Final Report

Measuring Emissions from the On-Road Vehicle Fleet in West Los Angeles

Contract No. 17RD015

November 5, 2019

Prepared for the California Air Resources Board and the California Environmental Protection Agency

Dr. Tao Zhan
California Air Resources Board
1001 I Street
Sacramento, CA 95814
tzhan@arb.ca.gov

Submitted by:

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

Prepared by:

Gary A. Bishop**,** Principle Investigator

Disclaimer

The statements and conclusions in this report are those of the contractor and not necessarily those of the California Air Resources Board. The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such products.

Acknowledgements

The successful outcome of this project would not be possible without the assistance of Caltrans and Ms. Annette Bishop. Comments from the various reviewers of this report were also useful.

This Report was submitted in fulfillment of California Air Resources Board contract no. 17RD015 Measuring Emissions from the On-road Vehicle Fleet in West Los Angeles by the University of Denver under the sponsorship of the California Air Resources Board.

Table of Contents

List of Figures

List of Tables

Abstract

A sixteen-year record of on-road emission measurements at a West Los Angeles site (La Brea Ave. and I-10) was continued with an additional data collection campaign in May of 2018. During this campaign, the University of Denver collected 19,259 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 84% (70.3 to 11 g/kg), the HC mean emissions by 79% (7.0 to 1.5 g/kg) and the NO mean emissions by 76% (6.6 to 1.6 g/kg). These decreases have happened despite an older fleet (8.9 years) now than prior to the 2008 recession. Over this same time, the 99^{th} percentiles have dropped by more than a factor of three for CO and HC (773 to 212 gCO/kg of fuel and 93 to 31 gHC/kg of fuel) and a factor of 1.6 for NO (53 to 32 gNO/kg of fuel). However, during recent campaigns, the reductions in the 99^{th} percentiles have leveled out for HC and may be slowing for CO, which will likely slow future emissions reductions despite gradual electrification of the fleet.

Executive Summary

The University of Denver has completed an additional measurement collection campaign at the West Los Angeles sampling site in May of 2018. 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.

Measurements were collected between Monday, May 14 through Saturday, May 19 2018 resulting in a vehicle and emissions database containing 19,259 records. This is the eighth data set that has now been collected at this site since 1999. This database, 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 1999 the CO mean emissions have decreased by 84% (70.3 to 11 g/kg), the HC mean emissions by 79% (7.0 to 1.5 g/kg) and the NO mean emissions by 76% (6.6 to 1.6 g/kg). These decreases have happened despite an older fleet (8.9 years) since the 2008 recession. Figure E1 plots the g/kg of fuel emissions for CO, HC and NO for the 1999 and 2018 data sets against vehicle age. The zero year vehicles are 2000 model year vehicles for the 1999 data and 2018 model year vehicles for the 2018 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 2018 (1994 models) have HC and NO emissions that are similar to 10 year old vehicles in 1999 (1990 models). 24 year old vehicles measured in 2018 (1994 models) have CO emissions that are similar to 8 year old vehicles in 1999 (1992 models). This indicates that not only have large reductions in emissions taken place over this time but also emissions deterioration on a fleet mean basis is low.

Along with these large reductions the emissions distribution continues to become more skewed. The 99^{th} percentile in 1999 was responsible for 14% and 17% of the CO and HC emissions. In 2018, the same fleet is responsible for 38% and 43% of the CO and HC emissions. With the phase in of LEV II vehicles, which was completed in 2009, the NO emissions distribution has followed the CO and HC emissions distributions increasing the emissions contribution of the 99^{th} percentile from 10% in 1999 to 27% in 2018. Figures E2 and E3 plot the fuel specific 99^{th} percentile emissions for CO, HC and NO for all of the data sets collected at the West LA site. The 99^{th} percentiles for CO and HC have dropped by more than a factor of three (773 to 212 gCO/kg of fuel and 93 to 31 gHC/kg of fuel) and a factor of 1.6 for NO (53 to 32 gNO/kg of

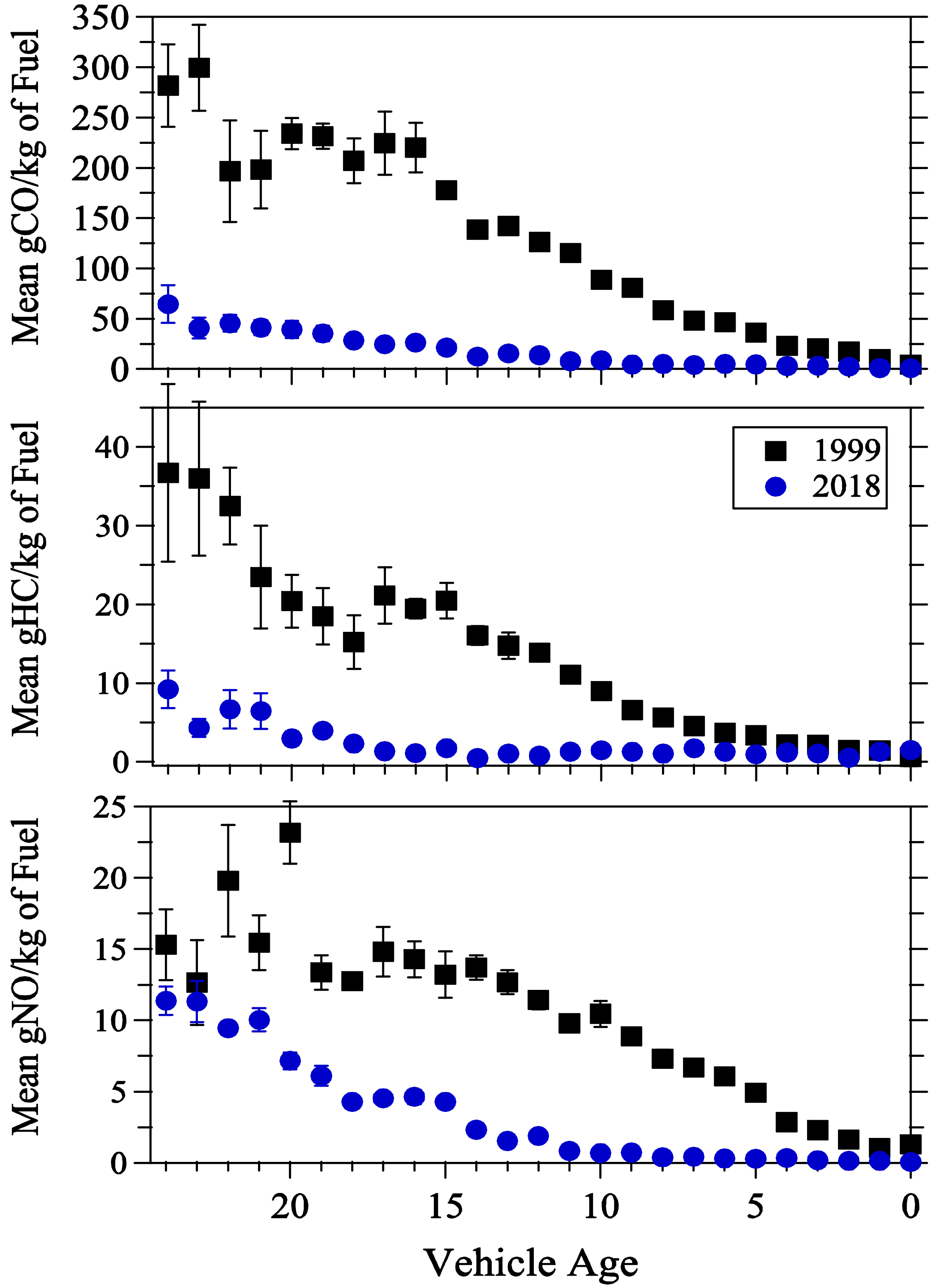

Figure E1. Fuel specific CO (top panel), HC (middle panel) and NO (bottom panel) emissions versus vehicle age for data sets collected at the West Los Angeles site in 1999 (squares) and 2018 (circles). The uncertainties plotted are standard errors of the mean estimated from the daily measurements. Zero model years are 2000 (1999 data) and 2018 (2018 data).

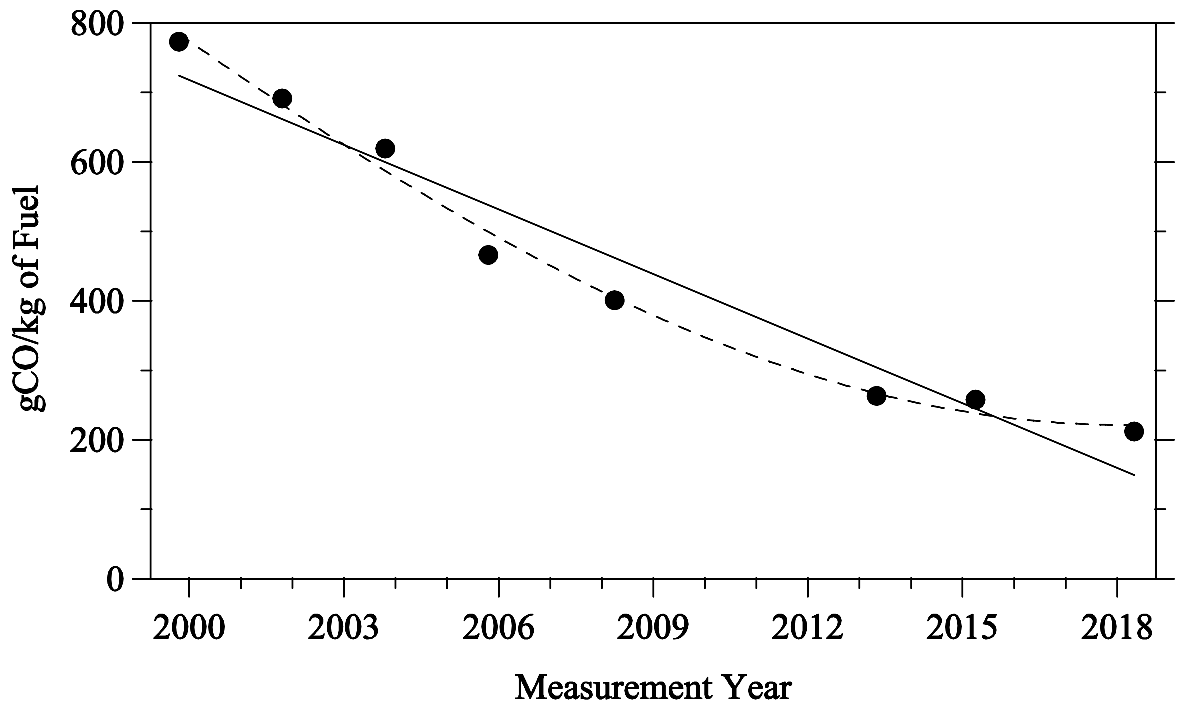

Figure E2. The gCO/kg of fuel 99th percentile for each of the West Los Angeles data sets plotted against measurement year. Linear (solid line) and an exponential decay (dashed line) fits are shown.

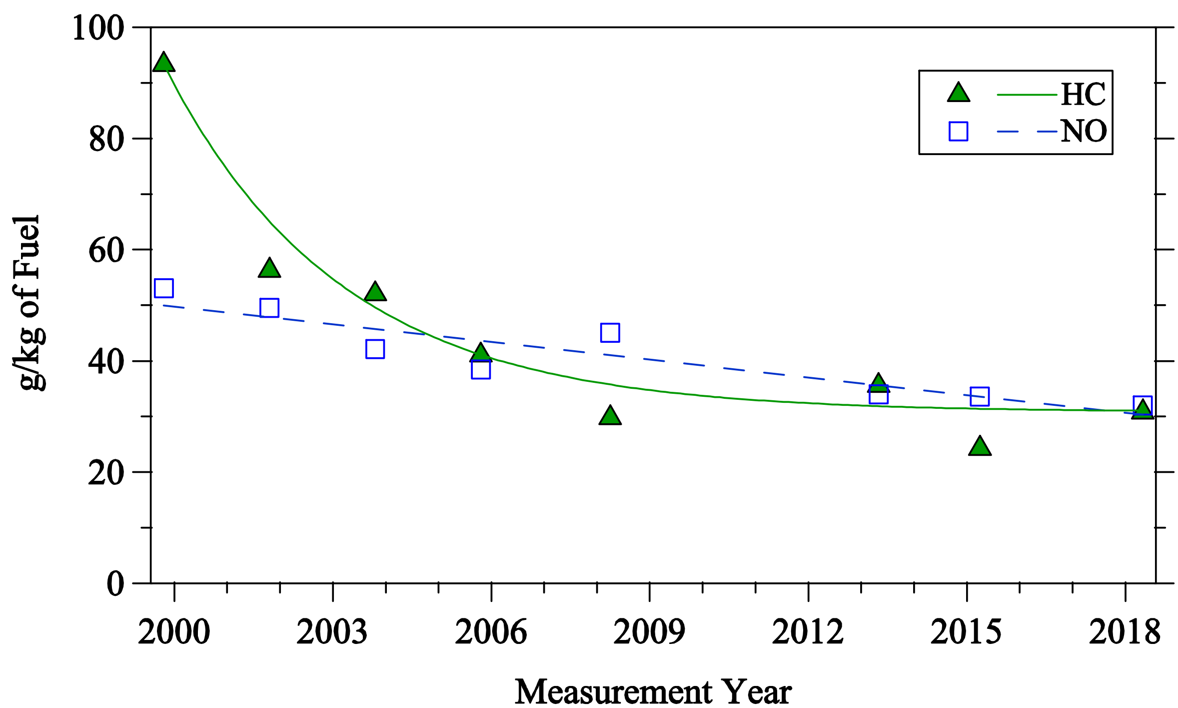

Figure E3. The gHC/kg of fuel and gNO/kg of fuel 99th percentiles for each of the West Los Angeles data sets plotted against measurement year. Lines are an exponential decay for HC and a linear fit for NO.

fuel). While these reductions are impressive, with the collection of the 2018 data it is more apparent that the decreases have leveled out for HC and may be slowing for CO. The slowing in the reductions of the 99th percentiles for CO and HC portend a floor for the CO and HC mobile source emissions inventory in the Los Angeles basin beyond which future reductions will require new ideas that specifically target the 99th percentile vehicles. Electrification of the fleet, unless targeted at the highest emitting vehicles, will unlikely reverse this slowing trend until a large majority of the fleet is electrified.

The portion of the West Los Angeles fleet that is diesel-powered is the lowest that has been observed to date with only 1.75% of the measurements being contributed by diesel vehicles. However, the diesel fleet is the oldest at ~9.3 years old seen since measurements began in 1999. Diesel CO emissions have decreased by 83% since 1999 and NO emissions have declined by 36% over the same period. NO and NO_x emissions only show declines with the 2013 measurements and have similar reductions of 41% (14.4 ± 0.8 to 9.2 ± 0.6 gNO/kg of fuel) and 40% (25.3 ± 1.4 to 15.2 ± 0.9 gNO_x/kg of fuel). In 2018, the diesel vehicles observed at the West Los Angeles site are responsible for ~10% of the fleets NO_x emissions.

Introduction

Since the early 1970's, many heavily populated U.S. cities have violated the National Air Quality Standards (NAAQS) established by the United States 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 from 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 and while emissions of all of these species have dropped dramatically over the last two decades on-road vehicles are still major sources. As of 2015, on-road vehicles continued to be estimated as one of the larger sources for major atmospheric pollutants, contributing approximately 39% of the CO, 14% of the volatile organic carbons, 3% of the ammonia (NH_3) and 36% of the NO_x to the national emission inventory.[3] In California the State's 2016 SIP Emission Projection data estimates that 55% of the CO, 26% of the reactive organic gases, 7.0% of the NH_3 and 50% of the NO_x in the statewide inventory originate from mobile sources.[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 dominant 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 most recent on-road emission measurements collected at the West Los Angles site in the spring of 2018, under California Air Resources Board (CARB) agreement no. 17RD015. Measurements were made on six consecutive days, May 14 - 19, 2018 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 California 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, 2013 and 2015 for CARB sponsored projects.[17-20] 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.[21-23] 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 directs the light across the four infrared detectors: CO, CO_2, HC and reference.

The UV light is reflected off the surface of the dichroic mirror and 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.[24]

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.[25] 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.

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

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 molar ratios 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.[25]

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

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.[26, 27] 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 inter-comparison 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.[22] 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.[28]

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.

2018 Results and Discussion

Measurements were made on six consecutive days, from Monday, May 14, to Saturday, May 19, between the hours of 6:45 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

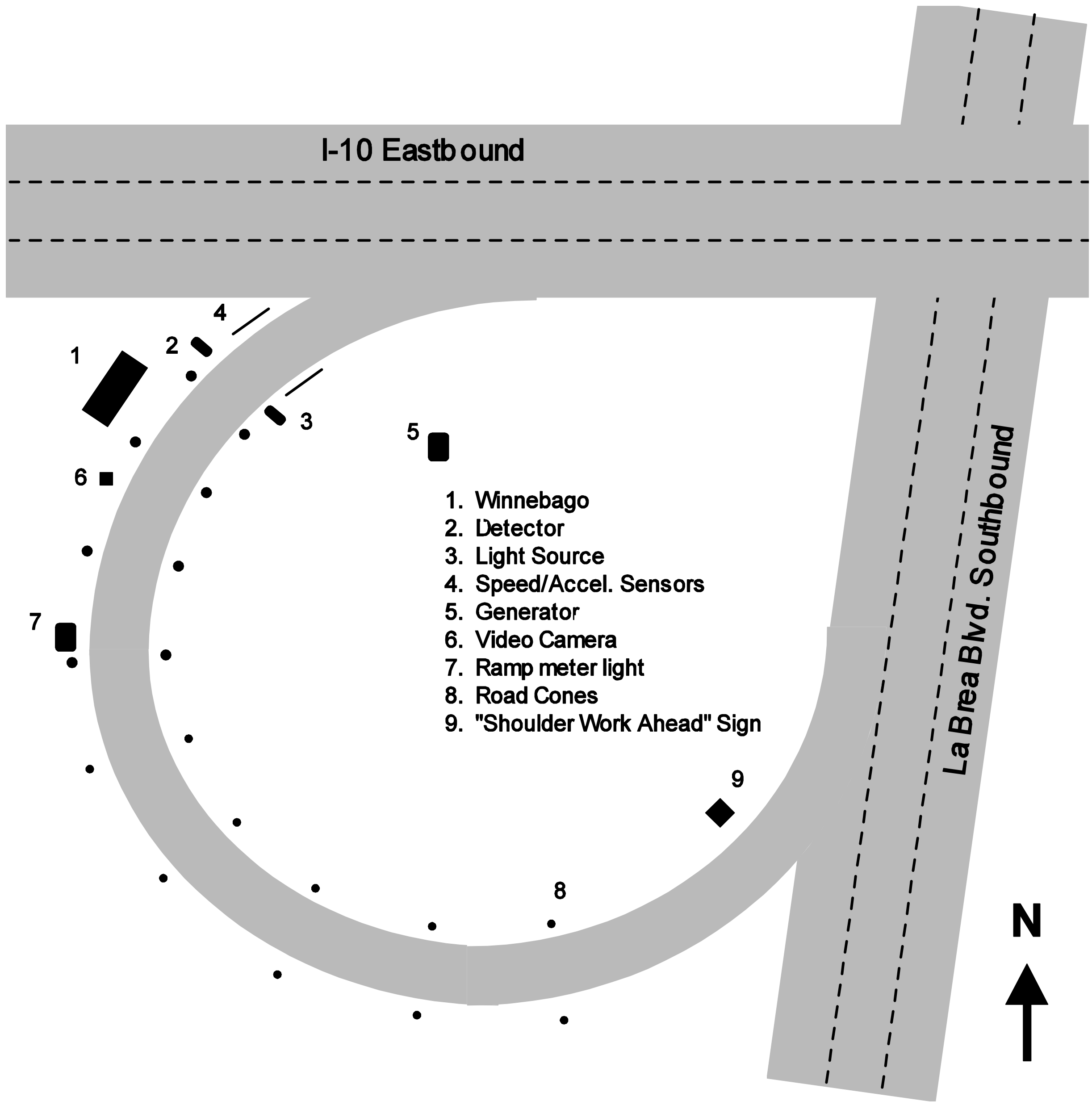

Figure 1. A schematic drawing of the on-ramp from southbound La Brea Ave. to eastbound I-10. The location and safety equipment configuration was the same for all measurement days.

see that this is a traffic light metered on-ramp with the light regulated by congestion on I-10. The uphill grade at the measurement location is 2°. The agreement called for five days of measurements but because of an unexpected drop in traffic volume (-25%) a sixth day (Saturday) was added to bolster the number of measurements. Appendix C gives temperature and humidity data for the 2018 and prior campaigns obtained from Los Angeles International Airport, approximately eight miles southwest of the measurement site. Following the six days of measurements the vehicle images were read for license plate identification. Plates that appeared to be in state and readable were sent to the Air Resources Board to have the vehicle make and model year determined. The resulting database contained 19,259 records with make and model

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 first vehicle stopped at the light is 84ft. from the measurement location.

Table 1. 2018 Validity summary.

	CO	HC	NO	NH_3	NO_2
Attempted Measurements	25,841				
Valid Measurements	23,525	23,411	23,524	23,470	23,382
Percent of Attempts	91.0%	90.6%	91.0%	90.8%	90.5%
Submitted Plates	19,620	19,540	19,619	19,570	19,524
Percent of Attempts	75.9%	75.6%	75.9%	75.7%	75.6%
Percent of Valid Measurements	83.4%	83.5%	83.4%	83.4%	83.5%
Matched Plates	19,259	19,171	19,258	19,211	19,165
Percent of Attempts	74.5%	74.2%	74.5%	74.3%	74.2%
Percent of Valid Measurements	81.9%	81.9%	81.9%	81.9%	82.0%
Percent of Submitted Plates	98.2%	98.1%	98.2%	98.2%	98.2%

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 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, out-of-state vehicles and vehicles with unreadable plates (dealer placard, obscured, missing, temporary, 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 19,259 records used in this fleet analysis, 12,370 (64.2%) were contributed by vehicles measured only once, while the remaining 6,889 (35.8%) records were from vehicles measured at least twice. The analysis in this report, unless otherwise specified, has been conducted using all of the individual measurements, as opposed to aggregating values for repeated measurements of individual vehicles.

Table 2. Number of measurements of repeat vehicles in 2018.

Number of Times Measured	Number of Vehicles	Number of Measurements	Percent of Measurements
1	12,370	12,370	64.2%
2	1,341	2,682	13.9%
3	553	1,659	8.6%
4	343	1,372	7.1%
5	185	925	4.8%
6	31	186	1.0%
7	4	28	0.2%
>7	3	37	0.2%

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 the fall of 1999, 2001, 2003, 2005 and the spring of 2013, 2015 and 2018.

Mean fleet emissions continue to decrease at the La Brea site, though at a slower pace, in much the same manner as they are at other sites across the country. The mean model year in La Brea

Table 3. West Los Angeles site historic data summary.

Study Year	1999	2001	2003	2005	2008	2013	2015	2018
Mean CO (%) (g/kg of fuel)	0.58 (71)	0.44 (53.9)	0.34 (42.6)	0.22 (27.3)	0.17 (21.4)	0.13 (16.4)	0.1 (13.0)	0.087 (11.0)
Median CO (%)	0.09	0.06	0.06	0.03	0.02	0.03	0.01	0.013
Percent of CO from 99th Percentile	14.7%	18.1%	20.4%	26.6%	31.3%	33.2%	37.4%	38.0%
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	39 (1.5) 34
Median HC (ppm)[a]	70	39	45	40	10	27	12	24
Percent of HC from 99th Percentile	51.4%	36.4%	34.1%	33.4%	45.0%	31.1%	48.7%	43.3%
Mean NO (ppm) (g/kg of fuel)	477 (6.7)	411 (5.8)	323 (4.6)	242 (3.4)	265 (3.75)	153 (2.16)	136 (1.9)	113 (1.6)
Median NO (ppm)	116	72	48	24	11	5	2	3
Percent of NO from 99th Percentile	9.6%	10.5%	11.5%	14.6%	14.4%	20.6%	23.3%	27.2%
Mean NH_3 (ppm) (g/kg of fuel)	NA	NA	NA	NA	99 (0.79)	72 (0.58)	88 (0.70)	84 (0.68)
Median NH_3 (ppm)	NA	NA	NA	NA	34	24	32	31
Percent of NH_3 from 99th Percentile	NA	NA	NA	NA	11.0%	12.0%	10.8%	12.0%
Mean NO_2 (ppm) (g/kg of fuel)	NA	NA	NA	NA	4 (0.08)	7 (0.16)	0 (-0.01)	2 (0.05)
Median NO_2 (ppm)	NA	NA	NA	NA	2	3.5	-2	1
Percent of NO_2 from 99th Percentile	NA	NA	NA	NA	45.3%	32.8%	100%	47.1%
Mean Model Year	1992.4	1994.4	1996.5	1998.9	2001.2	2004.7	2006.9	2009.9
Mean Fleet Age[c]	7.9	7.8	7.8	7.4	7.4	9.1	8.9	8.9
Mean Speed (mph)	17.6	18.3	17.0	17.7	17.6	21.9	18.8	17.6
Mean Acceleration (mph/s)	1.4	1.4	1.9	1.7	1.9	-0.2	1.2	0.9
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°	7.8 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.

has not kept pace with the measurement schedule since the last recession in 2008-2009 leading to a significant increase in the age of the on-road fleet since the 2013 measurements. The percentage of emissions from the highest emitting 1% of the measurements increased for all species except HC and NO_2. The percent of HC contributed by the top 1% has varied around 40% since 2001, suggesting we have likely reached a plateau.

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 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 is subtracted (or added if negative) from all of the HC measurements (see Appendix D). 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.

Negative fuel-specific emissions can be seen in some of the results presented, which does not mean that the vehicles were cleaner than the background air but reflects true zero-emissions that are reported as negative values, as explained below. FEAT's basic units of measurement are molar emission ratios of pollutants (e.g. CO, HC, and NO) to CO_2, with the ratios being the linear regression slopes of the pollutant versus CO_2 measured 50 times during a half-second period. An "ideal" zero emission measurement would have a correlation plot with a slope of zero. In real-world measurements, however, instrument and environmental noises inevitably result in positive slopes in some true zero-emission incidents and negative slopes in some other true zero-emission incidents. In fact, properly calibrated instruments are expected to result in a zero-centered normal distribution for all the true zero-emission incidents. For this reason, we preserve the negative values in the FEAT database and include those values in this analysis to offset the positive tail of the zero-emission distribution, so that the sample average is not biased toward positive.

The inverse relationship between vehicle emissions and model year is shown in Figure 3 for CO (top panel), HC (middle) and NO (bottom), for all of the years sampled. The HC data have been offset adjusted here for comparison. As emissions have decreased, the plots for each successive campaign reflect the growing number of model years that have low average and unchanging emission levels. It is approximately 12 years of vehicle age before average CO and NO emissions begin to rise and 15 to 17 years for HC. The introduction of LEV II vehicles, and their emphasis on controlling NO_x emissions, has led to NO joining CO and HC in this aspect.

As originally shown by Ashbaugh et al.,[29] vehicle emissions by model year, with each model year divided into emission quintiles, were plotted for data collected in 2018. 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

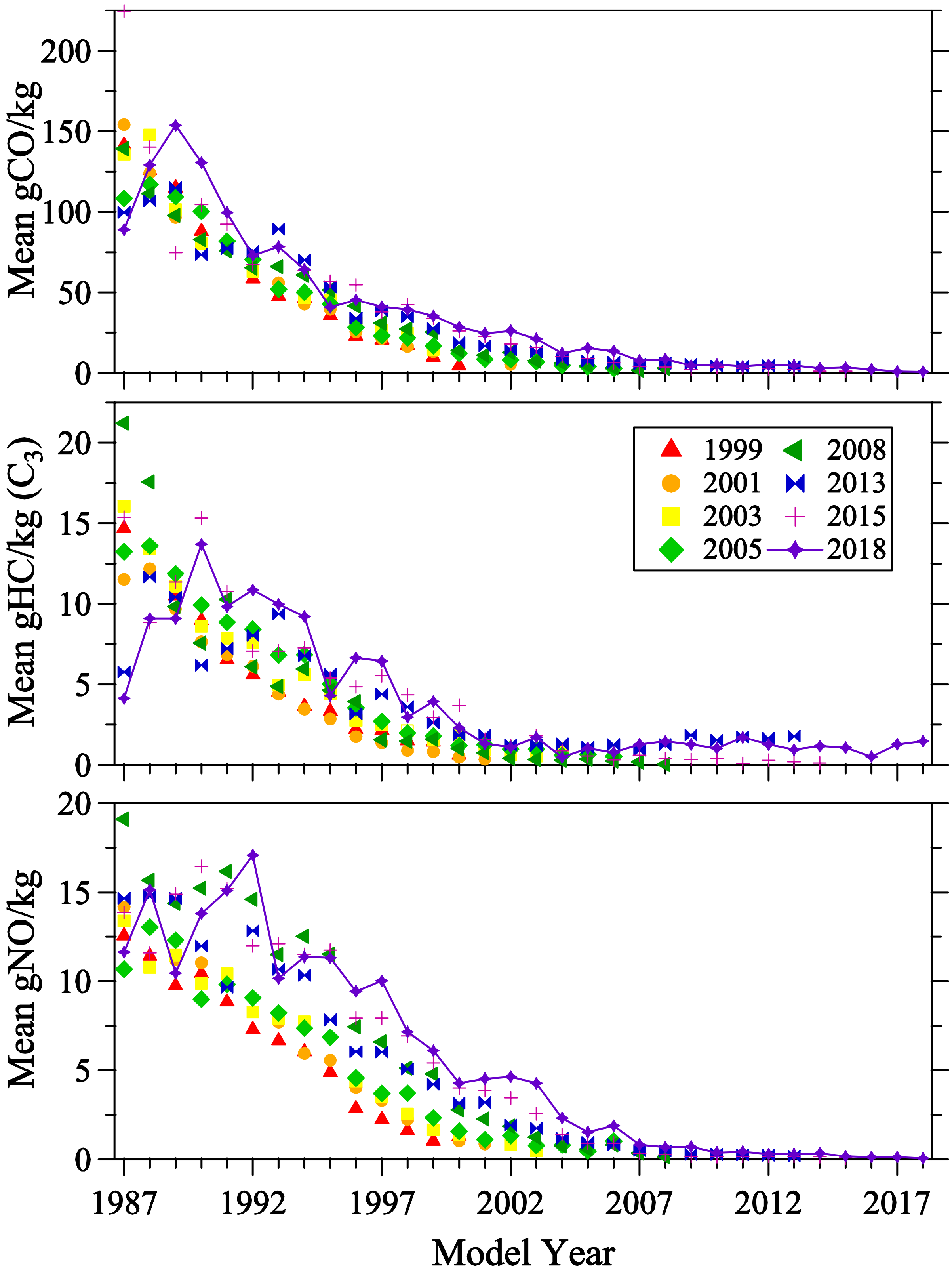

Figure 3. Mean vehicle emissions illustrated as a function of model year for all of the West Los Angeles campaign years. HC data have been offset adjusted as described in the text.

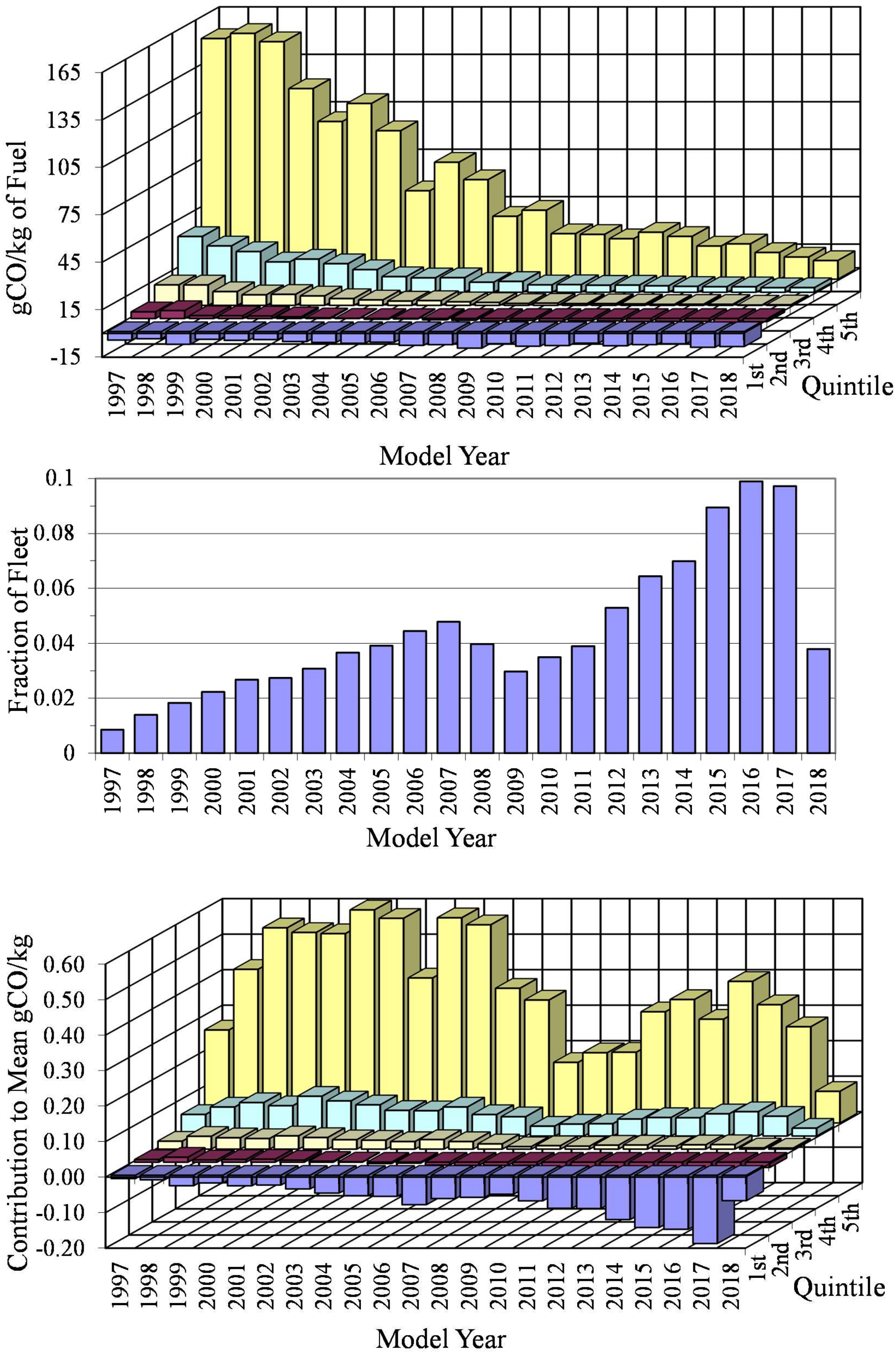

Figure 4. Mean gCO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gCO/kg of fuel emissions by model year and quintile (bottom).

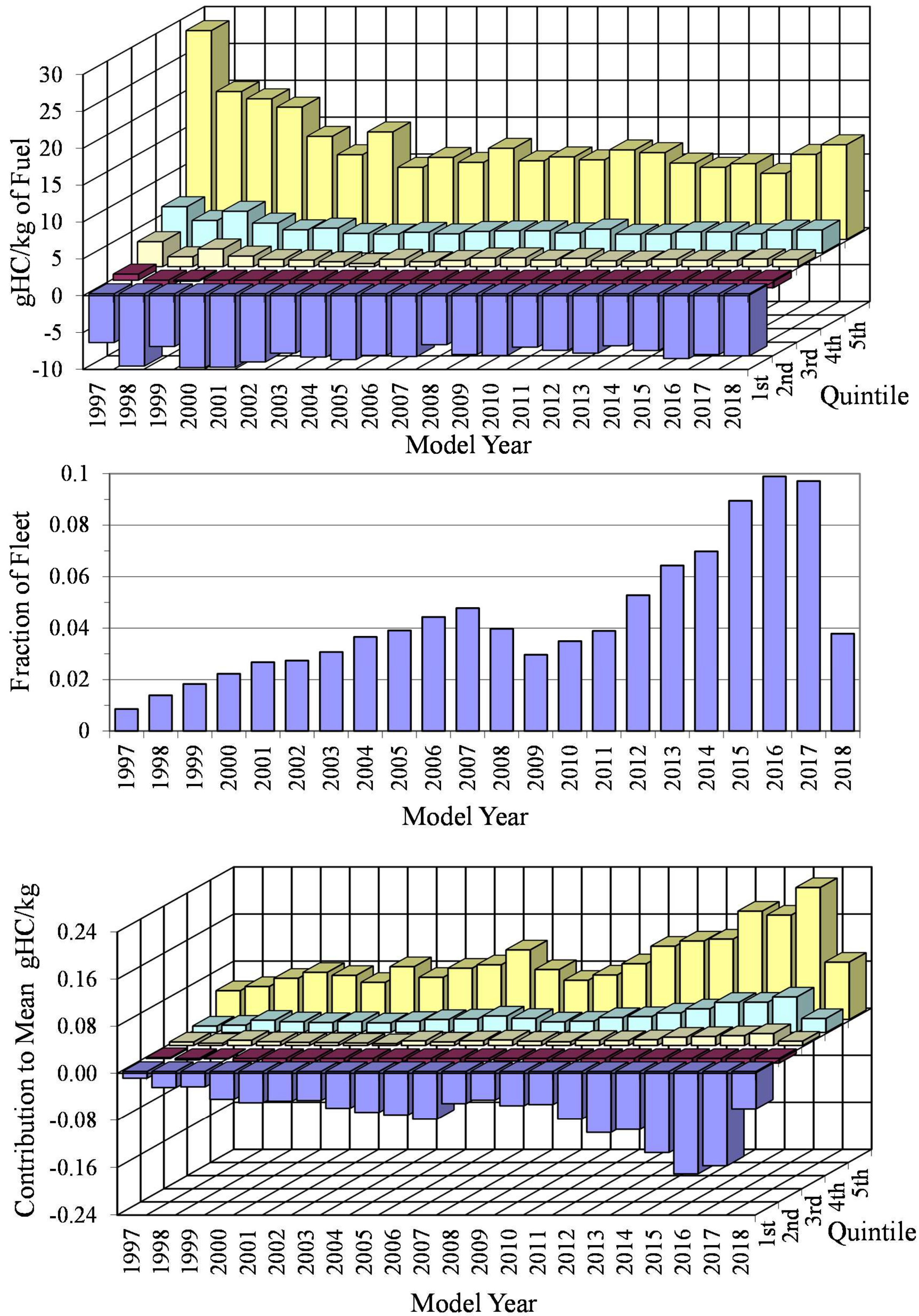

Figure 5. Mean gHC/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gHC/kg of fuel emissions by model year and quintile (bottom).

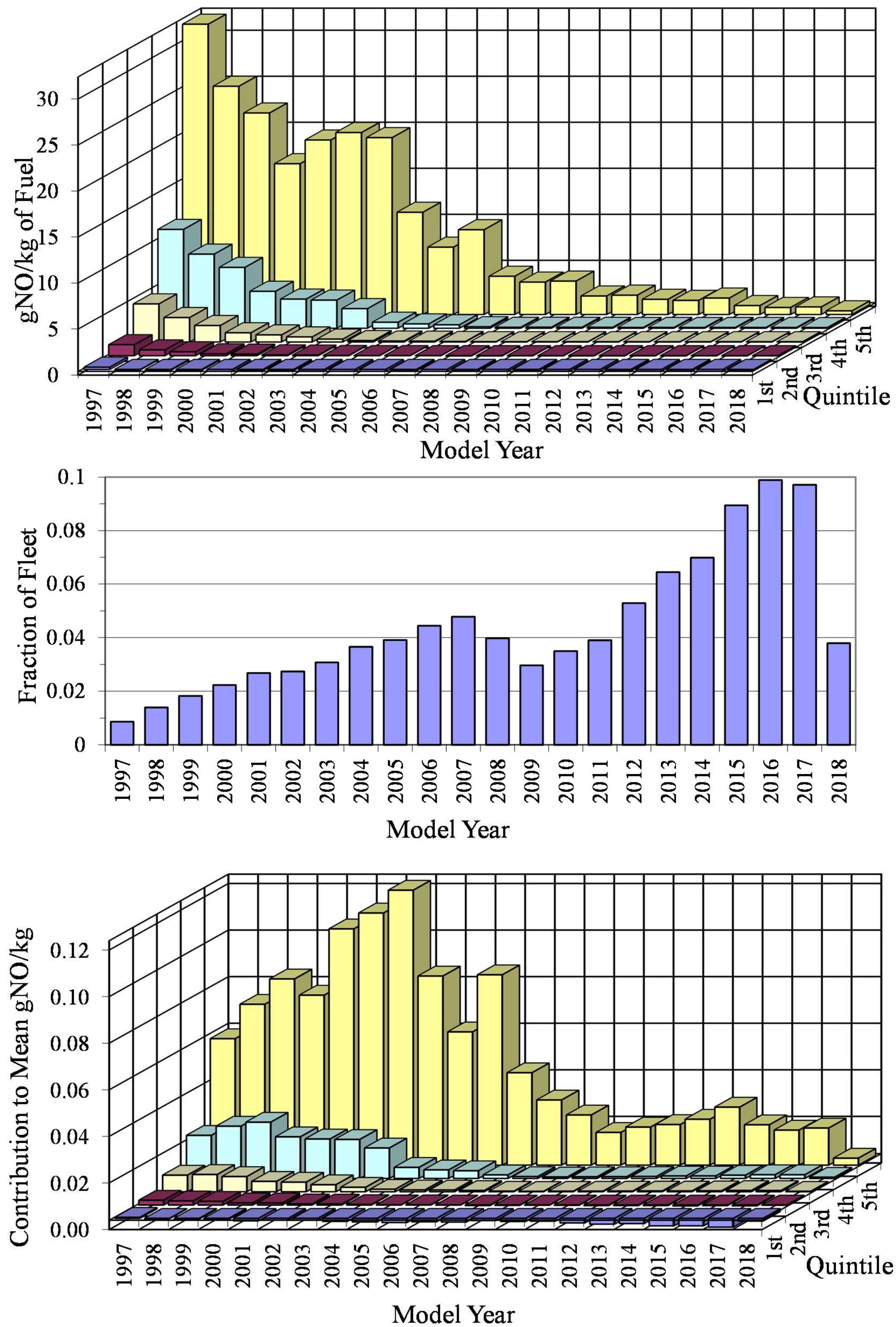

Figure 6. Mean gNO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gNO/kg of fuel emissions by model year and quintile (bottom).

middle graph shows the fleet fraction by model year for the first 19 model years, model years older than 1997 account for ~3.1% of the measurements and 23% of the CO and NO emissions and 18% of the HC. The bottom graph for each species is the combination of the top and middle figures. These figures illustrate 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. The instrument is designed such that when measuring a true zero emission plume, half of the readings will be negative and half will be positive (a normal distribution about zero) which is reflected in these plots for the newest model years.

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. We also assume that the driving mode captured at the West Los Angeles site covers similar driving conditions found in the certification testing. The LEV II, 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 of fuel, respectively. Inspection of Figures 4-6 shows that 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,[30] which takes the form

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

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 2018 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, 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. The solid line in the bottom panel is the measurement distribution for the 2018 data set.

The 2018 measurement distribution is quite symmetrical and centered around a VSP of 10 KW/tonne. This is largely a product of the ramp meter at this location which regulates the vehicles driving mode. The one exception was in 2013 (blue trace) when the ramp meter was not

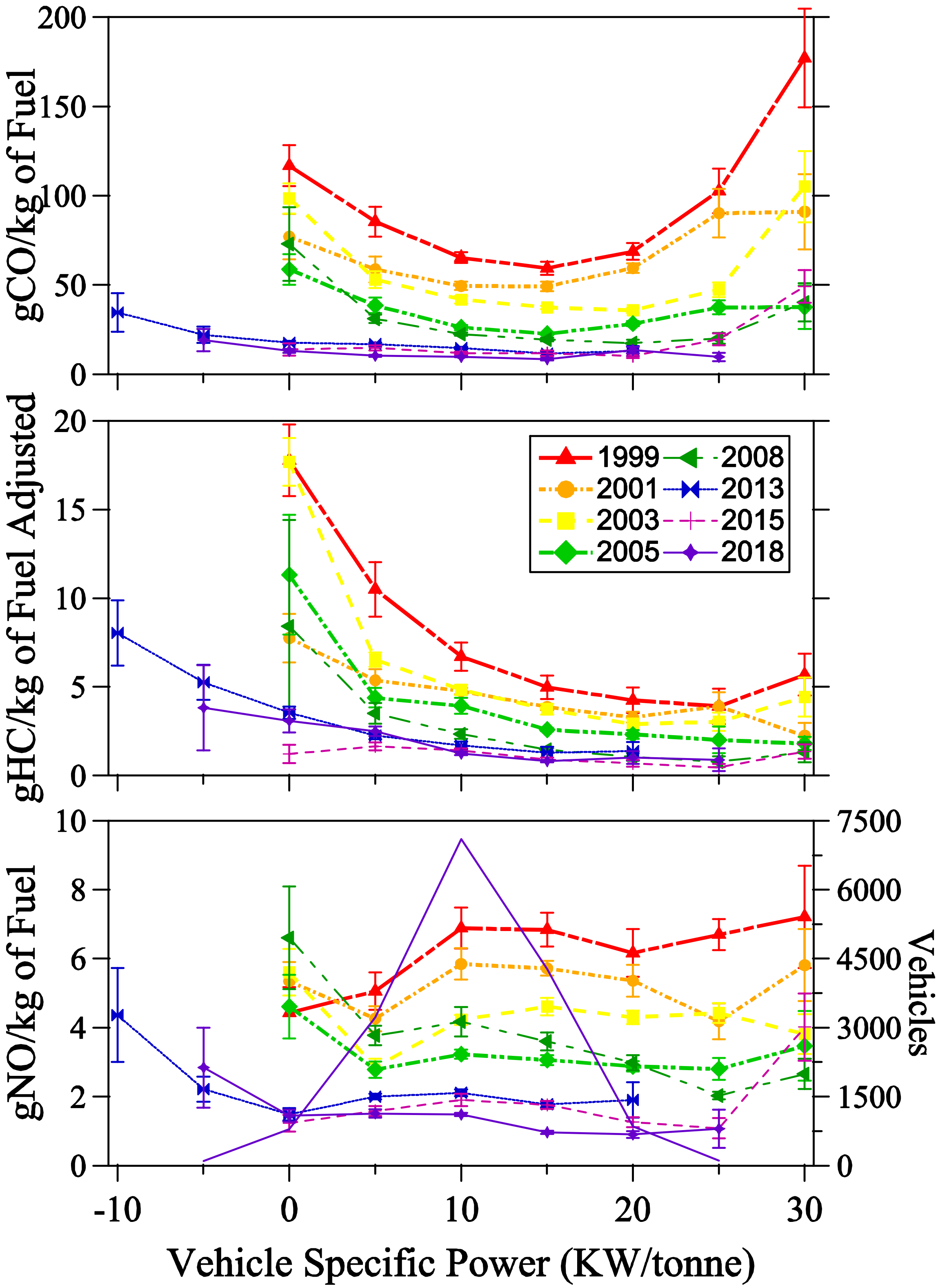

Figure 7. Fuel specific vehicle emissions (left axis) as a function of vehicle specific power for all of the West Los Angeles campaign years. Uncertainties are standard error of the mean calculated from the daily means. The solid line without markers (bottom panel) is the vehicle count (right axis) profile for the 2018 data set.

operational and the driving mode observed had a significant shift to lower and negative VSP values (decelerations) for the majority of the measurements. All of the emissions continue to decrease with each successive data set and reflect the elimination of the influence of driving mode for fuel specific emissions for all three species. The uncertainty bars included in the plot are standard error of the mean calculated using 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 are assumed to be an independent measurement at that VSP. Normal statistics were then applied to these daily averages (see Appendix E).

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 for vehicle specific power (all of the years HC data also include its offset adjustment) 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 VSP adjusted mean NO emissions, is shown in Appendix F.

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

Year	Mean gCO/kg of Fuel Measured (Adjusted)	Mean gHC/kg of Fuel[a] Measured (Adjusted)	Mean gNO/kg of Fuel Measured (Adjusted)
1999	68.1 ± 2.1 (68.1 ± 2.1)	9.1 ± 0.7 (6.7 ± 0.7)	6.4 ± 0.5 (6.4 ± 0.5)
2001	52.5 ± 2.5 (52.9 ± 2.6)	5.2 ± 0.2 (4.5 ± 0.2)	5.6 ± 0.3 (5.5 ± 0.3)
2003	40.3 ± 1.0 (43.7 ± 1.0)	5.7 ± 0.3 (4.9 ± 0.3)	4.3 ± 0.2 (4.2 ± 0.2)
2005	26.1 ± 0.6 (28.0 ± 0.7)	2.8 ± 0.7 (3.5 ± 0.1)	3.1 ± 0.1 (3.1 ± 0.1)
2008	21.1 ± 0.5 (23.8 ± 0.6)	2.2 ± 0.1 (2.5 ± 0.1)	3.7 ± 0.3 (3.8 ± 0.3)
2013	15.8 ± 0.7 (13.9 ± 0.6)	4.1 ± 0.2 (1.7 ± 0.2)	2.0 ± 0.2 (1.9 ± 0.1)
2015	12.1 ± 0.4 (12.2 ± 0.4)	1.2 ± 0.1 (1.2 ± 0.1)	1.7 ± 0.1 (1.7 ± 0.1)
2018	9.9 ± 0.3 (10.0 ± 0.3)	1.5 ± 0.1 (1.3 ± 0.1)	1.3 ± 0.1 (1.2 ± 0.1)

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

The measured and adjusted values of the three primary pollutants show large and continuous reductions since 1999 with the adjusted values of CO and HC dropping by a factor of 6 and NO adjusted means droping by a factor of 5. These rates of reduction are consistent with those reported by other researchers using ambient, airborne and tunnel measurements.[31-33] As shown in Figure 7, since 2015 driving mode has had little effect on fuel specific emissions and the means adjusted to the 1999 driving mode are no longer significantly different from the means reported in Table 3. The one exception to this is for HC emissions that still increase with deceleration as was evidenced in the 2013 measurements when the ramp meter was not 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 only the model years first measured in 1999. A sample calculation, for the model year adjusted mean NO emissions, is shown in Appendix G. Table 5 shows the mean emissions for all vehicles from model year 1984 to 2000, as measured in each of the eight measurement years (HC data 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 HC data include an offset adjustment). Measured CO and HC emissions for this model year grouping have gradually decreased since 1999 with measured CO and HC means having decreased 21 and 40% respectively. Measured NO emissions have increased overall (+29%) since 1999. The age adjustment calculation though indicates that all three species' fleet average emissions have increased since 1999 while the size of this fleet has shrunk by a factor of ten.

Table 5. Model year adjusted fleet fuel specific emissions (1999 fleet, MY 1984-2000 only). Uncertainties are standard error of the mean calculated from the daily means.

Year	Mean gCO/kg of Fuel Measured (Age Adjusted)	Mean gHC/kg of Fuel[a] Measured (Age Adjusted)	Mean gNO/kg of Fuel Measured (Age Adjusted)	Vehicles CO/HC/NO
1999	60.6 ± 2.0 (60.6 ± 2.0)	8.3 ± 0.6 (5.9 ± 0.6)	6.2 ± 0.4 (6.2 ± 0.4)	17,903 / 17,798 / 17,798
2001	52.1 ± 2.3 (61.1 ± 2.7)	5.2 ± 0.2 (5.2 ± 0.2)	6.1 ± 0.4 (7.0 ± 0.4)	17,304 / 17,194 / 17,194
2003	51.5 ± 1.6 (65.6 ± 2.0)	6.8 ± 0.3 (6.7 ± 0.3)	5.8 ± 0.2 (7.0 ± 0.3)	13,827 / 13,786 / 13,786
2005	43.0 ± 0.7 (61.4 ± 0.9)	4.5 ± 0.6 (6.9 ± 0.2)	5.5 ± 0.2 (7.3 ± 0.3)	10,125 / 10,111 / 10,111
2008	46.2 ± 0.9 (68.1 ± 1.3)	4.2 ± 0.3 (6.8 ± 0.5)	8.3 ± 0.6 (11.0 ± 0.8)	6,498 / 6,481 / 6,488
2013	44.8 ± 1.8 (71.0 ± 2.9)	4.4 ± 0.3 (6.7 ± 0.5)	6.5 ± 0.1 (9.3 ± 0.2)	6,069 / 6,049 / 6,064
2015	48.9 ± 1.7 (77.2 ± 2.7)	5.3 ± 0.5 (8.0 ± 0.7)	7.9 ± 0.5 (10.9 ± 0.7)	3,368 / 3,360 / 3,366
2018	47.9 ± 3.4 (80.8 ± 5.8)	5.0 ± 0.6 (7.3 ± 0.9)	8.0 ± 0.3 (10.6 ± 0.4)	1,784 / 1,772 / 1,783

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

If one plots the natural log of the age adjusted mean emissions in Table 5 against measurement year the slope of a least squares line fit to those data multiplied by 100 represents the year-over-year deterioration percent change for the species plotted. This of course assumes that fleet emissions deterioration can be modeled as a linear process. Figure 8 shows these plots for CO (top panel), HC (middle) and NO (bottom) for the West Los Angeles measurements (●).The uncertainties plotted are standard error of the mean calculated using each year's daily measurements. The year-over-year rate of emissions deterioration for this vehicle grouping is 1.5%/year for CO and HC and 3.0%/year for NO. The dwindling number of vehicles makes the uncertainty in this analysis grow with each measurement campaign; however, the slow growth in emissions over the last 19 years is likely the combination of a number of factors including breakage and attrition rates.

Another way to gauge vehicle emissions deterioration is to calculate 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 and 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. A minimum of three years of data are needed and with the 2018 measurements, we are able to calculate these statistics for 2013 and older model year vehicles. This covers an age range from 5 (model year 2013) to 34 (model year 1984) year old vehicles. Figure 9 is a plot of the slopes determined for each model year and is the emissions deterioration rate in grams of emissions per kilogram of fuel per year for CO (top), HC (middle) and NO (bottom). The uncertainties plotted are the standard error of the slope for the least squares fit. The inset graph in the CO panel (top graph) is an enlargement of the first 13 model years.

Some of the more recent model years have more variability and larger uncertainties due in part to the smaller number of years of measurements (only 3 for 2009 and newer model years) used in the calculation. For CO and HC the first 5 model years and the first 4 for NO graphed show a deterioration rate which is indistinguishable from zero. Making the assumption that model year vehicles newer than 2013 will have similar deterioration rates extends a zero deterioration rate out to the newest 9 to 10 year-old-vehicles. For HC one could argue that a near zero rate is likely extended out an additional 7 to 8 years to the 2001 – 2002 models. NO deterioration rates (bottom panel) are noticeably higher for LEV I vehicles and there is a break between model years 2003 and 2004 where the rate is cut approximately in half and then drifts lower to a zero rate with the 2010 models. This coincides with the phase in of LEV II vehicles that was started in 2004 and was completed in 2009.

All three species show slow increases in average emissions deterioration during the first 20+ years of life after which rates begin to decline. It is difficult to explain negative emissions deterioration rates among the oldest models without vehicle attrition being a major piece of that explanation as it represents one of the largest distinguishing factors between newer and older model year groupings (see 2018 vehicle counts for the pre-2001 fleet in Table 5). It is possible that survivability of the remaining oldest model year vehicles is correlated with additional

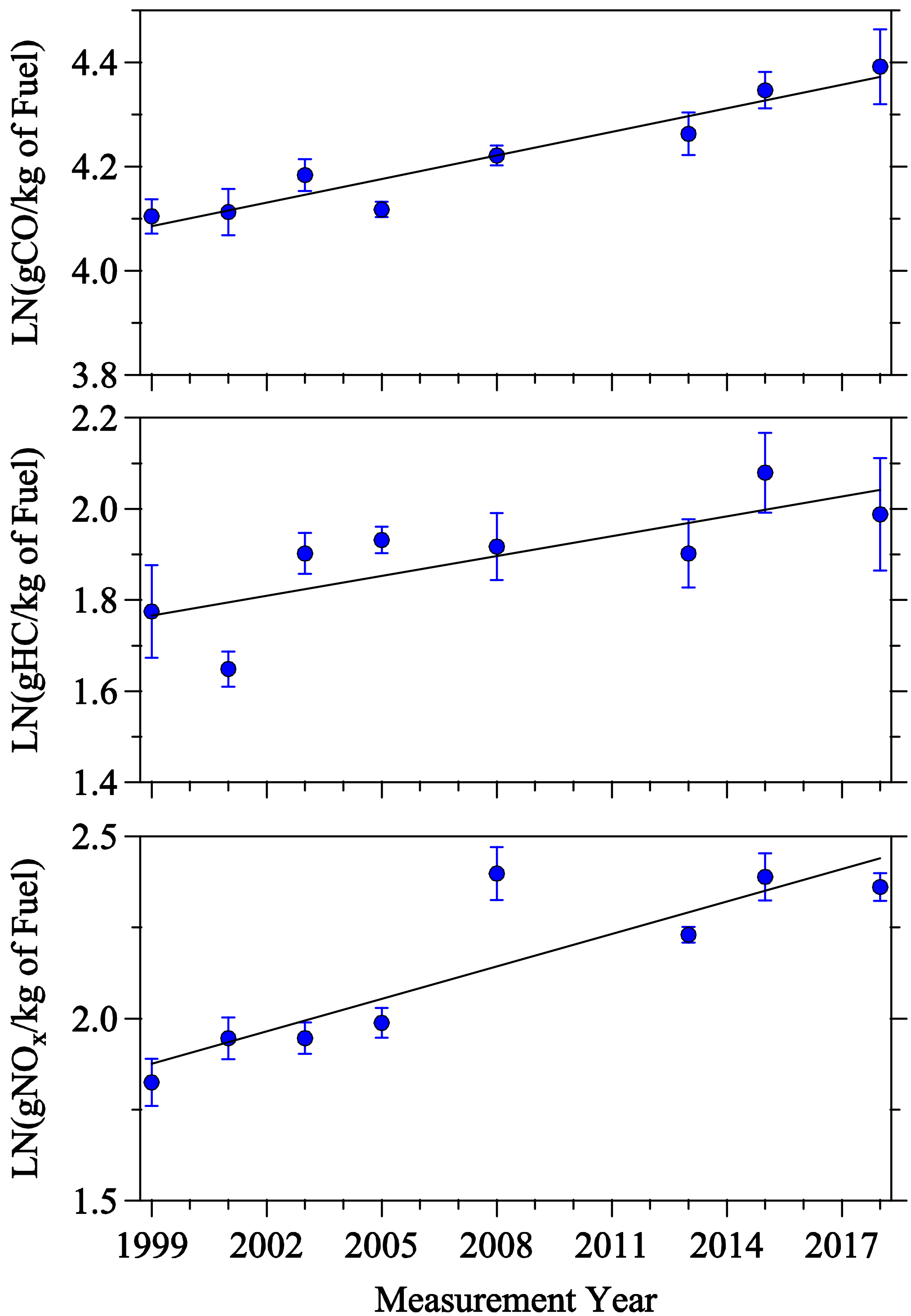

Figure 8. Natural log of the age adjusted West Los Angeles mean emissions for the 1984 – 2000 model year vehicles as distributed in 1999 versus measurement year for CO (top), HC (middle) and NO (bottom). The slopes of the best-fit lines represent the year-over-year percent change comparison or rate of fleet emissions deterioration for the 1999 fleet. The year-over-year percent change in emissions and are 1.5%, 1.5% and 3.0% for the CO, HC and NO respectively.

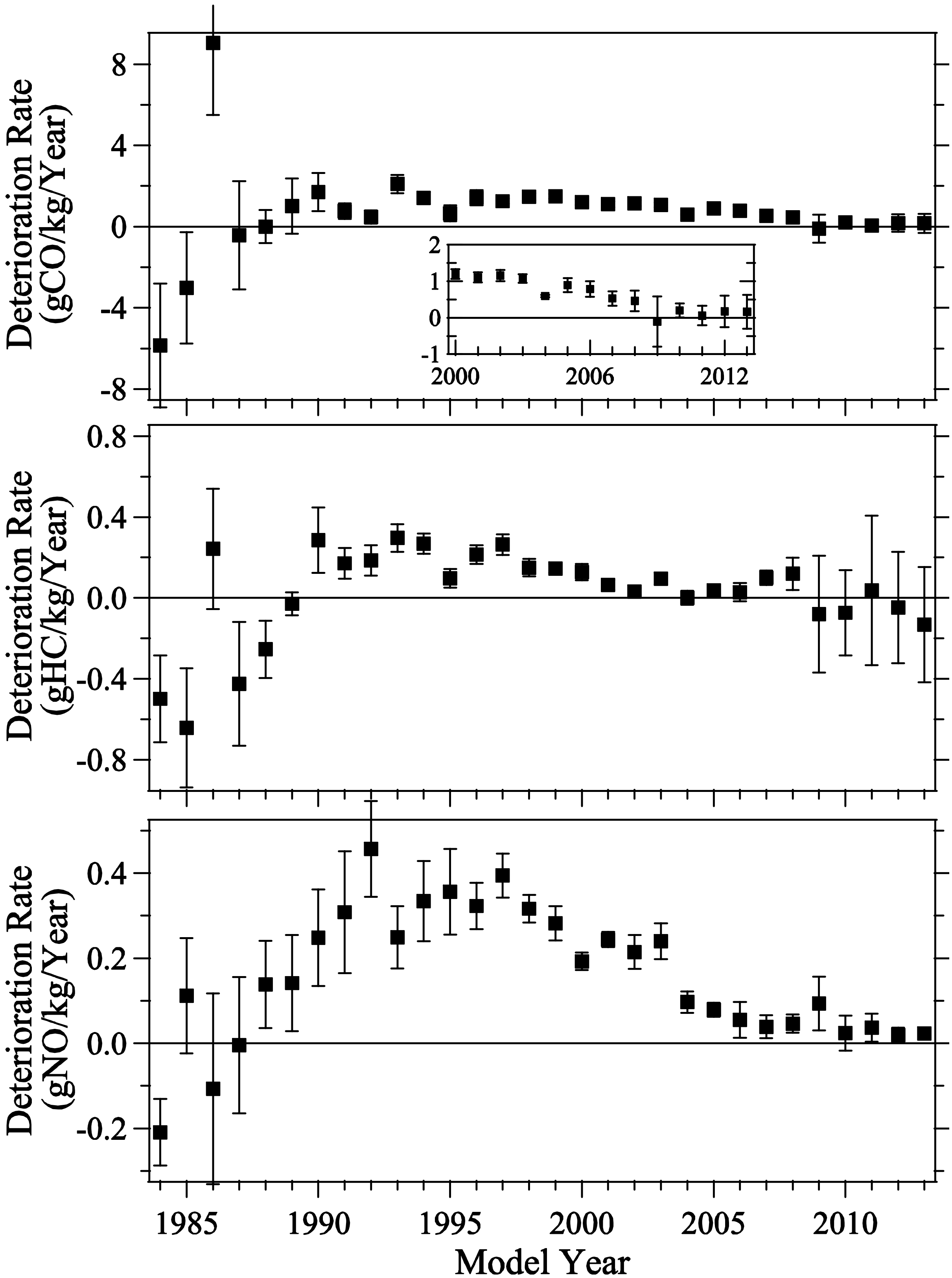

Figure 9. On-road fuel specific emissions deterioration rates vs. model year for the West LA sampling location incorporating the 2018 data. The uncertainty bars plotted are the standard error of the slope for the least squares fit.

maintenance, or lower mileage accumulation; hence, the low or even negative deterioration rates. However, as the vehicle numbers diminish the level of uncertainty increases.

2008 Recession Effects. The middle graph in Figures 4 – 6 previously showed the fleet fractions by model year for the 2018 West LA database. The dramatic drop in new car sales beginning in late 2008 and continuing through the 2011 model year is still very 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 in 2008 clearly showed its effects.[18] Figure 10 compares the fleet percentage by vehicle age for the 2015 and 2018 data sets. Zero year vehicles are model years 2015 and 2018 respectively. The peak in fleet percentage is near 10% for both groups and the zero model year percentages are similar though the 2018 campaign was a month later than the 2015 campaign.

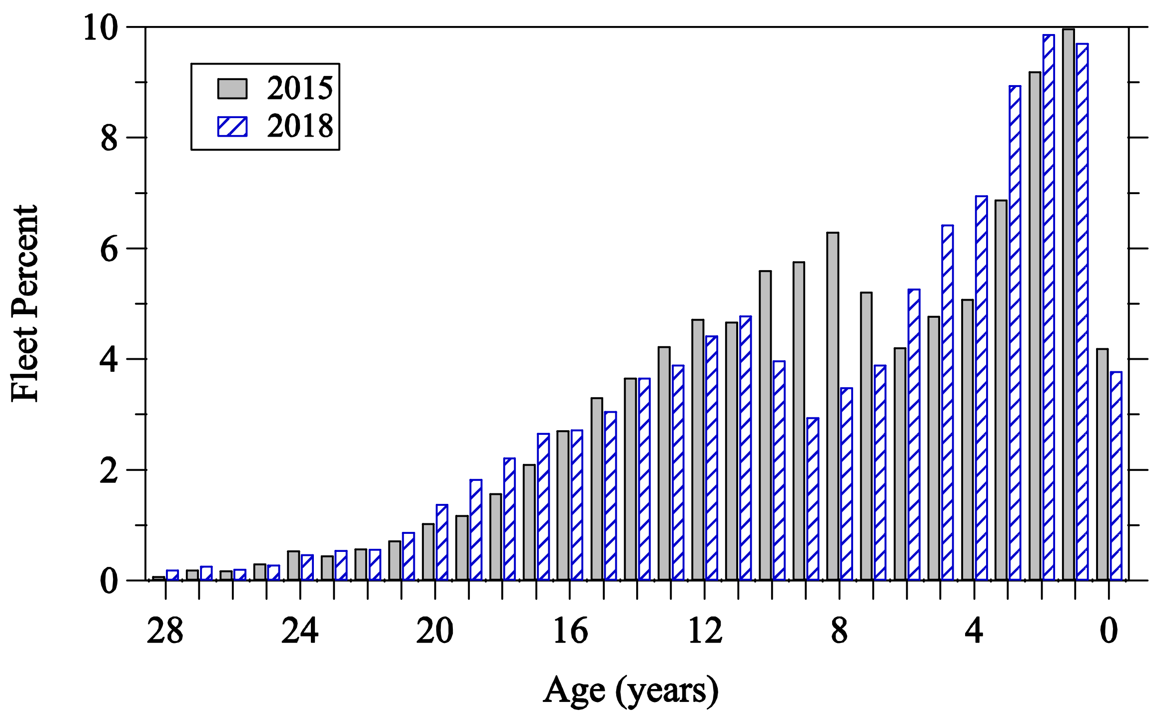

Figure 10. Fleet percentage versus vehicle age for the 2015 (grey bars) and 2018 (blue bars) West Los Angeles fleets.

Hybrid Vehicle Emissions. The matched data provided by the California DMV generally includes fuel type with a special fuel designation (Q prior to 2014 and B for more recent data sets) for hybrid drive train vehicles. We have previously discussed the observation that hybrid drive train vehicles have lower NO emissions with consequently higher HC emissions. Initially there was concern that this difference might be the result of a water interference, as the original data sets were collected in the late fall with cooler temperatures and higher humidity. Since then we have collected four data sets at the West LA site during the spring and one data set in late summer from Van Nuys in 2010.[31] The amount of hybrid drive train vehicles have grown from zero in the early 2000's to more than 5.1% of the measurements in the 2018 data set. Since the

2008 measurements, this accounts for a year over year increase of 15.7%. This number is likely a lower limit of the fleet makeup at the West LA site. Since, our measurement method requires a minimum amount of CO_2 emissions before a successful measurement, some fraction of the hybrid measurement attempts will not meet the minimum and not be counted. However, this process should be random and our hybrid data set is large enough (1136 records in 2018) that mean emission rates for these vehicles should not be underrepresented.

Table 6 contains a summary for all of these data sets and includes the mean emissions for the hybrid vehicles and an age-adjusted composite emission for the remaining non-diesel vehicles. The age adjustment matches the age of the non-diesel fleet to that of the hybrid fleet. It is constructed by using the mean emissions by model year for the non-diesel vehicles and then weighting those means according to the model year distribution of the hybrid vehicles. The uncertainties reported are standard error of the mean calculated using the daily means. For all of the West LA data sets included in Table 6 the HC emissions are higher for the hybrid vehicles, though the 2013 measurement differences are not statistically significant. The converse is true for the fuel specific NO emission measurements as in all but the 2008 data the identified hybrid vehicles have lower NO emissions than the age adjusted non-diesel fleet.

Ammonia Emissions. 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.[34] Ammonia is most often associated with farming and livestock operations but can also be produced by 3-way catalyst equipped gasoline and natural gas vehicles.[35] 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.[36] 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.[37-40] 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 Nuys site in 2010.[18, 31] In addition air borne measurements of ammonia were collected in 2010 over the South Coast Air Basin as part of the CalNex campaign.[12] The 2018 measurements are the fourth data set collected at the West LA in addition to the 2008, 2013 and 2015 measurements.

Figure 11 compares gNH_3/kg of fuel emissions collected at the West LA site for the 2008, 2015 and 2018 measurement campaigns by model year. We chose these three years to compare because the ramp meter was operational for all three campaigns. 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 catalyst reduction efficiency begins to wane and the emissions start decreasing. This is most obvious for the 2008 data where there are still significant number pre-1996 vehicles in use. The NH_3 mean emissions

Table 6. Comparison between hybrid and age adjusted non-diesel **v**ehicle fuel specific 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
non-diesel West LA 2005	4.3 ± 0.2	0.6 ± 0.1	0.31 ± 0.03	N.A.	N.A.	N.A.	2004.3	8,928
Hybrids West LA 2008	1.5 ± 0.3	0.32 ± 0.09	0.44 ± 0.28	0.04 ± 0.02	0.39 ± 0.04	0.72 ± 0.45	2005.9	269
Non-diesel West LA 2008	3.9 ± 0.1	0.18 ± 0.01	0.40 ± 0.03	0.03 ± 0.01	0.46 ± 0.01	0.63 ± 0.05	2005.9	11,977
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
Non-diesel 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	20,800
Hybrids West LA 2015	1.3 ± 0.4	0.7 ± 0.1	0.11 ± 0.04	-0.01 ± 0.05	0.36 ± 0.03	0.13 ± 0.08	2010.7	1,136
Non-diesel West LA 2015	3.5 ± 0.1	0.22 ± 0.01	0.20 ± 0.01	-0.11 ± 0.02	0.54 ± 0.02	0.21 ± 0.02	2010.7	17,256
Hybrids West LA 2018	1.9 ± 0.3	1.7 ± 0.2	0.22 ± 0.03	0.03 ± 0.01	0.37 ± 0.05	0.49 ± 0.04	2012.6	1,325
Non-diesel West LA 2018	5.0 ± 0.1	1.03 ± 0.09	0.35 ± 0.01	0.03 ± 0.01	0.57 ± 0.02	0.58 ± 0.01	2012.6	15,815

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

for these data sets are 0.79 ± 0.02, 0.71 ± 0.02 and 0.69 ± 0.01 gNH_3/kg of fuel for 2008, 2015 and 2018 respectively.

Because NH_3 emissions are a function of vehicle age, and these data were collected at different times, Figure 12 compares these same data sets by plotting them against vehicle age. The uncertainty bars plotted are the standard errors of the mean determined from the daily samples for each model year. Keep in mind that similarly aged vehicles do not share the same new

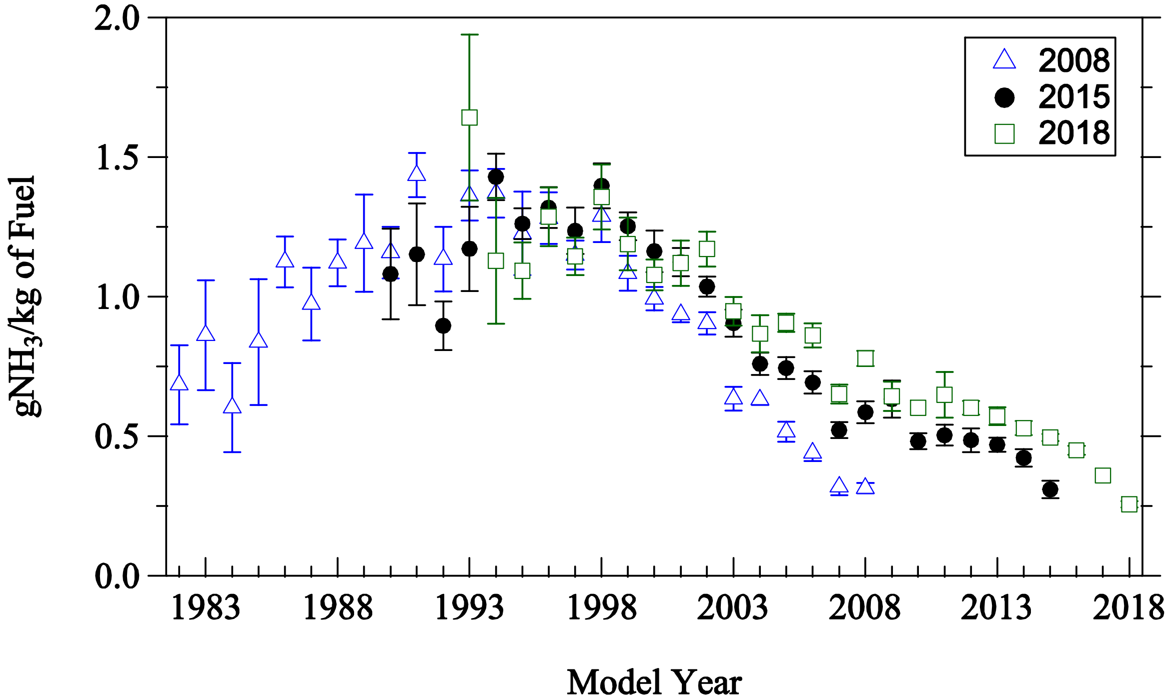

Figure 11. Mean gNH_3/kg of fuel emissions plotted against vehicle model year for the 2018 (squares), 2015 (circles) and 2008 (triangles) measurements at the West LA site. The uncertainty bars plotted are the standard error of the mean determined from the daily samples.

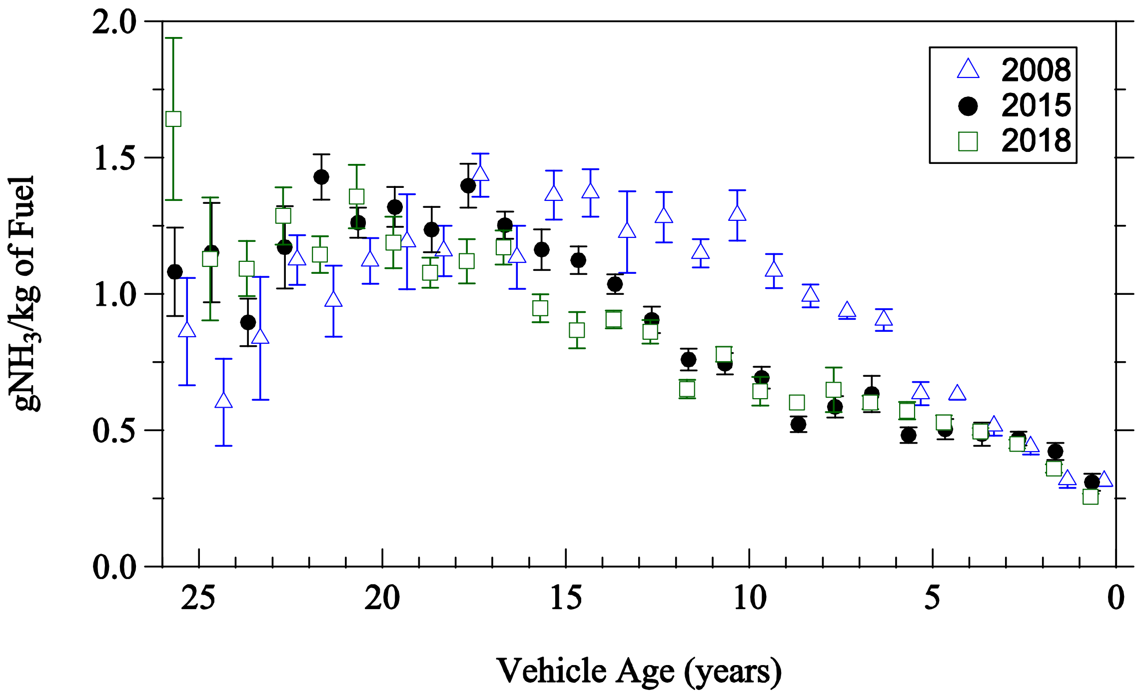

Figure 12. Mean gNH_3/kg of fuel emissions plotted against vehicle age for the 2018 (squares), 2015 (circles) and 2008 (triangles) measurements at the West LA site. The uncertainty bars plotted are the standard error of the mean determined from the daily samples.

vehicle emission certification standards. For example 10 year old vehicles in 2018 are dominated by LEV II vehicles and for the 2008 data set they are LEV I vehicles. Plotted in this manner it is easier to see that the peak in NH_3 emissions are similar between all three data sets though the peak occurs later in the 2015 and 2018 data sets indicating increased longevity of 3-way catalytic converters. The first 6 model years from each data set show NH_3 emissions that are increasing at a similar rate but beginning with 7 year old vehicles the 2008 data set (2001 model year) diverges from the other two. NH_3 emissions measured in 2008 follow a steeper path until eventually reaching a similar maximum average as the two newer data sets. This step increase in emissions between the 2002 and 2001 model year vehicles is less evident but still visible in both of the newer data sets. One possible explanation for this observation is highlighted in Figure 13 where fuel specific NO emissions for these three data sets are plotted against vehicle age. NO emissions in the 2008 data set also increase along a steeper path with the divergence happening beginning with 6-year-old vehicles (2002 MY). Higher emissions of NO provide the opportunity for larger NH_3 emissions, provided hydrogen is available, and may explain the different NH_3 emission levels in the 7 – 16 year old vehicles in 2008.

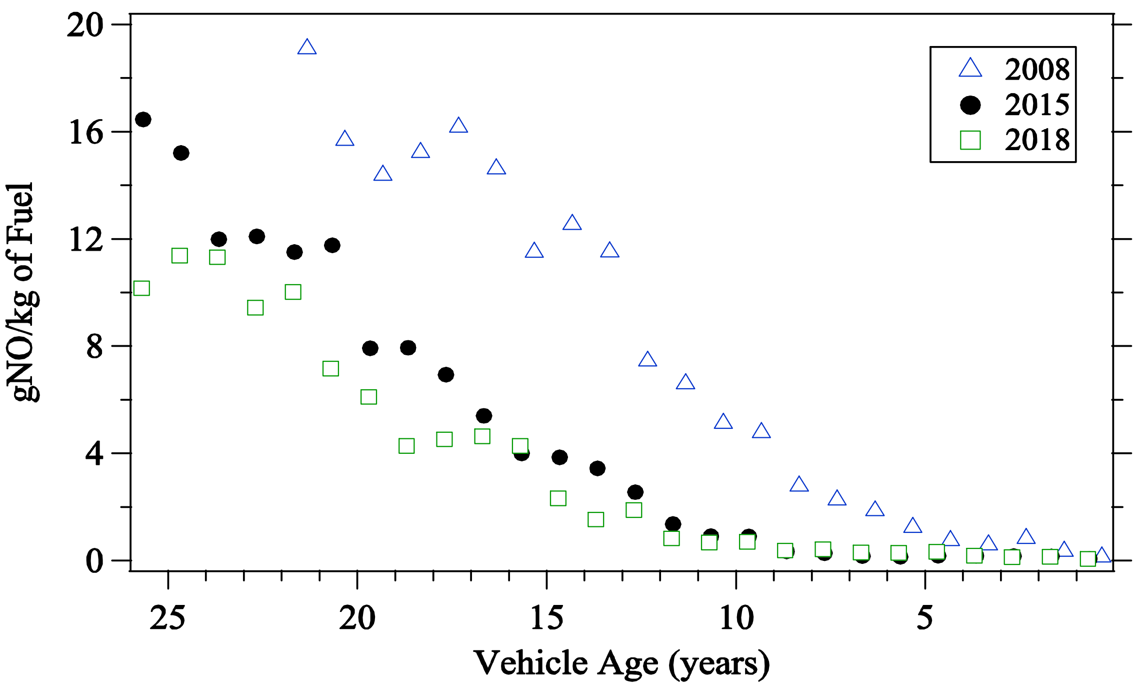

Figure 13. Mean gNO/kg of fuel emissions plotted against vehicle age for the 2018 (squares), 2015 (circles) and 2008 (triangles) measurements at the West LA site. The uncertainty bars plotted are the standard error of the mean determined from the daily samples.

<u>Historical Emission Changes.</u> 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. With this measurement campaign, the data sets collected now span 19 years since the first measurements.

Figure 14 plots the g/kg of fuel emissions for CO, HC and NO for the 1999 and 2018 data sets against vehicle age. The zero year model years are 2000 for the 1999 data and 2018 for the 2018 data set. The uncertainties plotted are the standard error of the mean calculated for each model year grouping using the daily means measured in each data set. We suspect that the very low NO means observed for 11 year old and newer vehicles will continue and the number of vehicle model years with negligible NO emissions will grow to look very similar to the CO and HC plots.

In both the CO and HC plots the 24 year old vehicles measured in 2018 (1994 models) have emissions that are very similar to that observed in 8 to 9 year old vehicles measured in 1999 (1990 and 1991 models). The lack of significant changes in the mean emissions for these model year vehicles may or may not be a true reflection of individual vehicle emissions deterioration as there are several dynamic factors that contribute to the mean emissions of a fleet as it ages, as discussed below.

Mean emissions are dictated by the number and emissions level of the broken vehicles. The fraction of broken vehicles can be operationally described by three rate constants as previously defined by Johnson and Pitchford.[41] 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, 1991 and 1994 model year vehicles the retirement rate is now likely the most important factor on the 2018 observed means. In 1999, the 1990, 1991 and 1994 model years accounted for 5.2%, 5.3% and 6.5% of the 1999 measurements. That has been significantly reduced in the 2018 fleet to only 0.2%, 0.3% and 0.5% respectively.

As documented at other sites around the United States the fleet observed at the West Los Angeles site has experienced significant reductions in tailpipe emissions since 1999.[42] CO emission have decreased 85% (71 ± 2.5 to 11 ± 0.2), HC emissions have decreased 79% (7 ± 0.7 to 1.5 ± 0.2) and NO emissions have decreased 76% (6.7 ± 0.5 to 1.6 ± 0.1). With eight data sets collected to date, there is sufficient historical data to compare with the reductions predicted by California's vehicle emissions model EMFAC. Mean running exhaust emission factors for CO, TOG (CH_2) and NO_x were generated using the EMFAC2017 web database by model year for summer in the South Coast Air Basin, gasoline only and LDA for the passenger vehicles and a combination of the LDT1, LDT2 and MDV categories for trucks for each of the West Los Angeles measurement years.[43] Vehicle category weighting for the composite model year emission factors and conversion into fuel specific emission factors was accomplished via the model estimated fuel consumption. Each years EMFAC model year results were weighted by the model year distribution observed at the West Los Angeles site for the same year and a composite mean emissions calculated. The 1999 West Los Angeles fleet distribution was used to weight the 2000 EMFAC emissions since the web database only predicts emissions back to year 2000. Because the comparison is made using fuel specific emissions, driving mode differences between the on-road and modeled emission factors should not be a significant issue for the most recent data sets (see Figure 7).

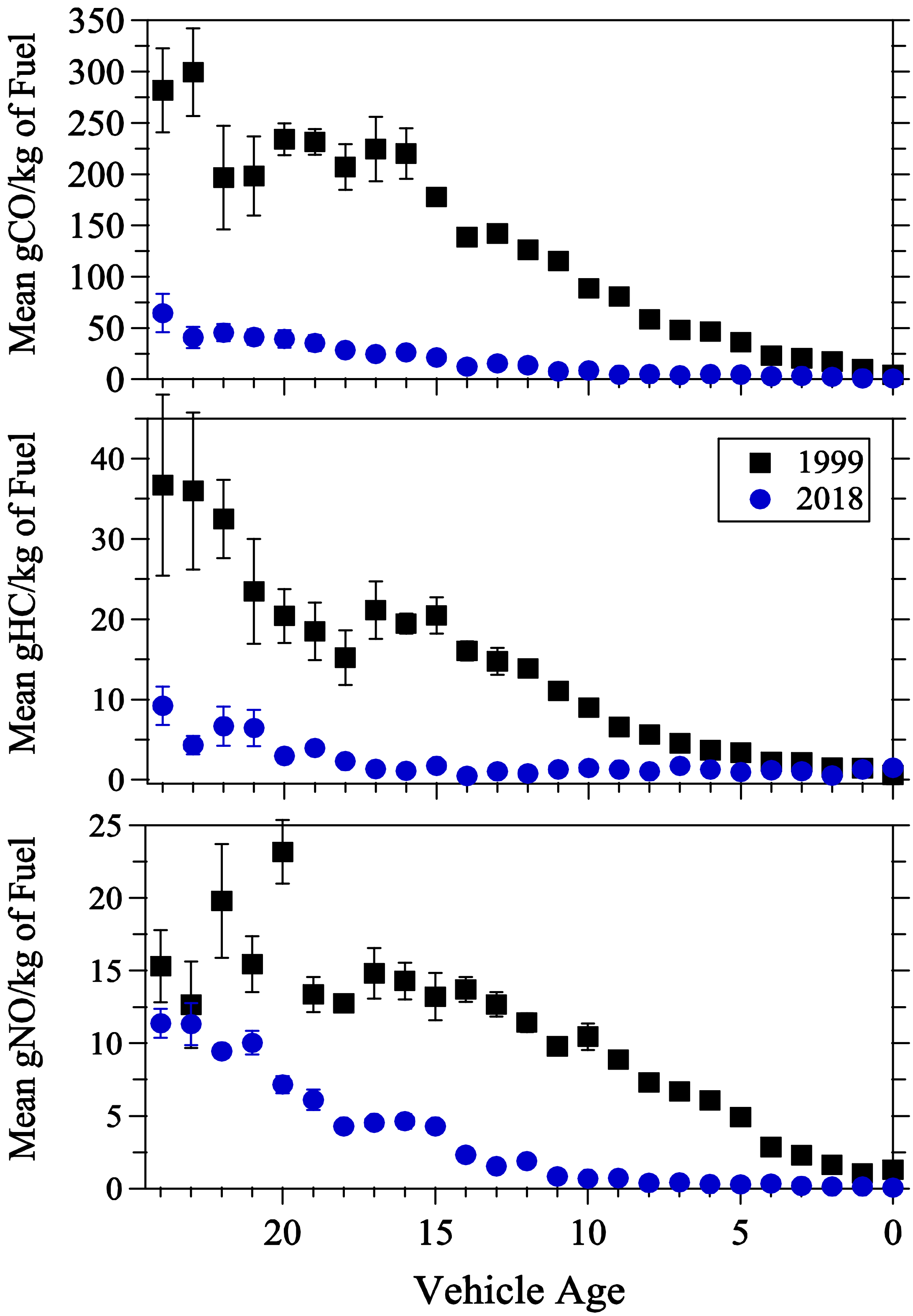

Figure 14. Fuel specific CO (top panel), HC (middle panel) and NO (bottom panel) emissions versus vehicle age for data sets collected at the West Los Angeles site in 1999 (squares) and 2018 (circles). The uncertainties plotted are standard error of the mean estimated from the daily measurements. Zero model years are 2000 (1999 data) and 2018 (2018 data).

Figure 15 compares the yearly measurements for CO (top), HC or Total Organic Gases (TOG) (middle) and NO_x (bottom) against those predicted by the EMFAC2017 model. West Los Angeles HC emissions have been converted from grams of propane to grams of CH_2 to match EMFAC2017 TOG values and NO_x emission means prior to the 2008 measurements contain only gNO/kg of fuel emissions that have been converted to grams of NO_2. Because we have restricted the comparison to only the gasoline fleet, any emission differences should be small. EMFAC2017 predicted mean CO emissions using the West Los Angeles fleet distribution have decreased 75% (44.6 to 11 gCO/kg of fuel), TOG predicted emissions have decreased 85% (2.4 to 0.4 gCH_2/kg of fuel) and predicted NO_x emissions have decreased 87% (6.8 to 0.8 gNO_x/kg of fuel) since 2000. These overall reduction estimates are similar to what has been observed in the West Los Angeles fleet and the predicted trends generally mirror those observed, mean CO, and TOG emission for the 2018 measurements agree with each other as well. The one exception may be that the fuel specific NO_x emissions are consistently under predicted and the difference has increased in the newer measurement years. Under reporting of NO_x emissions for the light and medium-duty gasoline fleet has been previously reported in the 2010 Van Nuys Tunnel measurement comparisons with earlier EMFAC models.[44]

To show what is behind the mean comparisons Figure 16 graphs the fuel specific CO (top), TOG (middle) and NO_x (bottom) emissions by model year for the 2018 West Los Angeles measurements and the EMFAC2017 (using vehicle types LDA, LDT1, LDT2 and MDV) predicted values for the gasoline fleet. Uncertainties for the FEAT measurements are standard error of the mean determined from the daily measurements. THE EMFAC2017 emission factors tend to be grouped by the vehicle emissions certification standards, which can result in step changes between those standards. Both the CO and TOG comparison show very low and stable emissions for the newest 15 model years, largely LEV II certified vehicles. After which the emissions begin to rise for both the measurements and the model predictions. The fuel specific NO_x emission for the FEAT measurements increase earlier and faster than the model predicted values perhaps indicating a higher in-use deterioration rate for the LEV I and pre-LEV vehicles. These age groups were previously shown to have the highest on-road gNO/kg of fuel/year emission deterioration rates (see Figure 9) that likely factor in to this difference.

Historical 99^{th} Percentile Trends. Figures 17 and 18 are plots of the CO, HC and NO 99^{th} percentiles for all of the West LA databases as a function of measurement year. The 99^{th} percentile represents 38% of the total 2018 fuel specific CO emissions, 43% of the HC emissions and 27% of the 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 as large one might expect. The 99^{th} percentile for NO is 32 gNO/kg of fuel for all of the data and 31.3 gNO/kg of fuel when the diesel fuel vehicles are excluded, a 2% difference.

Since 1999, the 99^{th} percentile for CO has been reduced by a factor of 4. Linear (solid line) and an exponential fit (dashed line) are shown in Figure 17. The exponential fit predicts a leveling out of the reductions around 200 gCO/kg of fuel. Mean model years for the 99^{th} percentile CO

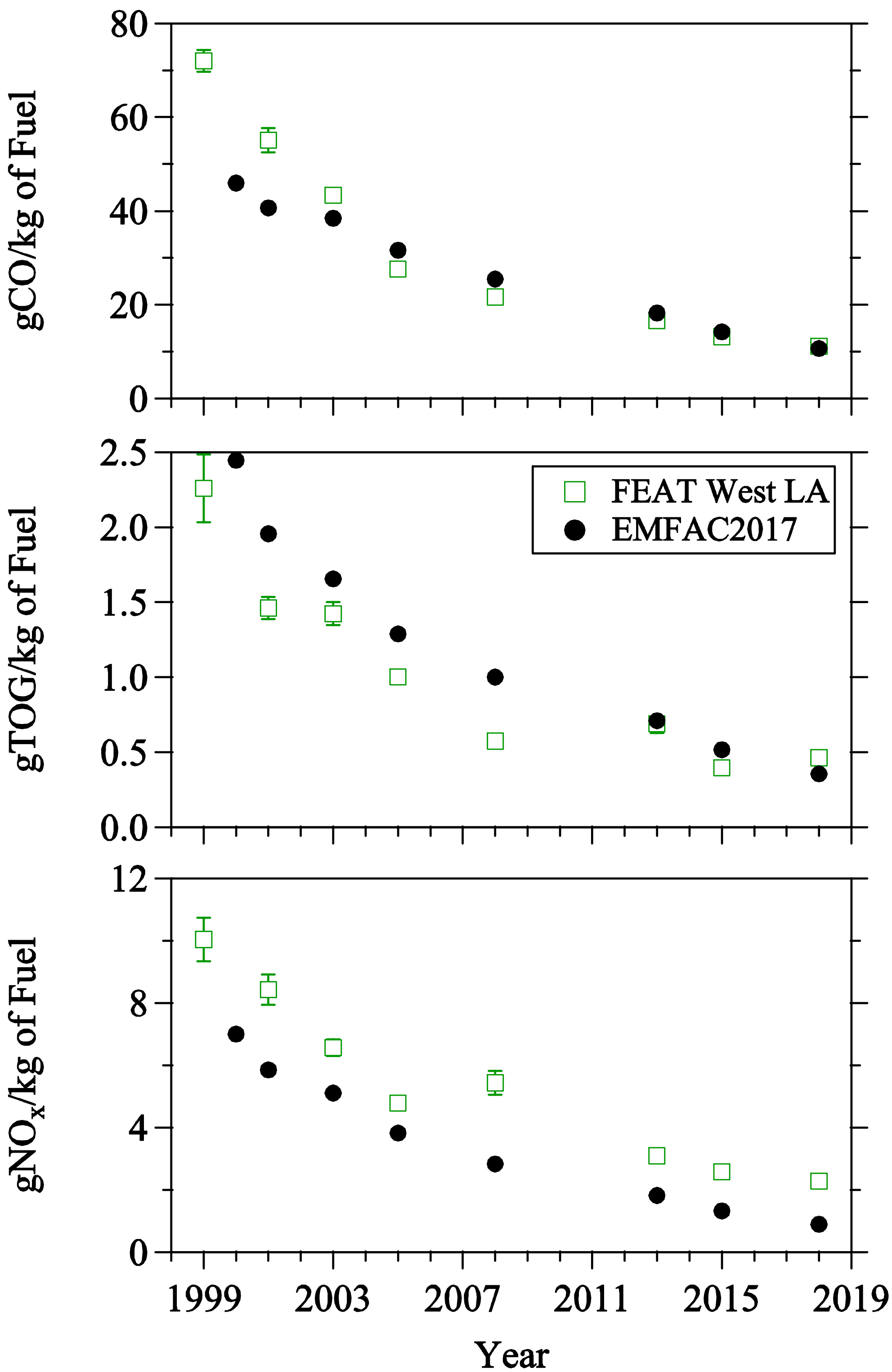

Figure 15. Mean fuel specific CO (top), TOG (middle) and NO_x (bottom) emissions comparison between the values measured at the West Los Angeles site for gasoline only vehicles with those predicted by the EMAFAC2017 (vehicle types LDA, LDT1, LDT1 and MDV) model. Uncertainties for the measured values are standard error of the mean calculated using the daily values.

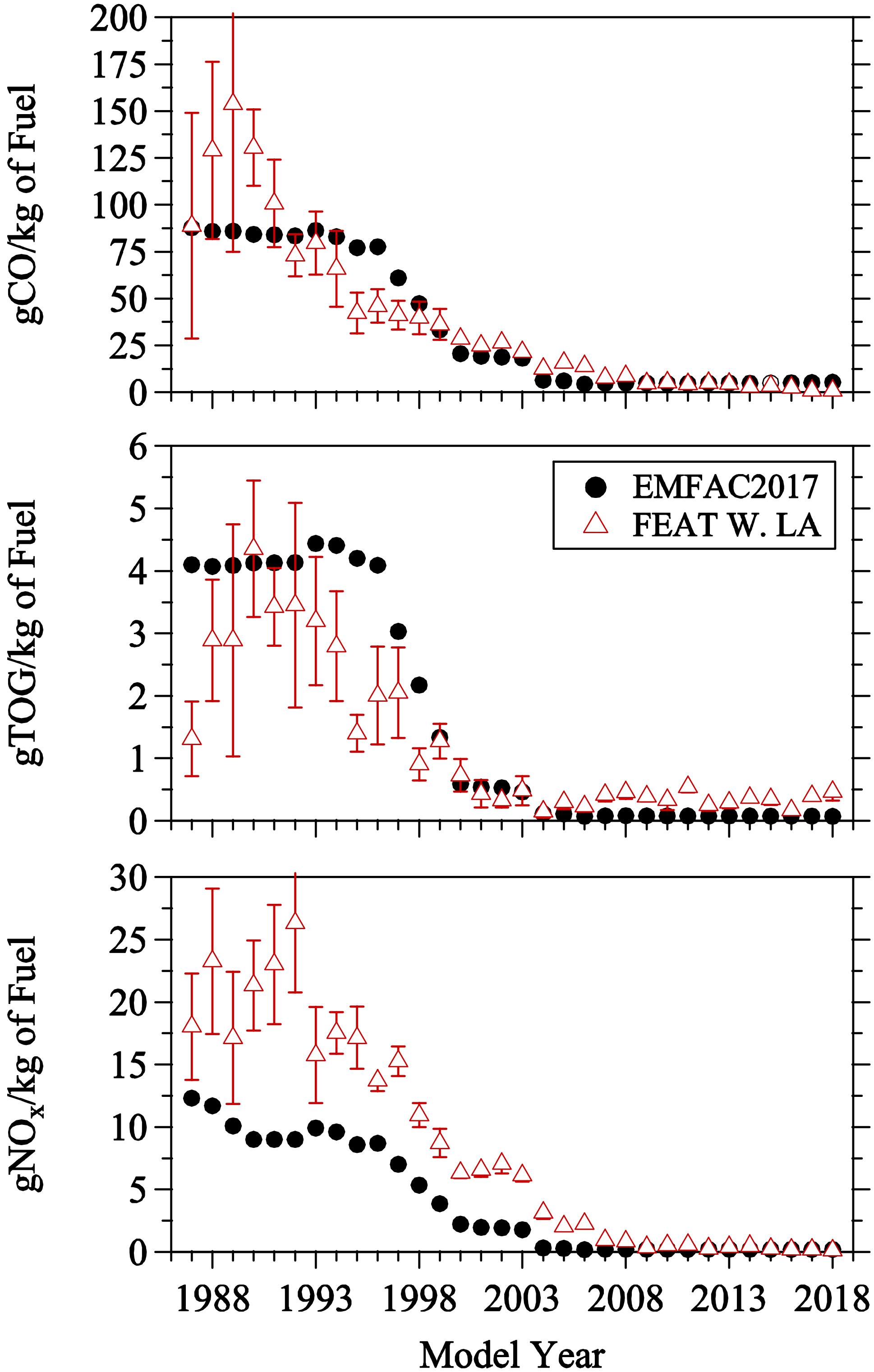

Figure 16. Mean fuel specific CO (top), TOG (middle) and NO_x (bottom) emissions by model year comparison between the values measured at the West Los Angeles site in 2018 for gasoline only vehicles with those predicted by the EMAFAC2017 (vehicle types LDA, LDT1, LDT1 and MDV) model. Uncertainties for the measured values are standard error of the mean calculated using the daily values.

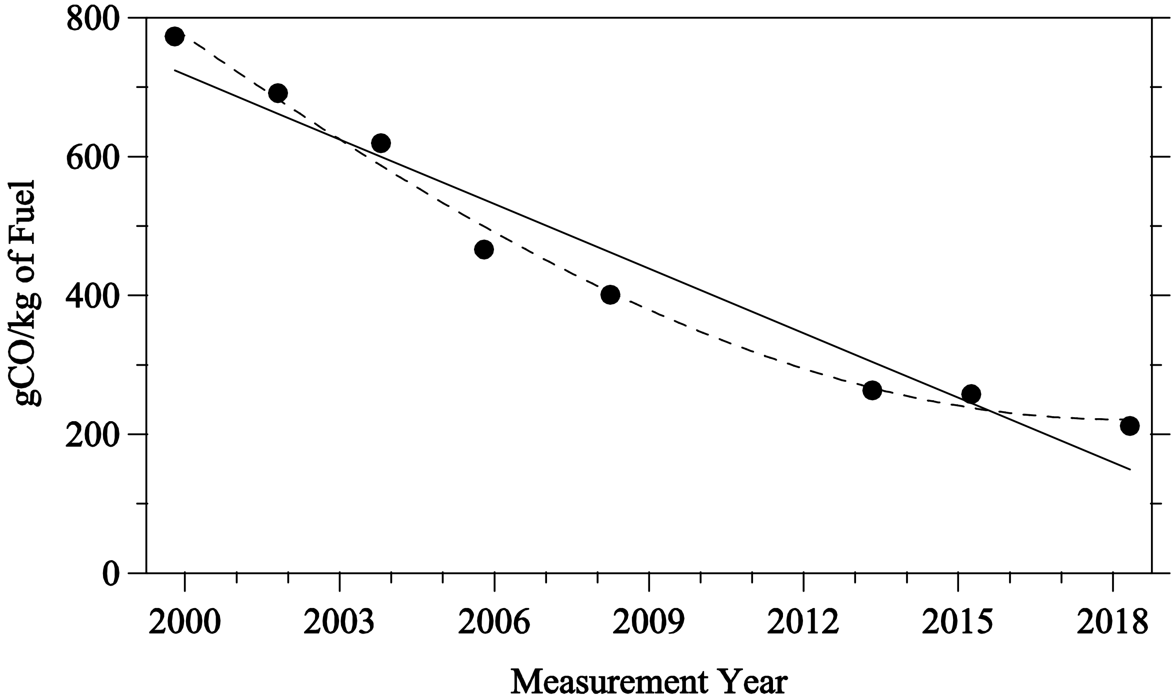

Figure 17. The gCO/kg of fuel 99th percentile for each of the West Los Angeles data sets plotted against measurement year. Linear (solid line) and an exponential decay (dashed line) fits are shown.

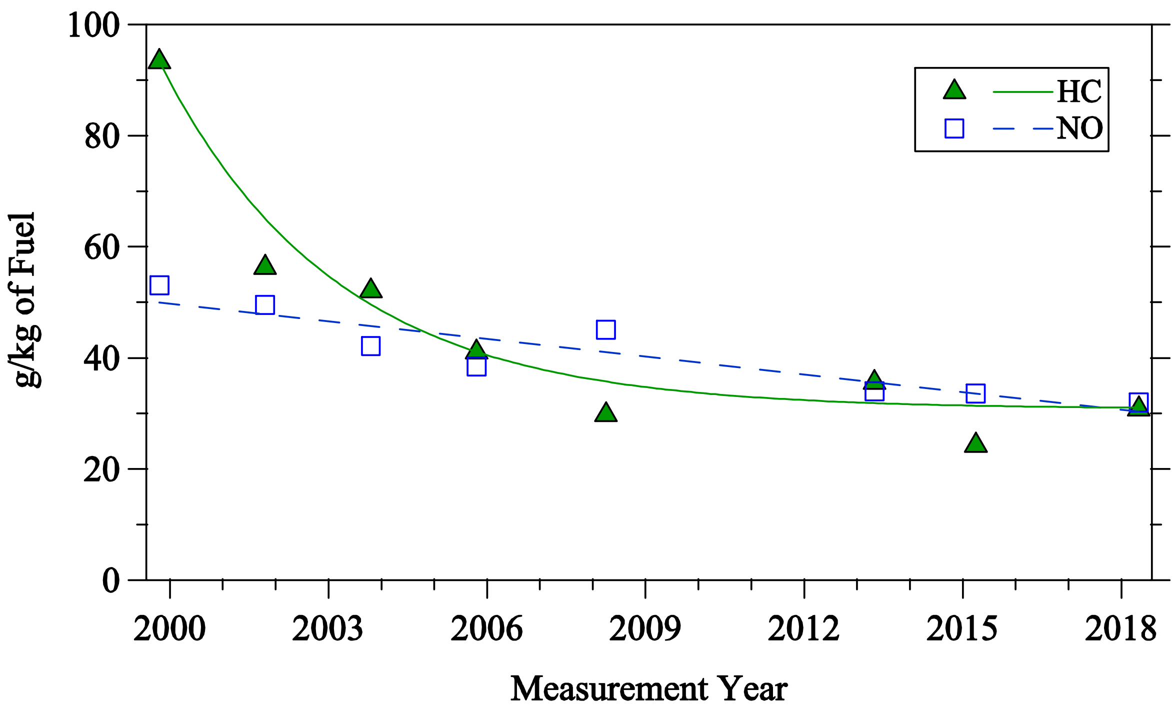

Figure 18. The gHC/kg of fuel and gNO/kg of fuel 99th percentiles for each of the West Los Angeles data sets plotted against measurement year. Lines are an exponential decay for HC and a linear fit for NO.

vehicles have changed from 1984 models in the 1999 measurements (~15 years-old) to 1997.1 models for the 2018 measurements (~21 years-old).

The HC 99th percentiles have been reduced by a similar factor as CO and an exponential fit to the HC data shows that reductions have stopped around 30 gHC/kg of fuel. Mean model years of the 99th percentiles vehicles increased from 1986 in the 1999 measurements to 2004.6 models in the 2018 measurement maintaining a similar vehicle age for HC. The NO 99th percentiles have been reduced by a significantly smaller amount and the reductions observed to date are following a linear decrease as shown by the dashed best-fit line. For the NO 99th percentiles the age of the mean model year has increased from 1987 (~12 years old in 1999) to 1999.1 models (~19 years old in 2018). The introduction of LEV II vehicles is a major reason behind the fleet average NO emissions reduction (see Figure 3) and we believe this is also the main reason for the decrease of the 99th percentile values. It is expected that NO emissions will continue to decline going forward as low deterioration rates of LEV II vehicles should continue to lower fleet emissions, as they become a larger fraction of the on-road fleet.

The 99th percentile values for each pollutant are a critical metric that dictates the mean emissions levels for a fleet. As the 99th percentile values go so goes the inventory for that species. The slowing in the reductions of the 99th percentiles for CO and HC portend a floor for the CO and HC mobile source emissions inventory in the Los Angeles basin beyond which future reductions will require new ideas that target the 99th percentile vehicles. Electrification of the fleet on the surface appears to be the ideal solution with zero emission vehicles (ZEVs) replacing internal combustion engine vehicles and lowering emissions. Using the 2018 West LA data set if we assume that of the 2,316 attempted measurements that did not result in a valid emissions measurement (see Table 1), 1000 of these were actually ZEVs mean emissions per vehicle for CO, HC and NO would be reduced by an amount equal to their fleet representation, ~5%. However, total emissions emitted by the fleet would not be reduced. If ZEVs replace other internal combustion engine vehicles in a random process, that replacement is most likely to result in the median vehicle (~6 year old vehicle) being replaced. Replacing 1000 of the 2018 West LA measurements with median emissions on average the 2018 fleet averaged means and total emissions will be reduced by 0.8% for CO, by 3.5% for HC and 0.2% for NO. Replacing the lowest emitting 80% of the West LA fleet would not significantly change these reductions for CO and HC and would only increase the NO emissions reduction to 0.9%. These reductions likely will not have any significant impact on ozone levels in Los Angeles. For substantial and efficient criteria pollutant reductions, ZEV penetration may need to consider incorporating strategies that target the replacements of the highest emitting vehicles.

Diesel Vehicle Emissions. Diesel vehicles are only a small segment of the fleet observed at the West Los Angeles location but it is important to follow their historical contribution to the West Los Angeles fleet. Figure 19 is a plot showing the percent of diesel vehicles in the West Los Angeles fleet for each of the data sets collected at the site since 1999. At the top of the graph over each bar is the mean model year for the diesel portion and its age in years assuming that the new vehicle year begins on September 1. The diesel portions include light, medium and a few heavy-duty vehicles that have low exhaust and a readable license plate. The graph shows that the

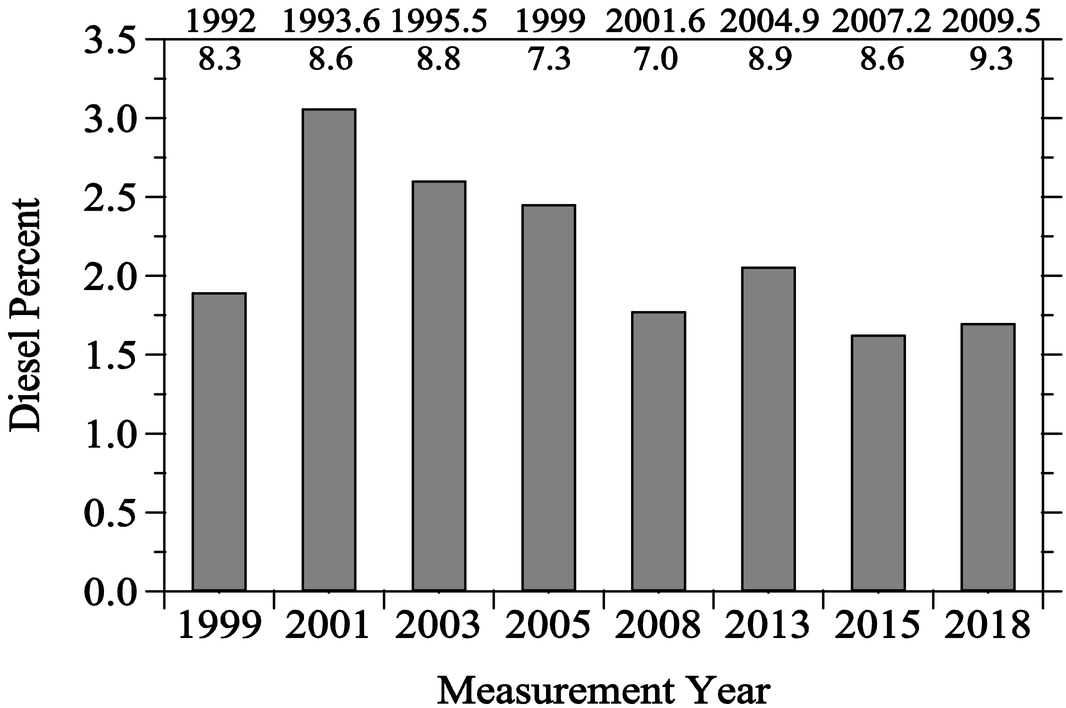

Figure 19. Percent of diesel vehicles observed in the West Los Angeles fleet during each measurement campaign. At the top of each bar is the mean model year and fleet age for the diesel portion.

diesel fleet percentage peaked with the 2001 measurements and since the 2008 measurements has remained around 1.75% of the fleet. The increase in the diesel fleet between the 2008 and 2013 measurements reflects the introduction of the Volkswagen and Audi light-duty vehicles that have since been largely removed from the fleet. The diesel fleet also saw a significant increase in its mean age after the 2008 – 2009 recession and with the completion of the 2018 campaign, it is now the oldest diesel fleet observed.

Figure 20 shows the fuel specific CO, HC and NO emissions for the diesel portion of the West Los Angeles fleet for each measurement year. The uncertainties plotted are standard errors of the mean calculated using the daily means. The two most notable features are the large drop in CO emissions (61%) between the 2005 and 2008 measurements and the decline in NO emissions that starts with the 2013 measurements. The CO reduction corresponds with the youngest fleet observed since 1999 (see Figure 19) and with the introduction of diesel particulate filters. However, the 2008 fleet is 7 years old and the penetration of diesel particulate filters is miniscule at this time. The continued reduction in CO emission with each of the subsequent year's measurements, however, is likely linked to the increased use of diesel after-treatment systems that favors lean air to fuel ratios. Likely the introduction of the diesel NOx after-treatment systems also explains the drop in NO emissions starting with the 2013 measurements. Between the 2008 and 2018 measurements NO emissions decreased by 41% while NO_x emissions have seen a similar 40% reduction (25.3 ± 1.4 to 15.2 ± 0.9).

The introduction of selective catalytic reduction (SCR) after-treatment systems in diesel vehicles is more apparent in Figure 21. This plot compares the 2013 and 2018 measurement year's diesel

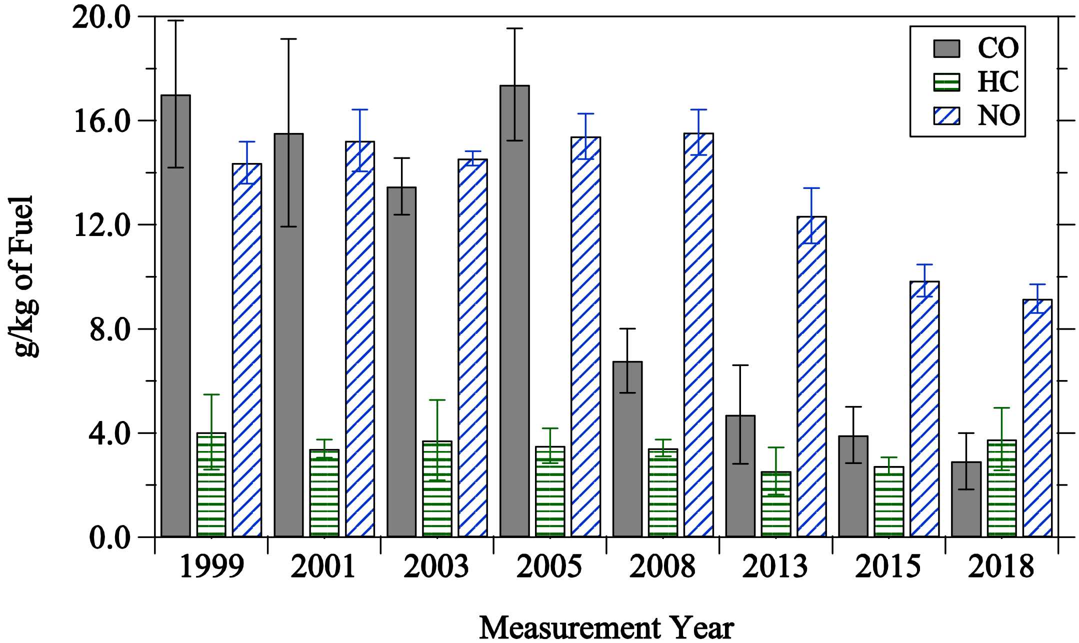

Figure 20. Mean fuel specific CO, HC and NO emissions for the diesel portion of the West Los Angeles fleet for each of the eight measurement campaigns. Uncertainties are standard error of the mean calculated using the daily means.

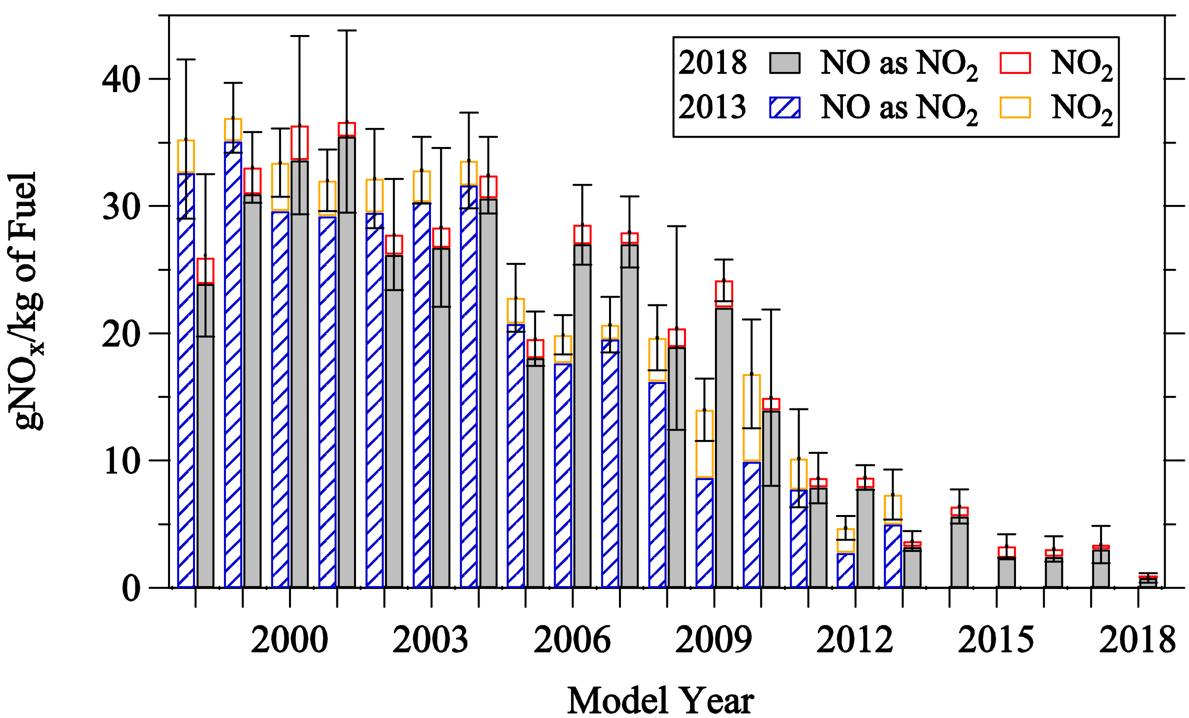

Figure 21. Fuel specific NO_x emissions by model year comparing the 2013 and 2018 West Los Angeles measurements. The solid portion of each bar denotes the portion emitted as NO in grams of NO_2 and the open portion indicates the amount of NO_2. Uncertainties are standard error of the mean calculated using the daily means.

fleets fuel specific NO_x emissions by model year. The height of each bar is the total NO_x emissions divided between the amount emitted as NO (in grams of NO_2, solid portion) and the fraction emitted as NO_2 (open portion). The uncertainties are standard error of the mean calculated using the daily means. It is evident that NO_x emission reductions have been occurring slowly since the 2005 model year vehicles. NO_x after treatment systems began to be introduced into diesel vehicles with the 2009 model year light-duty vehicles and in 2011 with medium and heavy-duty vehicles. Many of the model years prior to the 2011 models show NO_x increases between the 2013 and 2018 measurements. The large amounts of NO_2 emissions observed in the 2009 – 2013 model years in the 2013 measurements are from light-duty Volkswagen and Audi models. The average emissions in 2018 for 2013 and newer model years is 3.65 gNO_x/kg of fuel. This is an 84% reduction from the 23.3 gNOx/kg of fuel emissions average for the remaining fleet.

In the U.S., gasoline passenger car and truck NO_x emissions have been rapidly decreasing and this is the case at the West Los Angeles site.[42] The diesel fleet NO_x emissions are not insignificant, however, because of their numerical superiority gasoline vehicles still account for the majority of NO_x emissions at the West Los Angeles site. Figure 22 plots the percent of the sum total of the fuel specific NO and NO_x emissions that diesels contribute for each data set collected since 1999. Those contributions have risen from ~4% in 1999 to around 10% of the total in 2018 as fuel specific NO and NO_x have decreased with the introduction of LEV II vehicles (see Figure 3). This is a slight reduction from the largest contribution observed in 2013, which coincided with the increase in the number of light-duty diesel passenger vehicles in the fleet.[20]

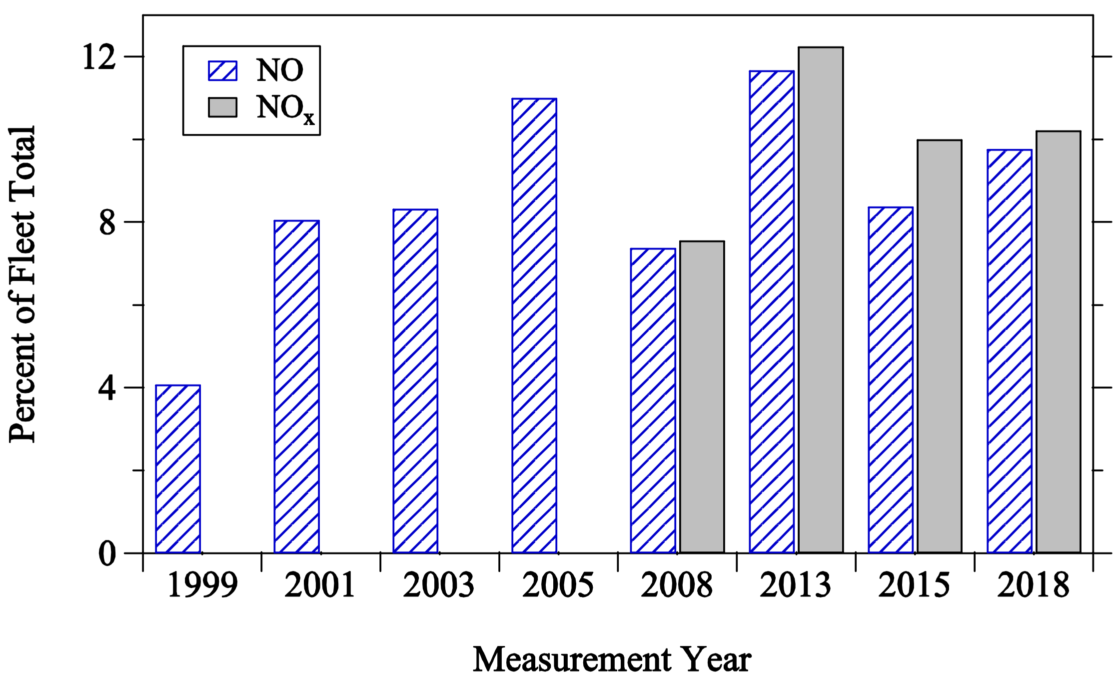

Figure 22. Percent of fleet sum total fuel specific NO and NO_x emissions by measurement year.

Many of these light-duty diesel vehicles were found to be in violation of the U.S. and California new vehicle certification standards and were to either be fixed or removed from the fleet for excess NO_x emissions. Figure 23 is a graph of fuel specific NO_x emissions plotted for individual diesel vehicle measurements collected at either the West Los Angeles site (9 vehicles) or from two measurement sites in the Lynwood CA area (5 measurements from 4 vehicles collected the week prior to the West Los Angeles measurements) ordered by their model year. The model year designation on the x-axis shows the beginning measurement for that model year and subsequent measurements continue for the same model year until a new model year designation. The height of each bar is the total amount of fuel specific NO_x emissions where the solid portion represents the amount emitted as NO in grams of NO_2 and the open bar the amount of NO_2 emitted. The asterisks above two of the 2010 model year measurements indicate the same vehicle. It is apparent that at least 4 of these vehicles still appear to be in their original operating conditions with elevated NO_x emissions made up of significant amounts of NO_2.

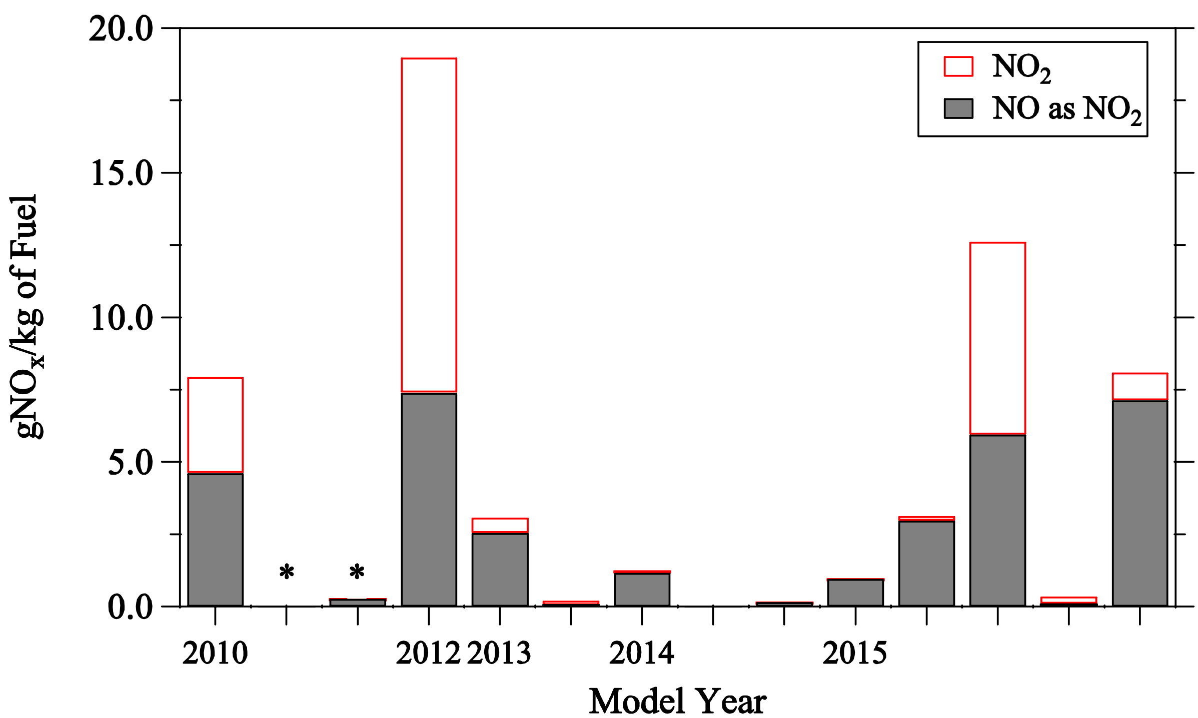

Figure 23. Fuel specific NO_x emissions for individual vehicles organized by model year with the model year designation marking the beginning of those model years' measurements. The solid portion of each bar represents the portion of the total NO_x emitted as NO in grams of NO_2 and the open portion indicates the amount of NO_2. The asterisks indicate the same vehicle.

<u>Instrument Noise Evaluation.</u> In the manner described in the Phoenix, Year 2 report,[45] 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 2018 data set were 3.8, 4.0, 0.3, 0.02 and 0.1 for CO, HC, NO, NH_3 and NO_2 respectively. These values indicate standard deviations of 5.4 g/kg (0.04%), 5.6 g/kg (122 ppm), 0.4 g/kg (47 ppm), 0.02 g/kg (5 ppm) and 0.2 g/kg (9 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 0.5 g/kg, 0.6 g/kg, 0.04 g/kg, 0.002 g/kg and 0.03 g/kg, respectively.

Summary and Conclusions

The University of Denver has successfully completed a new emissions measurement collection campaign at the West Los Angeles sampling site (southbound La Brea Ave. to eastbound I-10) in May of 2018. 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 measurements were collected between May 14 – 19, 2018 resulting in a vehicle and emissions database containing 19,259 records. This data set makes the eighth data set that has been collected at this site since 1999. 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.

The 2018 mean fuel specific emissions for CO, HC, NO, NH_3 and NO_2 were determined to be 11, 1.5, 1.6, 0.68 and 0.05, g/kg of fuel respectively. Since 1999 the CO mean emissions have decreased by 84% (70.3 to 11 g/kg), the HC mean emissions by 79% (7.0 to 1.5 g/kg) and the NO mean emissions by 76% (6.6 to 1.6 g/kg). These decreases have happened despite an older fleet (8.9 years) now than prior to the 2008 recession. When comparing CO and HC emissions by the age of the vehicle one finds that 24 year old vehicles measured in 2018 (1994 models) have emissions that are very similar to 8 or 9 year old vehicles measured in 1999 (1990 or 1991 models). While these large reductions have taken place the emissions distribution has become more skewed. The 99^{th} percentile in 1999 was responsible for 14% and 17% of the CO and HC emissions respectively. In 2018, the same 1% of the fleet is now responsible for 38% and 43% of the CO and HC emissions respectively.

Over the nineteen-year period the 99^{th} percentile emissions for CO and HC have dropped by more than a factor of three for CO (773 to 212 g/kg) and HC (93 to 31 g/kg) and a factor of 1.6 for NO (53 to 32 g/kg). While these reductions are impressive, with the collection of the 2018 data it is more apparent that the reductions have leveled out for HC and continue to slow for CO. The NO 99^{th} percentile is still decreasing linearly and this trend is expected to continue as LEV III vehicles enter the fleet. The slowing in the reductions of the 99th percentiles for CO and HC portend a floor for the CO and HC mobile source emissions inventory in the Los Angeles basin beyond which future reductions will require new ideas that target the 99th percentile vehicles.

Electrification of the fleet, unless targeted at the highest emitting vehicles, will unlikely reverse this slowing trend until a large majority of the fleet is electrified.

With eight data sets collected to date, there is sufficient historical data to compare with the reductions predicted by California's vehicle emissions model EMFAC. Running exhaust emission factors for CO, TOG and NO_x were generated using the EMFAC2017 web database by model year for summer in the South Coast Air Basin, gasoline only and using the LDA, LDT1, LDT2 and MDV categories for each of the measurement years. Fleet fuel specific emission factors by model year were calculated using the model estimated fuel consumption. EMFAC2017 fleet mean emissions were determined by combining the emissions by model year and the model year distribution observed at the West Los Angeles site for each measurement year. The 1999 West Los Angeles fleet model year distribution was used to weight the 2000 EMFAC emissions since the web database only predicts emissions back to year 2000.

EMFAC2017 predicted mean CO emissions using this approach have decreased 75% (44.6 to 11 gCO/kg of Fuel), TOG predicted emissions have decreased 85% (2.4 to 0.4 gTOG/kg of Fuel) and predicted NO_x emissions have decreased 87% (6.8 to 0.8 gNO_x/kg of Fuel). These overall reduction estimates are similar to what has been observed in the West Los Angeles fleet with CO emission in-use decreasing 85% (71 ± 2.5 to 11 ± 0.2 gCO/kg of Fuel), HC decreasing 79% (7 ± 0.7 to 1.5 ± 0.2 gHC/kg of Fuel) and NO emissions decreasing 76% (6.7 ± 0.5 to 1.6 ± 0.1 gNO/kg of Fuel).

The portion of the West Los Angeles fleet that is diesel-powered is the lowest that has been observed to date with only 1.75% of the measurements being contributed by diesel vehicles. However, the diesel fleet is the oldest at ~9.3 years old seen since measurements began in 1999. Diesel CO emissions have decreased by 83% since 1999 and NO emissions have declined by 36% over the same period. NO and NO_x emissions only show declines with the 2013 measurements and have similar reductions of 41% (14.4 ± 0.8 to 9.2 ± 0.6 gNO/kg of Fuel) and 40% (25.3 ± 1.4 to 15.2 ± 0.9 gNO_x/kg of fuel). In 2018, the diesel vehicles observed at the West Los Angeles site are responsible for ~10% of the fleets NO_x emissions.

Recommendations

Often the need for emissions data is not known until it is too late to collect it. 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 at a relatively low cost. The 2008 recession and Volkswagen emissions cheating scandal were both unforeseen events whose emissions impact could be evaluated from remote vehicle exhaust measurements and emphasizes the importance of regular on-road emissions data collection.

The new data collected in 2018 continues to suggest that emissions reductions of the last three decades may be slowing which could be a major problem for future ambient air improvements. Electrification of the fleet (fleet turnover to zero-emission vehicles) will eventually lead to significant fleet emission reductions; however, this process will be slow unless specific strategies are used to target the replacement of the highest emitting vehicles. We believe it remains important to track the emissions of the on-road fleet in Los Angeles and in particular, which vehicles new zero emission vehicles are replacing.

References

1. U. S. Environmental Protection Agency, Clean Air Act Text. http://www.epa.gov/air/caa/text.html.

2. U. S. Environmental Protection Agency, National Ambient Air Quality Standards. http://www.epa.gov/air/criteria.html.

3. U. S. Environmental Protection Agency, Our Nation's Air: Status and trends through 2015. http://www.epa.gov/air/trendsreport/2016/.

4. California Air Resources Board, 2016 SIP Emission Projection Data. https://www.arb.ca.gov/app/emsinv/2017/emssumcat_query.php?F_YR=2012&F_DIV=-4&F_SEASON=A&SP=SIP105ADJ&F_AREA=CA#7 (accessed Nov. 2018).

5. Heywood, J. B., *Internal combustion engine fundamentals*. McGraw Hill: New York, 1988.

6. Spengler, J. D.; Koutrakis, P.; Dockery, D. W.; Raizenne, M.; Speizer, F. E., Health Effects of Acid Aerosols on North American Children: Air Pollution Exposures *Environ. Health Perspect.* **1996,** *104* (5), 492-499.

7. Ghio, A. J.; Kim, C.; Devlin, R. B., Concentrated Ambient Air Particles Induce Mild Pulmonary Inflammation in Healthy Human Volunteers. *American Journal of Respiratory and Critical Care Medicine* **2000,** *162* (3), 981-988.

8. Gauderman, J. W.; McConnell, R.; Gilliland, F.; London, S.; Thomas, D.; Avol, E.; Vora, H.; Berhane, K.; Rappaport, E. B.; Lurmann, F.; Margolis, H. G.; Peters, J., Association between Air Pollution and Lung Function Growth in Southern California Children. *American Journal of Respiratory and Critical Care Medicine* **2000,** *162* (4), 1383-1390.

9. Pope III, C. A., Health effects of fine particulate air pollution: Lines that connect. *J. Air Waste Manage. Assoc.* **2006,** *56* (6), 709-742.

10. Pitchford, M. L.; Poirot, R. L.; Schichtel, B. A.; Malm, W. C., Characterization of the winter Midwestern particulate nitrate bulge. *J. Air Waste Manage. Assoc.* **2009,** *59*, 1061-1069.

11. Eatough, D. J.; Farber, R., Apportioning visibility degradation to sources of $PM_{2.5}$ using positive matrix factorization. *J. Air Waste Manage. Assoc.* **2009,** *59*, 1092-1110.

12. Nowak, J. B.; Neuman, J. A.; Bahreini, R.; Middlebrook, A. M.; Holloway, J. S.; McKeen, S.; Parrish, D. D.; Ryerson, T. B.; Trainer, M., Ammonia sources in the California South Coast Air Basin and their impact on ammonium nitrate formation. *Geophys. Res. Lett.* **2012,** *39*, L07804.

13. Saylor, R.; Myles, L.; Sibble, D.; Caldwell, J.; Xing, J., Recent trends in gas-phase ammonia and $PM_{2.5}$ ammonium in the Southeast United States. *J. Air Waste Manage. Assoc.* **2015,** *65* (3), 347-357.

14. MacArthur, R.; Mobley, D.; Levin, L.; Pierce, T.; Feldman, H.; Moore, T.; Koupal, J.; Janssen, M., Emission characterization and emission inventories for the 21st century. *EM* **2009,** *(October)*, 36-41.

15. Lefohn, A. S.; Shadwick, D. S.; Ziman, S. D., The Difficult Challenge of Attaining EPA's New Ozone Standard. *Environ. Sci. Technol.* **1998,** *32* (11), 276A-282A.

16. U. S. Environmental Protection Agency, National Ambient Air Quality Standards for Ozone. https://www.gpo.gov/fdsys/pkg/FR-2015-10-26/pdf/2015-26594.pdf (accessed Feb 2018).

17. Bishop, G. A.; Stedman, D. H., A decade of on-road emissions measurements. *Environ. Sci. Technol.* **2008,** *42* (5), 1651-1656.

18. Bishop, G. A.; Peddle, A. M.; Stedman, D. H.; Zhan, T., On-road emission measurements of reactive nitrogen compounds from three California cities. *Environ. Sci. Technol.* **2010,** *44*, 3616-3620.

19. Bishop, G. A.; Stedman, D. H., The recession of 2008 and it impact on light-duty vehicle emissions in three western U.S. cities. *Environ. Sci. Technol.* **2014,** *48*, 14822-14827.

20. Bishop, G. A.; Stedman, D. H., Reactive Nitrogen Species Emission Trends in Three Light-/Medium-Duty United States Fleets. *Environ. Sci. Technol.* **2015,** *49* (18), 11234-11240.

21. Bishop, G. A.; Stedman, D. H., Measuring the emissions of passing cars. *Acc. Chem. Res.* **1996,** *29*, 489-495.

22. Popp, P. J.; Bishop, G. A.; Stedman, D. H., Development of a high-speed ultraviolet spectrometer for remote sensing of mobile source nitric oxide emissions. *J. Air Waste Manage. Assoc.* **1999,** *49*, 1463-1468.

23. Burgard, D. A.; Bishop, G. A.; Stadtmuller, R. S.; Dalton, T. R.; Stedman, D. H., Spectroscopy applied to on-road mobile source emissions. *Appl. Spectrosc.* **2006,** *60*, 135A-148A.

24. Burgard, D. A.; Dalton, T. R.; Bishop, G. A.; Starkey, J. R.; Stedman, D. H., Nitrogen dioxide, sulfur dioxide, and ammonia detector for remote sensing of vehicle emissions. *Rev. Sci. Instrum.* **2006,** *77* (014101), 1-4.

25. Singer, B. C.; Harley, R. A.; Littlejohn, D.; Ho, J.; Vo, T., Scaling of infrared remote sensor hydrocarbon measurements for motor vehicle emission inventory calculations. *Environ. Sci. Technol.* **1998,** *32*, 3241-3248.

26. Lawson, D. R.; Groblicki, P. J.; Stedman, D. H.; Bishop, G. A.; Guenther, P. L., Emissions from in-use motor vehicles in Los Angeles: A pilot study of remote sensing and the inspection and maintenance program. *J. Air Waste Manage. Assoc.* **1990,** *40*, 1096-1105.

27. Ashbaugh, L. L.; Lawson, D. R.; Bishop, G. A.; Guenther, P. L.; Stedman, D. H.; Stephens, R. D.; Groblicki, P. J.; Johnson, B. J.; Huang, S. C. In *On-road remote sensing of carbon monoxide and hydrocarbon emissions during several vehicle operating conditions*, Proceedings of the A&WMA International Specialty Conference on PM10 Standards and Non-traditional Source Control, Phoenix, Phoenix, 1992.

28. Pokharel, S. S.; Stedman, D. H.; Bishop, G. A. In *RSD Versus IM240 Fleet Average Correlations*, Proceedings of the 10th CRC On-Road Vehicle Emissions Workshop, San Diego, San Diego, 2000.

29. Ashbaugh, L. L.; Croes, B. E.; Fujita, E. M.; Lawson, D. R. In *Emission characteristics of California's 1989 random roadside survey*, Proceedings of the 13th North American Motor Vehicle Emissions Control Conference, Tampa, Tampa, 1990.

30. Jimenez, J. L.; McClintock, P.; McRae, G. J.; Nelson, D. D.; Zahniser, M. S., Vehicle specific power: A useful parameter for remote sensing and emission studies. In *Ninth Coordinating Research Council On-road Vehicle Emissions Workshop*, Coordinating Research Council, Inc.: San Diego, CA, 1999; Vol. 2, pp 7-45 - 7-57.

31. Bishop, G. A.; Schuchmann, B. G.; Stedman, D. H.; Lawson, D. R., Multispecies remote sensing measurements of vehicle emissions on Sherman Way in Van Nuys, California. *J. Air Waste Manage. Assoc.* **2012,** *62* (10), 1127-1133.

32. McDonald, B. C.; Gentner, D. R.; Goldstein, A. H.; Harley, R. A., Long-term trends in motor vehicle emissions in U.S. urban areas. *Environ. Sci. Technol.* **2013,** *47* (17), 10022-10031.

33. Pollack, I. B.; Ryerson, T. B.; Trainer, M.; Neuman, J. A.; Roberts, J. M.; Parrish, D. D., Trends in ozone, its precursors, and related secondary oxidation products in Los Angeles, California: A synthesis of measurements from 1960 to 2010. *Journal of Geophysical Research, [Atmospheres]* **2013,** *118*, 1-19.

34. Kim, E.; Turkiewicz, K.; Zulawnick, S. A.; Magliano, K. L., Sources of fine particles in the south coast area, California. *Atmos. Environ.* **2010,** *44*, 3095-3100.

35. Durbin, T. D.; Wilson, R. D.; Norbeck, J. M.; Miller, J. W.; Huai, T.; Rhee, S. H., Estimates of the emission rates of ammonia from light-duty vehicles using standard chassis dynamometer test cycles. *Atmos. Environ.* **2002,** *36*, 1475-1482.

36. Huai, T.; Durbin, T. D.; Miller, J. W.; Pisano, J. T.; Sauer, C. G.; Rhee, S. H.; Norbeck, J. M., Investigation of NH_3 emissions from new technology vehicles as a function of vehicle operating conditions. *Environ. Sci. Technol.* **2003,** *37*, 4841-4847.

37. Kean, A. J.; Littlejohn, D.; Ban-Weiss, G. A.; Harley, R. A.; Kirchstetter, T. W.; Lunden, M. M., Trends in on-road vehicle emissions of ammonia. *Atmos. Environ.* **2009,** *43* (8), 1565-1570.

38. Baum, M. M.; Kiyomiya, E. S.; Kumar, S.; Lappas, A. M.; Kapinus, V. A.; Lord III, H. C., Multicomponent remote sensing of vehicle exhaust by dispersive absorption spectroscopy. 2. Direct on-road ammonia measurements. *Environ. Sci. Technol.* **2001,** *35*, 3735-3741.

39. Burgard, D. A.; Bishop, G. A.; Stedman, D. H., Remote sensing of ammonia and sulfur dioxide from on-road light duty vehicles. *Environ. Sci. Technol.* **2006,** *40*, 7018-7022.

40. Kean, A. J.; Harley, R. A.; Littlejohn, D.; Kendall, G. R., On-road measurement of ammonia and other motor vehicle exhaust emissions. *Environ. Sci. Technol.* **2000,** *34*, 3535-3539.

41. Pitchford, M.; Johnson, B., Empirical model of vehicle emissions. *Environ. Sci. Technol.* **1993,** *27*, 741.

42. Bishop, G. A.; Haugen, M. J., The story of ever diminishing vehicle tailpipe emissions as observed in the Chicago, Illinois area. *Environ. Sci. Technol.* **2018,** *52* (13), 7587-7593.

43. California Environmental Protection Agency; Air Resources Board, EMFAC Emissions Database. http://www.arb.ca.gov/emfac/ (accessed July, 2019).

44. Fujita, E. M.; Campbell, D. E.; Zielinska, B.; Chow, J. C.; Lindhjem, C. E.; DenBleyker, A.; Bishop, G. A.; Schuchmann, B. G.; Stedman, D. H.; Lawson, D. R., Comparison of the MOVES2010a, MOBILE6.2 and EMFAC2007 mobile source emissions models with on-road traffic tunnel and remote sensing measurements. *J. Air Waste Manage. Assoc.* **2012,** *62* (10), 1134-1149.

45. Pokharel, S. S.; Bishop, G. A.; Stedman, D. H. *On-road remote sensing of automobile emissions in the Phoenix area: Year 2*; Coordinating Research Council, Inc: Alpharetta, 2000.

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 Labrea18.dbf database.

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.
Vin	Vehicle identification number neutered to first 10 digits.
Make	Manufacturer of the vehicle.
Year	Model year.
Series	Manufacturer vehicle line.
Model	Series appointment level of model type.
Fuel	Fuel type G (gasoline), D (diesel), N (natural gas) and B (hybrid).
Gvw_code	DMV gross vehicle weight code.
Unladen_wt	Vehicle weight in pounds.
Disp_ci	DMV engine displacement cubic inches.
Body_type	California dmv designated body type.
County	County number for registration.
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.
Hcgkg_off	Grams of HC per kilogram of fuel using 860 gC/kg of fuel and using the HC_offset value for this calculation.
VSP	Vehicles specific power calculating using the equation provided in the report.
V_body	VIN decoded body type information.
V_cyl	VIN decoded number of engine cylinders.
V_disp	VIN decoded engine size in liters.
V_gvwr	VIN decoded weight class.
V_trim	VIN decoded model information.
V_trans	VIN decoded transmission information.
V_type	VIN decoded vehicle type information (passenger or truck).
V_eng	VIN decoded engine information.

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

2018 West Los Angeles Temperature and Humidity Data												
Time	5/14 °F	5/14 %RH	5/15 °F	5/15 %RH	5/16 °F	5/16 %RH	5/17 °F	5/17 %RH	5/18 °F	5/18 %RH	5/19 °F	5/19 %RH
6:53	60	75	60	75	61	72	61	72	61	75	61	78
7:53	62	73	62	70	63	65	64	63	62	75	62	75
8:53	64	65	63	65	66	54	65	56	62	75	62	75
9:53	67	59	64	65	69	53	66	63	64	70	63	73
10:53	65	66	66	61	68	59	68	59	65	66	64	73
11:53	67	59	67	59	68	59	68	59	66	63	65	70
12:53	65	66	66	61	67	59	68	59	66	63	67	68
13:53	66	63	66	63	68	51	68	61	67	61	66	68
14:53	65	63	66	59	67	55	67	63	66	63	65	73
15:53	65	61	65	61	67	59	66	65	66	63	65	73
16:53	63	68	64	65	65	63	64	70	64	70	63	78
17:53	62	70	62	70	64	65	63	73	62	78	62	80
18:53	61	70	61	70	63	68	62	73	60	80	61	81

APPENDIX D: Methodology to Normalize Mean gHC/kg of fuel Emissions

The hydrocarbon channel on FEAT has the lowest signal to noise ratio of all the measurement channels in large part because the absorption signals are the smallest (millivolt levels). FEAT 3002 uses one detector for the target gas absorption and a second detector for the background IR intensity (reference). These channels are ratioed to each other to correct for changes in background IR intensities that are not the result of gas absorption. The detector responses are not perfectly twinned and for the low signal HC channel this lack of perfect intensity correction can result in small systematic artifacts, which can be a positive or negative offset of the emissions distribution, being introduced into the measurement. In addition the region of the infrared spectrum that is used for HC absorption measurements is overlapped by an absorption band for liquid water. Normally this is not an issue as fully warmed up vehicles emit little if any liquid water at the tailpipe. However, there are times when low temperatures and high dew points cause water vapor to condense at the tailpipe and create an additional absorption artifact in the measurements that are not related to HC emissions. In these cases the normalization value calculated will be larger because it includes an additional adjustment for the liquid water emissions.

The offset is calculated by computing the mode and means of the newest model year vehicles, and assuming that these vehicles emit negligible levels of hydrocarbons and that their emissions distribution should have a median value very near zero, using the lowest of either of these values as the offset. The offset value is then added (for negative offsets) or subtracted from all of the hydrocarbon measurements adjusting the zero point of the emissions distribution. Since it is assumed that the newest vehicles are the lowest emitting this approximation will slightly over correct because the true offset will be a value somewhat less than the average of the cleanest model year and make.

As an example of the process the calculation is demonstrated using data collected in Chicago in 2014 and shown in Table D1. The Chicago 2014 measurement included a correction for both of the previously discussed issues as the first three days of measurements were with normal temperatures and low humidity while the last three days experienced the exact opposite. FEAT ratios are first reported as percent emissions and the normalization calculations are performed using these percent values. Below are the data tables used for estimating the HC normalization value for the 2014 Chicago measurements.

For the Monday through Wednesday time slot Honda's vehicles had the lowest average HC emissions with a mean %HC of 0.0013. In Table S2 the mode calculation has two values that are very close to each other 0.001 and 0.0015. It was decided to average those two values and the HC normalization value for the first time period used was 0.00125% which is approximately 0.5 gHC/kg of fuel.

For the Thursday through Saturday time period Honda vehicles again had the lowest HC emission. The average of 2009 – 2014 Honda vehicles is 0.003% which is the same as the mode shown in Table S2. This is approximately 1.25 gHC/kg of fuel.

2014 Chicago Mode Calculations
For model year 2009 and newer vehicles

Table D1. HC Normalization Mode Calculation.

Monday – Wednesday		Thursday - Saturday	
%HC	Counts	%HC	Counts
-0.0015	129	-0.0015	73
-0.001	147	-0.001	59
-0.0005	138	-0.0005	75
0	125	0	67
0.0005	126	0.0005	79
0.001	152	0.001	69
0.0015	155	0.0015	75
0.002	143	0.002	85
0.0025	104	0.0025	51
0.003	131	0.003	94
0.0035	129	0.0035	68
0.004	120	0.004	77
0.0045	115	0.0045	80
0.005	124	0.005	88

This method will successfully normalize the fleet HC means but may over or under correct smaller sub-fleets.

APPENDIX E: How Standard Errors of the Mean for our Reported Uncertainties are Estimated

Vehicle emissions from US vehicle fleets are not normally distributed, thus the assigning of uncertainties on fleet emission means involves a process that many readers may not be familiar with. Standard statistical methods that were developed for normally distributed populations, when used on a skewed distribution, result in uncertainties that are unrealistically too small due to the large number of samples. The Central Limit Theorem in general indicates that the means of multiple samples, randomly collected, from a larger parent population will be normally distributed, irrespective of the parent populations underlying distribution. Since multiple days of emission measurements are almost always collected at each site, these daily measurements are used as our randomly collected multiple samples from the larger population and the reported uncertainties are based on their distribution. Next the means, standard deviations and standard errors of the mean for this group of daily measurements is calculated. Next an error percentage is calculated from the ratio of the standard error of the mean for the daily measurements divided by the daily measurement mean. The fleet weighted means for all of the emission measurements are reported and the standard error of the fleet mean is calculated by multiplying the error percentage obtained previously against the fleet mean. An example of this process is provided below for the 2017 Denver gCO/kg of fuel and gNO/kg of fuel measurements. While this example is for a fleet mean this technique is also used when reporting uncertainties for other statistics such as individual model years, specific fuel or technology types, and VSP. For example each model year will have its daily means averaged and then its standard error of the mean for the daily average computed and that percent uncertainty (Daily STD Error MY/Daily MY average) will be applied to that entire model year's mean emissions.

Denver 2017

Date	Mean gCO/kg of fuel	Counts	Mean gNO/kg of fuel	Counts
12/15/17	8.72	4300	1.80	4299
12/19/17	7.48	5430	1.92	5429
12/20/17	8.37	5027	1.77	5027
1/9/17	7.48	4910	1.60	4908
1/18/17	8.17	2599	1.75	2598
Average for Daily Mean	8.04		1.77	
Standard Error for the daily means	0.25		0.05	
Weighted Fleet Mean	8.00		1.77	
Standard Error calculated for the fleet means	0.24		0.05	
As reported	8.0 ± 0.2		1.77 ± 0.05	

APPENDIX F: 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 G: 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 H: Field Calibration Records.

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

2018 West Los Angeles (FEAT 3002)						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
5/14	7:55	1.96	1.90	1.68	0.82	1.62
5/14	10:00	1.71	1.66	1.48	0.87	1.36
5/14	12:54	1.55	1.52	1.36	0.84	1.27
5/15	6:40	2.14	2.07	1.98	0.80	1.97
5/15	9:20	1.74	1.73	1.61	0.85	1.44
5/15	12:20	1.55	1.55	1.43	0.85	1.24
5/16	6:28	2.19	2.14	1.89	0.87	2.06
5/16	9:00	1.69	1.67	1.49	0.92	1.41
5/16	12:10	1.61	1.63	1.44	0.97	1.24
5/17	6:36	2.13	2.11	1.86	0.82	2.11
5/17	9:00	1.74	1.70	1.54	0.87	1.37
5/17	12:15	1.60	1.61	1.41	0.88	1.33
5/18	6:58	1.86	1.80	1.59	0.87	1.77
5/18	9:25	1.68	1.66	1.47	0.92	1.41
5/18	12:30	1.68	1.67	1.48	0.91	1.29
5/19	7:30	1.93	1.86	1.72	0.78	1.77
5/19	9:53	1.83	1.82	1.71	0.81	1.57
5/19	12:45	1.74	1.72	1.57	0.84	1.49
5/19	15:15	1.59	1.60	1.42	0.82	1.28