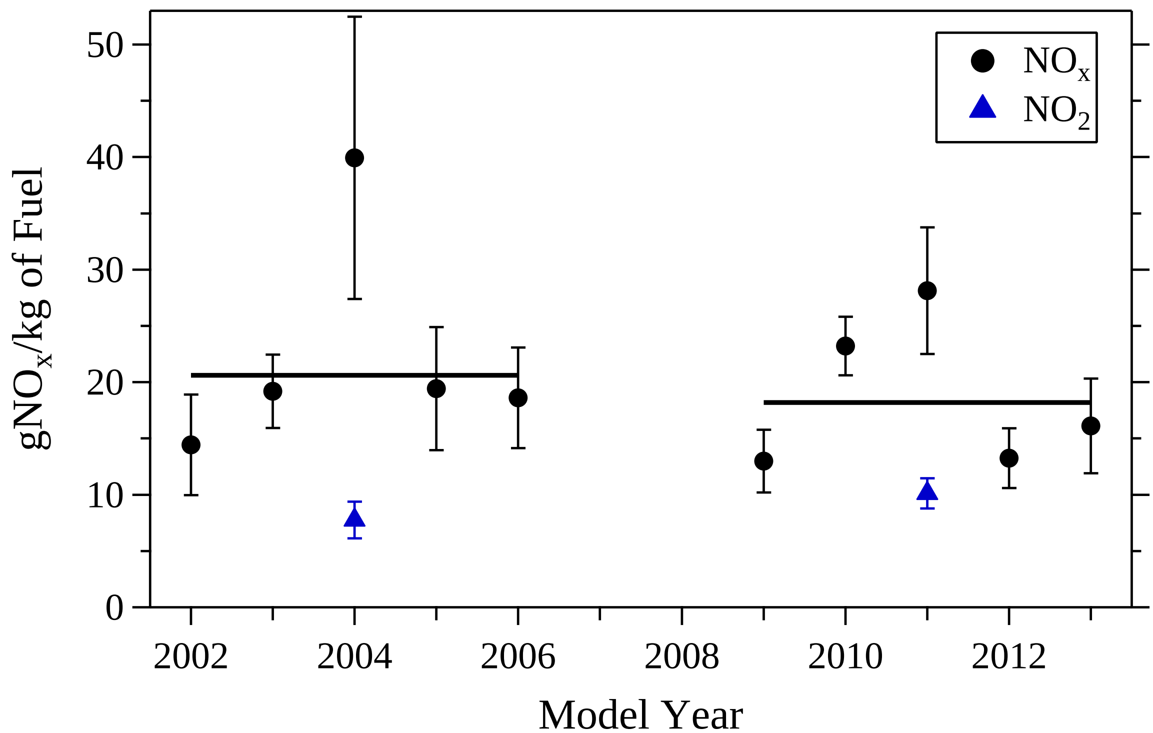

Figure 37. Diesel passenger vehicle gNO$_x$/kg of fuel emissions for passenger vehicles with engine sizes of 2L and smaller (circles) versus model year for data collected in 2013 in Denver CO, Los Angeles CA and Tulsa OK. The horizontal lines and triangles show the mean gNO$_x$/kg and gNO$_2$/kg of fuel emission levels for the 2002 – 2006 (left) and 2009 – 2013 (right) models. Uncertainties plotted are standard errors of the mean determined from the daily means.

Summary and Conclusions

The University of Denver has successfully completed two measurement collection campaigns at the West Los Angeles sampling site (southbound La Brea Ave. to eastbound I-10) in the spring of 2013 and 2015. The remote sensor used in this study measures the molar ratios of CO, HC, NO, NH_3 and NO_2 to CO_2 in motor vehicle exhaust. From these ratios, we can derive the fuel specific emissions in grams per kilogram of fuel for CO, HC, NO, NH_3 and NO_2 in the exhaust. In addition, the system used in this study was configured to determine the speed and acceleration of the vehicle, and was accompanied by a video system to record the license plate of the vehicle for matching with state records to identify vehicle make and model year.

The first campaign collected measurements between April 27- May 4, 2013 resulting in a vehicle and emissions database containing 27,247 records. The second sampling campaign was conducted March 28 – April 3, 2015 at the same location and resulted in a vehicle emissions database containing 22,124 records. These two data sets make the sixth and seventh data set that has been collected at this site since 1999. New for these sampling campaigns the data collection was also carried out on Saturday and Sunday. These databases, as well as all of the previous compiled by the University of Denver, can be found at our website www.feat.biochem.du.edu.

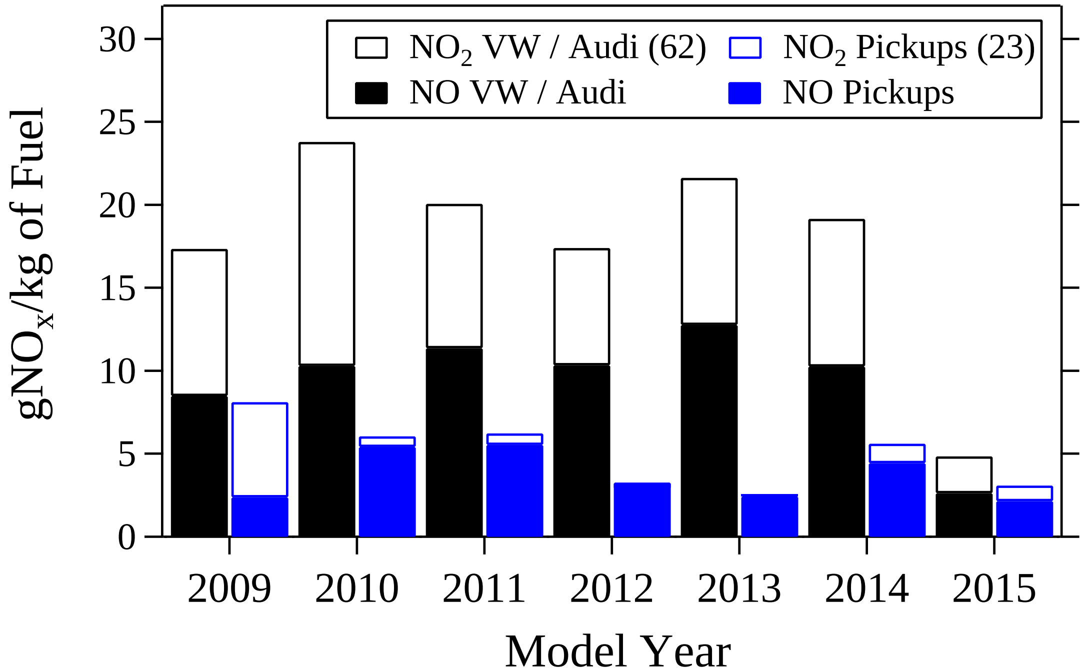

Figure 38. Total gNO_x/kg of fuel emissions versus model year for 2009 and newer diesel vehicles manufactured by Volkswagen and Audi (62 measurements) compared with diesel pickups manufactured by Ford, Chevrolet, Dodge and GMC (23 measurements) for the 2015 data. The filled portion of each bar is the contribution of NO (graphed as grams of NO_2) to the total and the open portion is the NO_2 contribution.

The 2013 mean fuel specific emissions for CO, HC, NO, NH_3 and NO_2 were determined to be 16.4, 2.2, 2.2, 0.6 and 0.2, g/kg of fuel respectively. The emissions measurements collected as part of this study continue to exhibit a gamma distribution, with the highest emitting 10% of the measurements responsible for 77%, 99%, 83%, 53% and 86% of the CO, HC, NO, NH_3 and NO_2 emissions respectively. The ramp metering lights, which have properly functioned for all of the previous campaigns, were not operational at all during our eight days of measurements. This altered the driving mode observed with 2013 mean speeds being more than 4 miles per hour faster (21.9 vs 17.6 mph in 2008) and an average deceleration versus pervious acceleration rates (-0.2 vs 1.7 mph/sec in 2008). These differences are most apparent in the HC, NO and NH_3 emissions which are sensitive to throttle position.

The 2015 mean emissions for CO, HC, NO, NH_3 and NO_2 were determined to be 13, 1.3, 1.9, 0.7 and -0.01, g/kg of fuel respectively. The highest emitting 10% of the measurements were responsible for 87%, 100%, 89%, 51% and 100% of the CO, HC, NO, NH_3 and NO_2 emissions. In 2015 the ramp metering lights return to the operating mode that had been the norm prior to the 2013 measurements. However, on Sunday March 29, 2015 they were turned off and driving modes on that day were like those observed in 2013 with increased speeds and decreased accelerations.

Since the first measurements were collected in the fall of 1999 the CO emissions have dropped 82% (70.3 to 13), the HC emissions have decreased by 81% (7.0 to 1.3 g/kg) and the NO mean emissions by 71% (6.6 to 1.9 g/kg). These decreases have happened despite the fact that fleet age has increased by more than 1.5 model years as a result of the lost vehicle sales during the 2008 – 2009 recession. When comparing emissions by the age of the vehicle one finds that 24 year old vehicles measured in 2015 (1991 models) have emissions that are very similar to 10 year old vehicles in 1999 (1990 models). While these large reductions have taken place the emissions distribution has become more skewed. The 99th percentile in 1999 was responsible for 14% and 17% of the CO and HC emissions respectively. In 2015 the same 1% of the fleet is now responsible for 35% and 46% of the CO and HC emissions respectively.

Over the sixteen year period the 99th percentiles for CO and HC emissions have dropped by more than a factor of three (773 to 258 g/kg, HC (93 to 24 g/kg). NO (53 to 34 g/kg) 99th percentiles have also dropped but not as quickly. While the reductions are impressive the more concerning trend is that all three species show signs that the large reductions may be leveling out. The driving mode changes that affected the 2013 data set introduces some uncertainty into whether this is in fact the case. This is important because as the 99th percentile goes so goes fleet emission means. Additional data sets will be needed to fully answer this question.

A major change observed in 2013 was a dramatic increase in the age of the vehicle fleet. Since 1999 the vehicle fleet age at this site had been trending downward from 7.9 years old in 1999 to 7.4 years old in 2005 and 2008. The dramatic economic downturn that began in late 2008 and continued through 2010 increased the average age of the West LA fleet to 9.1 years old. California new vehicle registrations as reported by the National Automobile Dealers Association for 2009 were 45% lower than for 2007. For the 2013 West LA data there are 38% fewer 2009 model year vehicles than 2007 models but 2008 – 2011 model years also show the effects. Fleet age recovered slightly in 2015 with the observed fleet age decreasing slightly to 8.9 years old. Recovery from the 08-09 recession does not appear as if it will be very fast as at this rate it will take more than 20 years to return to the previous fleet age of 7.4 years measured in 2008.

The sudden increase in the fleet age has resulted in tailpipe emissions not decreasing at the same rate they had been before the downturn. When we age adjusted the 2013 data to the fleet age distribution seen in 2008 we find that CO, HC, NO and NH_3 emissions would have been 23% (3.8 g/kg), 10% (0.2 g/kg), 28% (0.6 g/kg) and 14% (0.08 g/kg) lower respectively than measured absent the downturn. These differences are statistically significant for all of these species but the HC emissions. The emissions which would have been eliminated by fleet turnover were concentrated in the 10 to 20 year old vehicles.

For the first time we collected emission measurements during the weekend at the West LA site. To our surprise Saturday had the highest traffic volumes of the week. As expected we see fewer diesel powered vehicles on the weekend days (2013 weekday average of 2.4%, Saturday 1.5% and Sunday 0.5% / 2015 weekday average of 2.0%, Saturday 0.8% and Sunday of 0.5%) although low exhaust, diesel powered vehicles in general are not a large segment of this fleet. Emission differences between the weekday and weekend days are very small with the fleet getting slightly newer on Sunday (2013 weekday and Saturday mean model year of 2004.7 and 2005 for Sunday / 2015 weekday and Saturday mean model year of 2006.9 and 2006.6 and 2007 for Sunday). Sunday emissions are the lowest for all of the species in both years except NO_2 but the differences are not statistically significant when compared to the weekday means.

Data collected in 2013 at the West Los Angeles site were combined with measurements collected in Denver, CO and Tulsa, OK to highlight the fact that passenger diesel NO_x emissions were significantly higher than should have been expected under the new Lev II/Tier II standards. Mean gNO_x/kg of fuel emissions for 2009 and newer Volkswagens (33 measurements) and Audis (8 measurements) measured at the West Los Angeles site in 2013 averaged 18.4 and 30.6 gNO_x/kg of fuel respectively. Measurements collected concurrently from diesel passenger vehicles that were manufactured prior to 2009 showed their essentially uncontrolled mean gNO_x/kg of fuel emissions of 13.1. In addition the newer vehicles had a significantly higher proportion of their NO_x emissions emitted as NO_2 (0.5 versus 0.2). FEAT's ability to unobtrusively monitor on-road emissions is one method that can be exploited to certify emissions certification compliance.

Recommendations

Remote vehicle exhaust sensors are capable of quickly and unobtrusively collecting a large number of emission measurements that can be used to track fleet emission trends. The recent recession and Volkswagen emissions cheating scandal are both important events that emphasize the need for regular on-road emissions data collection in order to have data to evaluate the importance of unforeseen events. These two new data sets suggest that emissions reductions of the last two decades may be slowing which could be a major problem for future fleet emission reductions. Future data collections will be needed to answer this question.

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APPENDIX A: FEAT criteria to render a reading "invalid" or not measured.

Not measured:

1) Beam block and unblock and then block again with less than 0.5 seconds clear to the rear. Often caused by elevated pickups and trailers causing a "restart" and renewed attempt to measure exhaust. The restart number appears in the database.

2) Vehicle which drives completely through during the 0.4 seconds "thinking" time (relatively rare).

Invalid :

1) Insufficient plume to rear of vehicle relative to cleanest air observed in front or in the rear; at least five, 10ms averages >0.25% CO_2 in 8 cm path length. Often heavy-duty diesel trucks, bicycles.

2) Too much error on CO/CO_2 slope, equivalent to $\pm$20% for %CO. >1.0, 0.2%CO for %CO<1.0.

3) Reported %CO , <-1% or >21%. All gases invalid in these cases.

4) Too much error on HC/CO_2 slope, equivalent to $\pm$20% for HC >2500ppm propane, 500ppm propane for HC <2500ppm.

5) Reported HC <-1000ppm propane or >40,000ppm. HC "invalid".

6) Too much error on NO/CO_2 slope, equivalent to $\pm$20% for NO>1500ppm, 300ppm for NO<1500ppm.

7) Reported NO<-700ppm or >7000ppm. NO "invalid".

8) Excessive error on NH_3/CO_2 slope, equivalent to $\pm$50ppm.

9) Reported NH_3 < -80ppm or > 7000ppm. NH3 "invalid".

10) Excessive error on NO_2/CO_2 slope, equivalent to $\pm$20% for NO_2 > 200ppm, 40ppm for NO_2 < 200ppm

11) Reported NO_2 < -500ppm or > 7000ppm. NO_2 "invalid".

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

APPENDIX B: Explanation of the Labrea13.dbf and Labrea15.dbf databases.

The files are a Microsoft FoxPro database file, and can be opened by any version of MS FoxPro. The file can be read by a number of other database management programs as well, and is available on our website at www.feat.biochem.du.edu. The following is an explanation of the data fields found in the databases:

License	California license plate.
Date	Date of measurement, in standard format.
Time	Time of measurement, in standard format.
Percent_CO	Carbon monoxide concentration, in percent.
CO_err	Standard error of the carbon monoxide measurement.
Percent_HC	Hydrocarbon concentration (propane equivalents), in percent.
HC_err	Standard error of the hydrocarbon measurement.
Percent_NO	Nitric oxide concentration, in percent.
NO_err	Standard error of the nitric oxide measurement.
PercentNH3	Ammonia concentration, in percent.
NH3_err	Standard error of the ammonia measurement.
PercentNO2	Nitrogen dioxide concentration, in percent.
NO2_err	Standard error of the nitrogen dioxide measurement.
Percent_CO2	Carbon dioxide concentration, in percent.
CO2_err	Standard error of the carbon dioxide measurement.
Opacity	Opacity measurement, in percent.
Opac_err	Standard error of the opacity measurement.
Restart	Number of times data collection is interrupted and restarted by a close-following vehicle, or the rear wheels of tractor trailer.
HC_flag	Indicates a valid hydrocarbon measurement by a “V”, invalid by an “X”.
NO_flag	Indicates a valid nitric oxide measurement by a “V”, invalid by an “X”.
NH3_flag	Indicates a valid ammonia measurement by a “V”, invalid by an “X”.
NO2_flag	Indicates a valid nitrogen dioxide measurement by a “V”, invalid by an “X”.
Opac_flag	Indicates a valid opacity measurement by a “V”, invalid by an “X”.
Max_CO2	Reports the highest absolute concentration of carbon dioxide measured by the remote sensor over an 8 cm path; indicates plume strength.
Speed_flag	Indicates a valid speed measurement by a “V”, an invalid by an “X”, and slow speed (excluded from the data analysis) by an “S”.
Speed	Measured speed of the vehicle, in mph.

Accel	Measured acceleration of the vehicle, in mph/s.
Tag_name	File name for the digital picture of the vehicle.
Data_fn	File name for file which contains this vehicles high frequency data.
Body_type	California dmv designated body type (2013 database only).
Body_style	California dmv designated body type (2015 database only).
Year	Model year.
Vin	Vehicle identification number.
Model	California dmv designated model type
Model_info	Expanded model information (2015 database only).
Make	Manufacturer of the vehicle.
Fuel	Fuel type G (gasoline), D (diesel), N (natural gas) and Q (hybrid).
City	Registrant's mailing city (2013 database only).
Zipcode	Registrant's mailing zip code.
CO_gkg	Grams of CO per kilogram of fuel using 860 gC/kg of fuel.
HC_gkg	Grams of HC per kilogram of fuel using 860 gC/kg of fuel and the molecular weight of propane which is our calibration gas.
NO_gkg	Grams of NO per kilogram of fuel using 860 gC/kg of fuel.
Nh3_gkg	Grams of NH_3 per kilogram of fuel using 860 gC/kg of fuel.
NO2_gkg	Grams of NO_2 per kilogram of fuel using 860 gC/kg of fuel.
NOx_gkg	Grams of NO_x per kilogram of fuel using 860 gC/kg of fuel.
HC_offset	Hydrocarbon concentrations after offset adjustment (2013 database only).
Hcgkg_off	Grams of HC per kilogram of fuel using 860 gC/kg of fuel and using the HC_offset value for this calculation (2013 database only).
VSP	Vehicles specific power calculating using the equation provided in the report.
V_model	VIN decoded model information (2013 database only).
V_body	VIN decoded body information (2013 database only).
V_type	VIN decoded vehicle type information (2013 database only).
V_engine	VIN decoded engine size in liters (2013 database only).
V_wtclass	VIN decoded weight class (2013 database only).
V_gvw	VIN decoded gross vehicle weight (2013 database only).
V_fuel	VIN decoded fuel type (2013 database only).
V_trans	VIN decoded transmission type (2013 database only).
V_model	VIN decoded model information (2013 database only).

V_xdrive VIN decoded all-wheel drive information (2013 database only).

APPENDIX C: Temperature and Humidity Data as Recorded at Los Angeles International Airport

1999 Temperature and Humidity Data										
Time	11/09 °F	11/09 %RH	11/10 °F	11/10 %RH	11/11 °F	11/11 %RH	11/12 °F	11/12 %RH	11/13 °F	11/13 %RH
5:50	54	87	53	93	52	89	58	93	56	100
6:50	55	80	55	83	57	75	57	100	57	100
7:50	57	78	57	81	60	70	59	96	58	100
8:50	60	72	61	70	63	65	59	90	59	93
9:50	63	68	64	63	67	59	62	84	61	84
10:50	66	61	65	66	68	59	61	87	61	84
11:50	68	55	65	70	68	61	62	84	61	84
12:50	67	66	64	75	68	63	61	84	62	81
13:50	64	73	64	75	69	57	62	81	62	81
14:50	64	75	64	70	67	66	62	84	62	81
15:50	62	81	64	68	65	76	61	87	62	81
16:50	61	84	63	73	63	81	61	90	61	87

2001 Temperature and Humidity Data										
Time	10/15 °F	10/15 %RH	10/16 °F	10/16 %RH	10/17 °F	10/17 %RH	10/18 °F	10/18 %RH	10/19 °F	10/19 %RH
8:03	64	90	66	90	61	90	62	93	64	84
9:03	67	87	66	81	63	87	65	78	67	76
10:03	68	79	69	73	65	78	70	64	69	73
11:03	71	73	70	71	67	73	69	73	68	76
12:03	68	68	67	79	67	73	70	68	66	78
13:03	69	76	69	73	66	75	69	70	66	78
14:03	69	76	68	76	67	76	70	66	63	84
15:03	67	76	68	76	66	78	68	70	64	84
16:03	65	84	66	81	65	81	67	79	63	87
17:03	63	87	64	90	63	87	64	87	63	87
18:03	63	93	63	90	62	90	63	90	62	90

2003 Temperature and Humidity Data										
Time	10/27 °F	10/27 %RH	10/28 °F	10/28 %RH	10/29 °F	10/29 %RH	10/30 °F	10/30 %RH	10/31 °F	10/31 %RH
7:50	71	31	69	41	64	87	64	73	57	78
8:50	78	24	75	33	66	81	64	73	58	72
9:50	84	21	79	30	68	73	65	70	61	56
10:50	87	24	81	29	69	70	67	66	62	56
11:50	84	29	80	41	67	81	66	59	62	58
12:50	82	27	75	58	69	76	65	59	63	52
13:50	83	24	77	54	67	81	63	63	62	56
14:50	82	26	77	50	66	81	64	54	61	58
15:50	79	32	75	54	64	87	62	52	61	60
16:50	74	54	70	76	63	90	60	62	61	63
17:50	72	60	70	82	64	87	60	62	61	60
18:50	73	62	67	97	63	87	60	62	60	62

2005 Temperature and Humidity Data										
Time	10/17 °F	10/17 %RH	10/18 °F	10/18 %RH	10/19 °F	10/19 %RH	10/20 °F	10/20 %RH	10/21 °F	10/21 %RH
7:50	65	81	59	93	61	84	61	87	61	90
8:50	66	84	60	93	63	78	63	84	62	86
9:50	67	76	61	87	63	81	65	81	64	84
10:50	67	79	62	84	65	76	67	76	64	84
11:50	66	78	64	78	66	70	68	73	63	87
12:50	64	87	65	70	66	70	68	73	63	87
13:50	60	93	63	78	67	68	66	81	64	84
14:50	60	93	63	78	65	73	64	87	62	90
15:50	60	93	62	81	64	78	61	93	62	90
16:50	60	93	62	78	62	84	61	93	61	93
17:50	60	90	61	84	61	90	60	96	61	90
18:50	60	86	61	84	61	90	60	96	61	93

2008 West Los Angeles Temperature and Humidity Data										
Time	3/17 °F	3/17 %RH	3/18 °F	3/18 %RH	3/19 °F	3/19 %RH	3/20 °F	3/20 %RH	3/21 °F	3/21 %RH
7:50	59	13	56	49	55	77	57	69	57	62
8:50	63	14	60	56	58	70	58	67	63	48
9:50	67	9	63	46	61	60	58	70	66	42
10:50	69	10	67	36	59	67	59	67	69	32
11:50	66	17	65	50	60	65	60	65	70	41
12:50	66	28	64	48	60	65	59	70	69	44
13:50	65	24	63	52	60	65	60	67	69	41
14:50	63	26	61	63	58	70	60	70	69	39
15:50	62	28	60	67	57	72	60	67	67	39
16:50	62	22	59	65	55	77	60	70	67	40
17:50	59	20	58	72	54	80	60	70	66	43
18:50	57	11	57	78	54	80	58	75	63	56

2013 West Los Angeles Temperature and Humidity Data														
Time	4/28 °F	4/28 %RH	4/29 °F	4/29 %RH	4/30 °F	4/30 %RH	5/1 °F	5/1 %RH	5/2 °F	5/2 %RH	5/3 °F	5/3 %RH	5/4 °F	5/4 %RH
6:53	60	81	60	84	60	75	62	75	62	78	73	13	62	78
7:53	61	78	61	81	61	70	63	73	67	66	81	9	64	73
8:53	64	73	61	81	62	67	64	70	69	61	85	8	66	65
9:53	66	70	64	73	62	70	66	65	70	59	88	5	67	63
10:53	66	70	67	66	63	68	69	59	75	43	89	6	68	61
11:53	66	70	70	59	64	65	71	53	75	45	82	26	71	53
12:53	66	68	67	63	65	63	69	55	75	48	79	31	71	51
13:53	65	70	66	65	66	63	69	59	74	54	79	26	72	48
14:53	64	73	66	65	66	63	68	61	74	46	79	27	71	53
15:53	63	75	63	73	64	68	67	66	70	59	76	37	70	55
16:53	61	81	63	73	63	70	66	70	71	53	77	21	65	73
17:53	59	87	61	78	61	78	64	73	69	55	72	41	64	75
18:53	58	90	59	84	62	75	63	78	66	63	71	41	63	78

2015 West Los Angeles Temperature and Humidity Data														
Time	3/28 °F	3/28 %RH	3/29 °F	3/29 %RH	3/30 °F	3/30 %RH	3/31 °F	3/31 %RH	4/1 °F	4/1 %RH	4/2 °F	4/2 %RH	4/3 °F	4/3 %RH
6:53	60	97	57	100	59	90	57	90	59	87	59	65	62	35
7:53	62	90	58	100	60	87	58	87	61	81	61	63	69	23
8:53	65	78	63	81	62	81	62	75	64	63	62	63	74	15
9:53	71	59	63	81	65	75	66	68	66	68	67	47	78	12
10:53	66	78	65	75	66	73	64	73	67	66	69	39	81	10
11:53	68	73	67	70	66	70	63	75	66	73	67	57	81	16
12:53	69	71	67	70	66	70	63	73	67	66	67	55	76	32
13:53	69	71	67	70	66	70	63	73	67	63	68	30	74	41
14:53	68	71	66	70	65	73	64	70	66	70	67	45	74	25
15:53	67	73	65	75	64	78	64	73	66	73	66	54	74	23
16:53	64	81	64	78	63	81	63	75	64	65	65	47	73	25

APPENDIX D: Example Calculation of Vehicle Specific Power Adjusted Vehicle Emissions

1997 (Measured)	VSP Bin	Mean NO (ppm)	No. of Measurements	Total Emissions
	-5	236	225	53200
	0	224	1609	360090
	5	307	4985	1531000
	10	431	6146	2648020
	15	548	2624	1438060
	20	590	456	269180
			16045	6299550
			Mean NO (ppm)	**393**
1998 (Measured)	VSP Bin	Mean NO (ppm)	No. of Measurements	Total Emissions
	-5	233	137	31951
	0	239	784	187394
	5	265	3613	956613
	10	385	6685	2576433
	15	475	6012	2856195
	20	483	2392	1156320
			19623	7764906
			Mean NO (ppm)	**396**
1998 (Adjusted)	VSP Bin	'98 Mean NO (ppm)	'97 No. of Meas.	Total Emissions
	-5	233	225	52474
	0	239	1609	384588
	5	265	4985	1319877
	10	385	6146	2368700
	15	475	2624	1246616
	20	483	456	220436
			16045	5592691
			Mean NO (ppm)	**349**

Note that the Mean NO readings listed here have been rounded to the nearest ppm values which results in the Total Emissions column appearing to not be a direct multiplication product. The -5 to 20 kw/tonne bins are chosen to preclude any "off-cycle" emissions.

The object of this adjustment is to have the 1998 fleet's emissions calculated as if they drove (VSP wise) like the 1997 fleet. This is accomplished by first binning and averaging the 1997 and 1998 data (the top two tables). We then combine the mean NO values from the 1998 fleet with the numerical VSP bin distribution from the 1997 fleet in the bottom table. The product of these two columns is summed and the sum total emissions are divided by the number of 1997 vehicles to produce the 1998 adjusted mean NO average. For this example, it shows that the 1998 fleet when driven like the 1997 fleet has lower NO emissions than the 1997 fleet.

APPENDIX E: Example Calculation of Model Year Adjusted Fleet Emissions

1997 (Measured)	Model Year	Mean NO (ppm)	No. of Measurements	Total Emissions
	83	690	398	274620
	84	720	223	160560
	85	680	340	231200
	86	670	513	343710
	87	690	588	405720
	88	650	734	477100
	89	610	963	587430
	90	540	962	519480
	91	500	1133	566500
	92	450	1294	582300
	93	460	1533	705180
	94	370	1883	696710
	95	340	2400	816000
	96	230	2275	523250
	97	150	2509	376350
			17748	7266110
			Mean NO (ppm)	**409**

1998 (Measured)	Model Year	Mean NO (ppm)	No. of Measurements	Total Emissions
	83	740	371	274540
	84	741	191	141531
	85	746	331	246926
	86	724	472	341728
	87	775	557	431675
	88	754	835	629590
	89	687	1036	711732
	90	687	1136	780432
	91	611	1266	773526
	92	538	1541	829058
	93	543	1816	986088
	94	418	2154	900372
	95	343	2679	918897
	96	220	2620	576400
	97	177	3166	560382
			20171	9102877
			Mean NO (ppm)	**451**

1998 (Adjusted)	Model Year	‘98 Mean NO (ppm)	‘97 No. of Meas.	Total Emissions
	83	740	398	294520
	84	741	223	165243
	85	746	340	253640
	86	724	513	371412
	87	775	588	455700
	88	754	734	553436
	89	687	963	661581
	90	687	962	660894
	91	611	1133	692263
	92	538	1294	696172
	93	543	1533	832419
	94	418	1883	787094
	95	343	2400	823200
	96	220	2275	500500
	97	177	2509	444093
			17748	8192167
			Mean NO (ppm)	**462**

APPENDIX F: Field Calibration Record.

2001 West Los Angeles (FEAT 3002)				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
10/15	8:00	1.56	1.40	2.01
10/15	13:00	1.22	1.05	1.26
10/16	7:00	1.47	1.25	1.85
10/16	15:30	1.23	1.02	1.39
10/17	7:00	1.47	1.50	2.30
10/17	12:50	1.39	1.12	1.53
10/18	8:30	2.17	1.87	2.67
10/18	10:55	1.63	1.46	2.02
10/19	7:55	1.68	1.39	1.42
10/19	10:09	1.50	1.26	1.31

2003 West Los Angeles (FEAT 3002)				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
10/27	12:30	1.228	1.27	2.14
10/27	17:20	1.333	1.19	1.7
10/28	8:00	3.14	2.91	7.2
10/28	9:45	2.22	2.2	4.87
10/28	11:23	1.6	1.5	2.53
10/29	7:50	1.666	1.47	1.89
10/29	11:30	1.31	1.15	1.42
10/29	14;20	1.31	1.14	1.228
10/29	17:30	1.41	1.28	1.62
10/30	6:05	1.48	1.35	2.53
10/30	9:30	1.41	1.29	2.03
10/30	14:30	1.42	1.28	1.73
10/31	5:50	1.55	1.35	2.85
10/31	10:35	1.34	1.19	1.79

2005 West Los Angeles (FEAT 3002)				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
10/17	8:18	1.8	1.5	1.4
10/17	12:18	1.37	1.17	1.46
10/18	9:45	1.82	1.36	1.53
10/18	13:20	1.7	1.17	1.32
10/19	6:17	2.74	1.94	2.04
10/19	8:40	2.15	1.65	1.83
10/19	12:30	1.66	1.17	1.4
10/20	6:18	2.45	1.84	1.84
10/20	8:30	2.64	2.00	1.89
10/20	11:30	1.66	1.26	1.28
10/21	6:20	1.76	1.26	1.55
10/21	8:31	2.06	1.55	1.94
10/21	11:33	1.65	1.17	1.4

2008 West Los Angeles (FEAT 3002)							
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	SO_2 Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
3/17	9:10	1.68	1.60	1.24	1.16	1.02	1.07
3/17	12:00	1.46	1.41	1.10	1.04	1.02	0.95
3/18	7:15	3.15	2.83	3.06	2.52	0.92	2.39
3/18	9:05	1.93	1.63	1.74	1.01	0.92	1.35
3/18	12:30	1.45	1.28	1.22	0.75	0.92	0.95
3/19	7:20	2.65	2.30	1.63	2.13	0.91	0.90
3/19	9:50	1.96	1.87	1.18	1.57	0.91	0.66
3/19	13:00	1.65	1.55	0.92	1.21	0.90	0.96
3/20	7:00	1.99	1.85	1.38	1.61	0.87	1.19
3/20	9:15	1.82	1.74	1.18	1.34	0.87	1.02
3/20	13:15	1.51	1.44	1.00	1.16	0.87	0.86
3/21	7:15	3.50	3.40	2.70	3.10	0.85	2.08
3/21	8:25	2.81	2.70	1.92	2.20	0.85	1.48
3/21	9:35	2.02	1.98	1.26	1.53	0.85	0.92
3/21	11:45	1.70	1.65	1.10	1.22	0.85	0.80

2013 West Los Angeles (FEAT 3002)						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
4/27	10:15	1.47	1.36	1.14	0.86	1
4/27	13:31	1.37	1.22	1.10	0.82	0.93
4/28	13:00	1.66	1.48	1.20	0.85	0.63
4/29	7:00	1.78	1.60	1.44	0.79	0.81
4/29	12:45	1.46	1.3	1.36	0.85	0.75
4/30	6:50	1.85	1.65	1.43	0.78	1
4/30	11:14	1.7	1.57	1.60	0.81	1
5/1	6:40	1.78	1.64	1.54	0.79	0.93
5/1	12:20	1.5	1.4	1.33	0.83	0.81
5/2	7:00	2.41	2.27	2.30	0.77	1.53
5/2	11:30	1.52	1.47	1.24	0.86	0.89
5/3	7:00	2.57	2.45	1.93	0.92	1.43
5/3	9:25	1.68	1.62	1.29	0.94	0.93
5/3	11:45	1.40	1.32	1.24	0.96	0.76
5/4	7:15	1.82	1.71	1.38	0.76	0.90
5/4	10:35	1.51	1.44	1.28	0.94	0.94

2015 West Los Angeles (FEAT 3002)						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
3/28	10:00	1.6	1.5	1.46	0.92	0.65
3/29	8:45	1.8	1.7	1.84	0.89	1.0
3/29	10:30	1.68	1.58	1.74	0.99	0.78
3/30	6:30	2.0	2.0	2.2	0.90	1.19
3/30	9:30	1.7	1.7	1.8	0.92	1.1
3/31	6:55	1.86	1.85	2.0	0.92	1.34
3/31	10:00	1.69	1.6	1.8	0.96	1.1
4/1	6:30	2.03	1.98	2.18	0.89	1.4
4/1	8:45	1.6	1.51	1.62	0.93	1.1
4/2	6:45	2.68	2.68	2.7	0.92	2.0
4/2	8:20	1.95	2.06	2.1	0.97	1.58
4/2	10:30	1.71	1.56	1.64	1.04	1.1
4/3	6:40	2.5	2.5	2.5	0.98	1.6
4/3	8:30	2.29	2.33	2.2	0.97	1.8
4/3	9:30	1.7	1.72	1.48	1.06	1.13
4/3	11:30	1.53	1.51	1.48	1.06	1.01