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REVISIT LYNWOOD, CA: ON-ROAD REMOTE SENSING OF AUTOMOBILE EMISSIONS IN THE LYNWOOD, CA AREA: 2018

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5755 NORTH POINT PARKWAY • SUITE 265 • ALPHARETTA, GA 30022

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Revisit Lynwood, CA: On-Road Remote Sensing of Automobile Emissions in the Lynwood, CA: 2018

Gary A. Bishop

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

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Alpharetta, Georgia 30022
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EXECUTIVE SUMMARY

The University of Denver conducted six days of remote sensing at two sampling locations in the Lynwood, California area in May of 2018. The remote sensor used in this study measures the ratios of CO, HC, NO, SO_2, NH_3 and NO_2 to CO_2 in motor vehicle exhaust. From these ratios, one can calculate the percent concentrations of CO, CO_2, HC, NO, SO_2, NH_3 and NO_2 in the exhaust that would be observed by a tailpipe probe, corrected for water and any excess oxygen not involved in combustion. Mass emissions per mass or volume of fuel can also be determined and are generally the preferred units for analysis. The equipment used in this study was configured to determine vehicle speed and acceleration, and included a video system to record license plate information. The latter was subsequently used to obtain non-personal vehicle registration information. Since fuel sulfur has been nearly eliminated in U.S. fuels SO_2 emissions have followed suit and while vehicle SO_2 measurements are collected they were not calibrated and the measurements are not included in the discussion of the results.

The University of Denver first visited the Los Angeles, CA area to collect in-use vehicle emission measurements in December 1989 with the first generation FEAT unit capable of only measuring the CO/CO_2 ratio from the tailpipes of passing vehicles (Lawson et al., 1990; Stedman et al., 1991). The South Coast AQMD operated an air quality monitor on Long Beach Blvd., just south of Lynwood, CA in south Los Angeles, which consistently reported some of the highest 8 hour CO maximum values in the basin (this monitor has since been moved). As a result, a number of the measurement sites that the California Air Resources Board chose for that first campaign were located in the Lynwood, CA area on and around Long Beach Blvd. One site was on Long Beach Blvd., several blocks north of the intersection with the Imperial Highway and a second site was on the off-ramp from northbound I-710 to westbound Imperial Highway. A second campaign in the Los Angeles Basin was carried out in the summer of 1991 with the third generation FEAT unit with the added capability to measure the HC/CO_2 ratio from the tailpipes of passing vehicles (Stedman et al., 1994; Beaton et al., 1995). During this second campaign, the 1989 Long Beach Blvd. location was revisited for one day of measurements.

In the spring of 2018 measurements were made on six consecutive days at two Lynwood sites. Measurements were collected from Monday May 7 through Wednesday May 9, 2018 between the hours of 8:00 and 17:30 on the on-ramp from southbound Long Beach Blvd. to eastbound I-105. Because of the redevelopment on and around Long Beach Blvd. it was not possible to sample at the identical location used in 1989 and 1991. The I-105 on-ramp was chosen as a location nearby (~7 blocks south) the 1989 and 1991 site that allowed vehicles exiting from Long Beach Blvd. to be sampled. This was followed with three additional days of measurements being collected between Thursday May 10 and Saturday May 12, 2018 during similar hours on the off-ramp from northbound I-710 to westbound Imperial Highway. This is the identical site used in 1989. Databases were compiled for each site with the Long Beach Blvd. / I-105 site containing 7,724 records and the I-710 / Imperial Highway location having 14,302 records for which the California Air Resources Board provided non-personal vehicle registration information. All of these records contained valid measurements for at least CO and CO_2, and most records contain valid measurements for the other species as well. The database, as well as others compiled by the University of Denver, can be found at www.feat.biochem.du.edu.

The 2018 mean CO, HC, NO, NH_3 and NO_2 emissions for the fleet measured at the Long Beach Blvd. / I-105 location were 10.4 ± 0.4 g/kg of fuel (0.08%), 2.1 ± 0.3 g/kg of fuel (56 ppm), 2.05

± 0.04 g/kg of fuel (145 ppm), 0.62 ± 0.01 g/kg of fuel (77 ppm) and 0.03 ± 0.01 g/kg of fuel (1.3 ppm) respectively. Average fleet model year was 2008.6 for an approximate age of 10.1 years (assuming a September 1 starting point for new model years). At the I-710 / Imperial Highway location the measured means were 12.3 ± 0.2 gCO/kg of fuel (0.1%), 2.0 ± 0.2 gHC/kg of fuel (52 ppm), 1.72 ± 0.08 gNO/kg of fuel (122 ppm), 0.43 ± 0.03 gNH$_3$/kg of fuel (54 ppm) and 0.03 ± 0.01 gNO$_2$/kg of fuel (1.6 ppm). The mean model year 2008.4 and age (10.3 years) of the fleet observed at the I-710/Imperial Highway site was slightly older than seen at the Long Beach Blvd/I-105 location.

Table ES1 summarizes the fleet fuel specific emission means from the three Lynwood campaigns along with the mean model year and age of the vehicle fleet observed. The uncertainties are standard error of the mean determined from the daily means for the multi-day measurements. For the measurements collected on a single day, the 1989 measurements at the I-710 off-ramp and the 1991 measurements on Long Beach Blvd., resampling statistics were used to estimate the standard error of the mean. When compared with the 1989 measurements there are dramatic decreases for mean CO (g/kg of fuel) of factors of 20 (Long Beach Blvd. site) and 10 (I-710 site) and for fuel specific HC emissions there is a reduction of a factor of 25 from the 1991 Long Beach Blvd. measurements. Fleet age has changed little at the Long Beach Blvd. site but increased significantly at the I-710 off-ramp from the 1989 measurements matching the age now observed along Long Beach Blvd.

Table ES1. Mean emission comparison by site for the 1989, 1991 and 2018 Lynwood measurements. Uncertainties are standard error of the mean.

	1989	1991		2018	
	Mean gCO/kg of Fuel	Mean gCO/kg of Fuel	Mean gHC/kg of Fuel	Mean gCO/kg of Fuel	Mean gHC/kg of Fuel
Long Beach Blvd. / I-105	210 ± 8	191.9 ± 13.6[a]	50.3 ± 3.9[a]	10.4 ± 0.4	2.1 ± 0.3
Mean Model Year (Age)[b]	1980.6 (9.7)	1981.7 (10.1)		2008.6 (10.1)	
I-710 Off-ramp	120.2 ± 7.6[a]	N.A.	N.A.	12.3 ± 0.2	2.0 ± 0.2
Mean Model Year (Age)[b]	1982.9 (7.4)	N.A.		2008.4 (10.3)	

[a] Single day of measurements. SEM estimated using resampling statistics.
[b] Mean model year calculated excluding missing model years and fleet age is calculated assuming the new model year starts September 1.

To place the newest measurements in context Figure ES1 graphs the historical mean fuel specific emissions for CO (left axis) and HC and NO (right axis) versus measurement year for all the data sets collected by the University of Denver in the South Coast Air Basin. Uncertainties are standard error of the mean calculated using the daily means for the sites with multiple days of

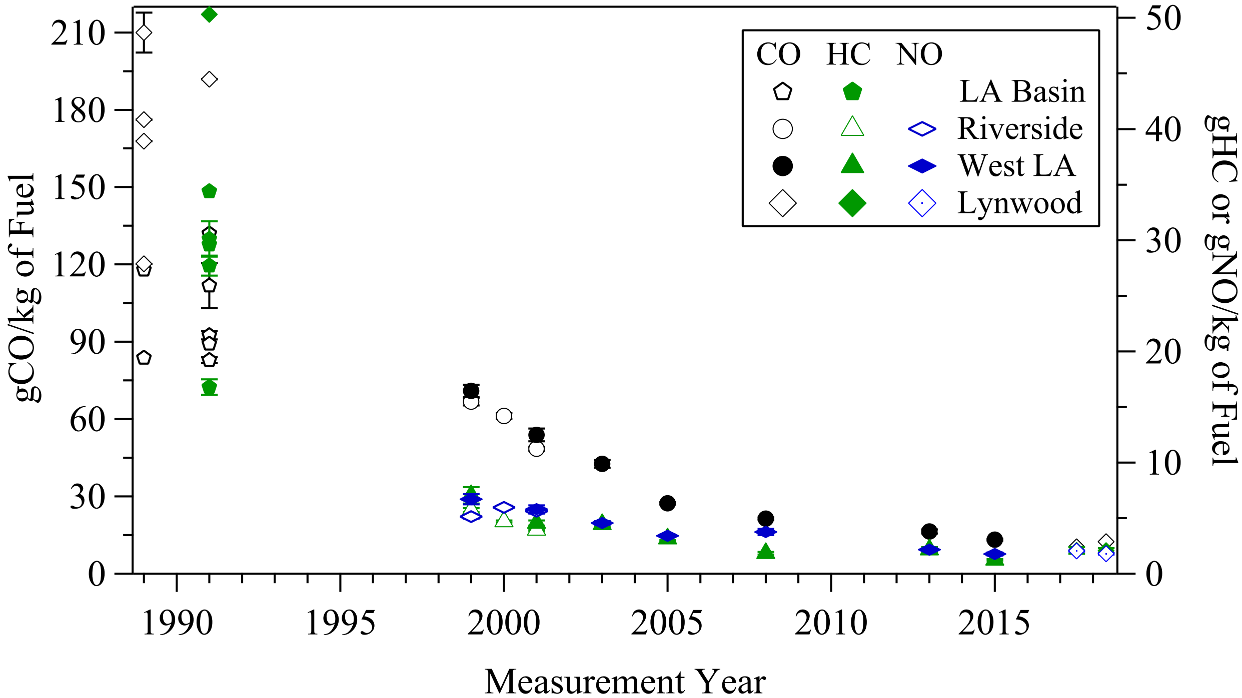

Figure ES1. Fuel specific CO (left axis), HC and NO (right axis) emissions collected in the South Coast Air Basin by the University of Denver. LA Basin measurements were collected at a variety of sites within the basin while the Riverside measurements were collected on the interchange ramp from NB 91 to WB 60 and the West LA data were collected at the on-ramp from SB La Brea Ave. to EB I-10. The 2018 Lynwood measurement years have been offset a half-year for the Long Beach Blvd. (2017.5) and I-710 (2018.5) sites to improve visibility. Uncertainties are standard error of the mean calculated using the daily means.

measurements. The LA Basin measurements in 1989 and 1991 include a number of sites around the basin in addition to sites in the Lynwood area (Stedman et al., 1991; Stedman et al., 1994).

The data show a consistent decrease in emissions for all three species with the rate of decrease slowing as the means approach zero. The 2018 Lynwood measurements are generally consistent with the last measurements collected at the West Los Angeles site in 2015 and now appear to have a fleet whose age and emissions are more in line with other locations across the basin unlike the measurements from the late 80's and early 90's (Bishop and Stedman, 2016).

Despite similar fleet average ages for the 1989 and 2018 Long Beach Blvd. measurements, the age distribution is different between the two data sets. Because of the 2008 recession the 2018 measurements contain fewer 7 to 10 year old vehicles (model years 2011 to 2008) and increased numbers of 15 year old and older vehicles (model years 2003 and older). A notable characteristic of the 1989 Long Beach Blvd. fleet was the large percentage of 11 and 12 year old vehicles (model years 1979 and 1978, ~16% of total) which have seen a reduction to 11% of the total in 2018, replaced in importance by 2 and 3 year old vehicles (15%).

Figure ES2 is a lognormal probability plot comparing the log of the fuel specific CO emissions in gCO/kg of fuel (top panel) for the 1989 (red ▲) and 2018 (blue ●) Long Beach Blvd.

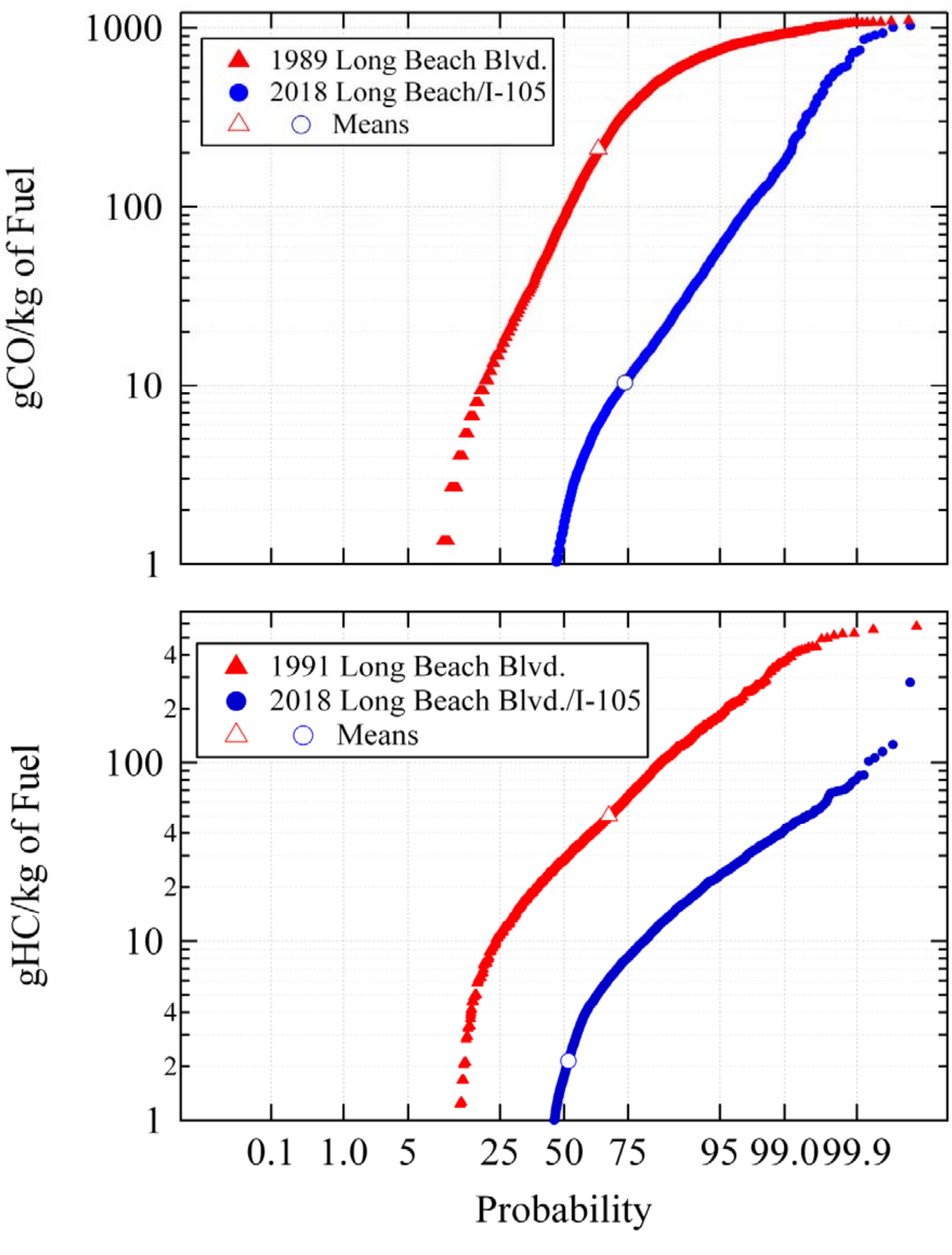

Figure ES2. Lognormal probability plots comparing the fuel specific CO emission distributions for the 1989 (red ▲) and 2018 (blue ●) measurements (top panel) and the fuel specific HC emission distributions for the 1991 (red ▲) and 2018 (blue ●) measurements (bottom panel) at the Long Beach Blvd. sites (bottom panel). Open symbols are the respective means for each distribution.

measurements against the probability for each measurement value occurring in the data set. The bottom panel compares the emission distributions for the fuel specific HC emissions in gHC/kg of fuel for the same sites but for the 1991 (red ▲) and 2018 (blue ●) measurements. These plots present the probability that a vehicle in the database will have a CO or HC emission rate that is less than or equal to the value on the y-axis. If the underlying data were from a lognormal distribution the data would plot as a straight diagonal line. The breaks present in the 1989 data occur because the CO measurements, which are recorded in percent space, were only recorded to two digits after the decimal point and the gaps correspond to the distance in gCO/kg of fuel space for a 0.01% change in %CO. For the 1991 HC measurements the readings were recorded to 0.001% values and the breaks, though still visible, are smaller.

The CO distributions for the 1989 and 2018 data sets converge to a similar value at or slightly above 1000 gCO/kg of fuel at the very top of the distribution that is above the 99.9th probability. The change, as a percent of the 1989 CO values, is reasonably constant between the 50th and the 95th probability level of a 95% reduction in fuel specific CO for the Long Beach Blvd. comparison. Above the 95th probability, the distributions converge and the percent reduction in emissions decreases. However, the age of the fleet at the top of the distribution is markedly different. The average age for the 99th percentile and above vehicles for the 1989 Long Beach Blvd. fleet was 13.7 (1976.6) years old while this groups age for the 2018 data is 21.7 (1997) or almost double the age. Differences in the fuel specific HC emissions for the two years show large reductions across all of the distribution, even for probabilities above the 99.9th probability line with the two distributions generally not converging. The ages of the vehicles above the 99th percentile for these data sets are 14.8 (1977) years old for the 1991 data and 10.4 years old for the 2018 measurements.

The mean fuel specific NH_3 emissions for the 2018 Lynwood I-105 measurements were ~30% higher (0.62 ± 0.01 versus 0.43 ± 0.03) than for the similar fleet measured at the I-710 site. This difference appears to be a result of the vehicles measured at the I-105 site being simply offset to a higher NH_3 emissions level than similarly aged vehicles measured at the I-710 site. Vehicle specific power (VSP) was higher at the I-105 site but NH_3 emissions at both sites are insensitive to VSP. Figure ES3 compares fuel specific NH_3 emissions by vehicle age from the two Lynwood data sets to the 2015 West Los Angeles data, which is the most recent publicly available data. Year 0 vehicles are represented by model year 2018 for the Lynwood sites and 2015 for the West Los Angeles site. The uncertainties plotted are standard error of the mean calculated from distributing the daily means for each year's model year data. The West Los Angeles measurement site is a traffic light controlled on-ramp to eastbound I-10 that is fed by traffic from southbound La Brea Ave., a traffic light controlled surface street. The 2018 Lynwood I-105 data generally follow the 2015 West Los Angeles measurements, especially for the first ~9 model years before falling consistently below the Wes Los Angeles data for the older model years.

Dynamometer studies have shown that decelerations followed by accelerations can increase the amounts of hydrogen stored on 3-way catalytic converters increasing its availability, a potentially limiting reagent in the reduction of NO to NH_3. One major difference between the Long Beach Blvd. and I-710 sites is the upstream traffic conditions. The I-105 site collects traffic off of a major surface street that is traffic light controlled at all of the major cross streets which

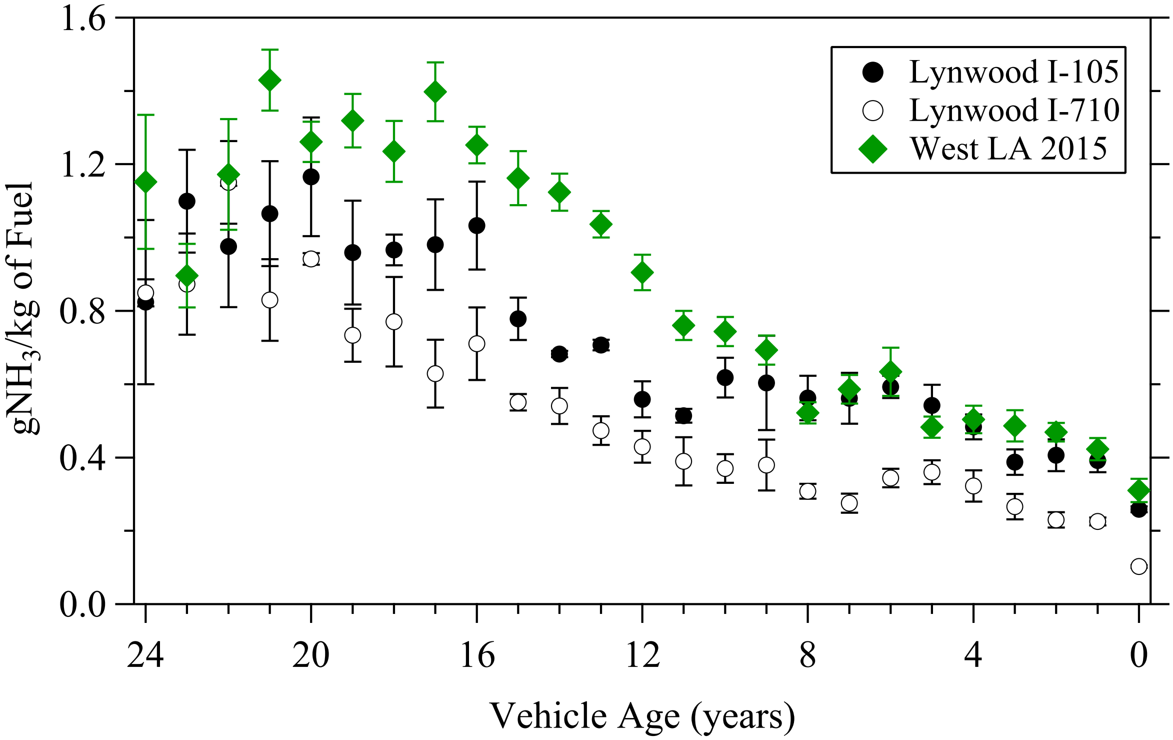

Figure ES3. Fuel specific NH_3 emissions plotted against vehicle age in years for the 2018 Lynwood I-105 (●), Lynwood I-710 (○) sites and the 2015 West Los Angeles (◆) data. Uncertainties are standard error of the mean calculated using the daily means. Zero year vehicles are model year 2018 for the Lynwood data and 2015 for the West Los Angeles data.

forces stop and go driving by these vehicles before they reach the on-ramp. The I-710 location samples vehicles coming directly from the freeway and while stop and go freeway traffic is common on LA freeways it is not as regular as traffic lights on Long Beach Blvd. The model year NH_3 emission differences between the two sites may reflect the consequences of the upstream driving patterns at the two sites and that stop and go driving along Long Beach Blvd. provides more hydrogen for NO reduction.

Total fixed nitrogen emissions from the gasoline fleet have been on a steep decline since the mid-nineties and are continuing to show decreases in the newest model years in the Lynwood data as well. However, the two Lynwood sites show that the percent of the remaining fixed nitrogen made up of NH_3 has continued to rise since the introduction of Lev II vehicles and is now the dominant reactive nitrogen species in exhaust. This is in contrast to the fleet observed in the 2017 Denver, CO measurements where the NH_3/NO_x ratios have leveled out and started declining with the newest model year vehicles and now favoring NO_x production. It is known that catalyst formulation, in regards to the amount and type of precious metals employed, can influence reduction (NH_3) or oxidation (NO_x) of the NO exhaust stream in addition to the control of the air to fuel ratio with slightly rich lambda settings producing NH_3 and slightly lean settings favoring NO_x formation. The differences observed in the NH_3/NO_x exhaust ratios in California and Colorado may be related to this fact or be influenced by driving mode differences.

INTRODUCTION

Since the early 1970's many heavily populated cities in the United States have been unable to comply with the National Air Quality Standards (NAAQS) that have been established by the Environmental Protection Agency (EPA) pursuant to the requirements of the Federal Clean Air Act.[1, 2] Carbon monoxide (CO) levels become elevated primarily due to direct emission of the gas. 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 and nitrogen dioxide (NO_2). 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]

The combustion of carbon-based fuels in the internal combustion engine is one of our primary means of transportation and a significant contributor of air pollutants covered by the NAAQS. For a description of the internal combustion engine and causes of pollutants in the exhaust, see Heywood.[4] Properly operating modern vehicles with three-way catalysts are capable of partially (or completely) converting engine-out CO, hydrocarbons (HC) and nitric oxide (NO) emissions to carbon dioxide (CO_2), water and nitrogen. Control measures to decrease mobile source emissions in non-attainment areas include inspection and maintenance (I/M) programs, reformulated and oxygenated fuel mandates, and transportation control measures, but the effectiveness of these measures are difficult to quantify. Many areas remain in non-attainment for ozone. The further reduction of the federal eight-hour ozone standards (first introduced by the EPA in 1997 and subsequently lowered in 2008 (75ppb) and again in 2015 (70ppb)) means that many new locations are likely to have difficulty meeting the standards in the future.[5]

In the summer of 1987 the University of Denver demonstrated the first vehicle exhaust remote sensor capable of measuring the CO/CO_2 ratio from the tailpipes of passing vehicles.[6] The instrument, dubbed the Fuel Efficiency Automobile Test or FEAT for short, was so named because the initial funding came from the Colorado Office of Energy Conservation and the program was aimed at finding high emitting CO vehicles, which after subsequent repairs, would not only have lower CO emissions but improved fuel economy. The capability to capture license plate images was added to the system in 1989 and the first out-of-state emission measurement campaigns were conducted in Chicago, IL during August and in Los Angeles, CA in December.[7-9] As part of the first Los Angeles campaign, emission measurements were collected at 4 locations in the Lynwood, CA area in addition to other sites within the basin. Lynwood was targeted because at the time the air quality sensor with the most basin violations for CO was located on Long Beach Blvd. just south of the Lynwood area. A follow-up Los Angeles measurement campaign was conducted in the summer of 1991 with a third generation FEAT instrument that added the capabilities to measure the HC/CO_2 ratio in vehicle exhaust and the Lynwood site on Long Beach Blvd. was revisited for a day of measurements.[10, 11]

Both the 1989 and 1991 measurements in the Lynwood area found a vehicle fleet that was significantly higher emitting and older than those at other sites visited within the basin. Table 1 provides a summary of the measurements collected during the 1989 and 1991 campaigns at the various sites around the LA basin. The 1991 measurements utilized the 3rd generation of the FEAT exhaust measurement system and included measurements for tailpipe HC. Speed and acceleration values were not yet measured. The locations sampled in the Lynwood, CA area have been shaded to highlight them. The Lynwood area fleet was found to have the highest CO and HC emissions along with the oldest vehicles (7.9 – 10.1 years old) among the sites surveyed.

Table 1. Summary for 1989 and 1991 Los Angeles Basin measurements.

Location / Year	Measurements	Mean gCO/kg of Fuel	Mean gHC/kg of Fuel	Mean Model Year[a] / Fleet Age[b]
La Cienega Blvd / 1989	1,790	117.9	N.A.	1983.8 / 6.5
Willow - Katella / 1989	1,367	83.8	N.A.	1984.6 / 5.7
Imperial Highway / 1989	1,056	176.2	N.A.	1981.8 / 8.5
SB I-710 Imperial / 1989	2,147	167.8	N.A.	1983.4 / 6.9
NB I-710 Imperial / 1989	2,937	120.2	N.A.	1982.9 / 7.4
Long Beach Blvd / 1989	7,160	210	N.A.	1980.6 / 9.7
Long Beach Blvd / 1991	1,807	191.9	50.3	1981.7 / 10.1
Beach Blvd - I-405 / 1991	9,198	82.7	16.8	1985.8 / 6.0
Broadway - I-10 / 1991	5,601	89.2	29.6	1985.9 / 5.9
Peck Rd - I-10 / 1991	5,156	111.3	30.1	1984.2 / 7.6
Rosemead Blvd / 1991	47,622	92.2	27.6	1984.8 / 7.0
Vermont Ave - I-10 / 1991	5,918	132.0	34.4	1984.4 / 7.4

[a] All values calculated excluding missing model years.
[b] Fleet age calculated assuming new model year starts on September 1.
Lynwood measurement locations are shaded.

The fleet age found at the Lynwood area sites was indicative of a lower income area. Using Census data and the zip code of owner registration from the 1991 measurements collected on Long Beach Blvd. the median household income for this sample is approximately $29,000 in 1989 dollars. For comparison, median household incomes for Los Angeles County and the state of California in 1989 were $35,000 and $36,000 respectively. Figure 1 plots mean fuel specific emissions for CO (left axis), HC and NO (right axis) for measurements collected by the University of Denver at sites within the South Coast Air Basin. Uncertainties plotted are standard error of the mean calculated using the daily averages (see Appendix A). The points labeled "LA Basin" are from the multiple sites sampled within the basin (refer to Table 1). The Riverside site was located at the freeway interchange ramp from NB 91 to WB 60 and the West Los Angeles site is located on the on-ramp from SB La Brea Ave. to EB I-10. These last two locations were originally chosen as a part of the CRC E-23 program.

Figure 1 shows large and consistent reductions for all three species at the West LA site, which has the longest record for measurements, and mirrors reductions that have been observed at other

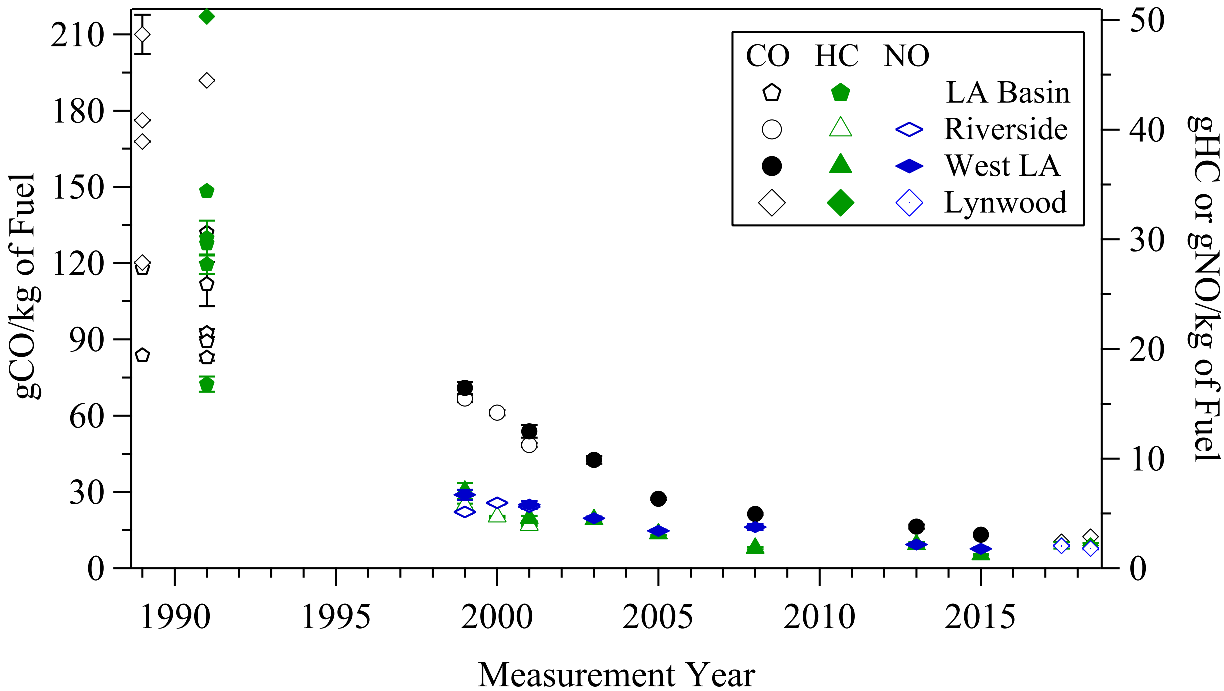

Figure 1. Historical fuel specific CO (left axis), HC and NO (right axis) emissions collected in the South Coast Air Basin. LA Basin measurements were collected at a variety of sites within the basin while the Riverside measurements were collected on the interchange ramp from NB 91 to WB 60 and the West LA data were collected at the on-ramp from SB La Brea Ave. to EB I-10. The 2018 Lynwood measurement years have been offset a half-year for the Long Beach Blvd. (2017.5) and I-710 (2018.5) sites to improve visibility. Uncertainties are standard error of the mean calculated using the daily means.

locations across the U.S.[12, 13] The very high average mean CO and HC emissions found in the Lynwood, CA area in 1989 and 1991 provides a baseline and an opportunity to investigate how fleet emission levels have changed in a lower economic area over the last 29 years. To accomplish this task two sites for measurements were selected within the Lynwood, CA area and revisited in 2018. One along Long Beach Blvd., near the location of the sites used in 1989 and 1991, and the second at the same I-710 off-ramp location used for the 1989 measurements.

MATERIALS AND METHODS

The FEAT 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.[14-16] The instrument consists of a non-dispersive infrared (NDIR) component for detecting CO, CO_2, and HC, and twin dispersive ultraviolet (UV) spectrometers for measuring oxides of nitrogen (NO and NO_2), SO_2 and NH_3 (0.26 nm/diode resolution). The source and detector units are positioned on opposite sides of the road in a bi-static arrangement. Collinear beams of infrared (IR) and UV light are passed across the roadway into the IR detection unit, and are then focused through a dichroic beam splitter, which serves to separate the beams into their IR and UV components. The IR light is then passed onto a spinning polygon mirror, which spreads the light across the four infrared detectors: CO, CO_2, HC and reference.

The UV light is reflected from the surface of the dichroic mirror and is focused onto the end of a quartz fiber bundle that is mounted to a coaxial connector on the side of the detector unit. The quartz fiber bundle is divided in half 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 while continuing 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 only measures NO_2 via an absorbance band at 438nm in the UV spectrum and comparing it to a calibration spectrum in the same region.[17] Since the removal of sulfur from gasoline and diesel fuel in the U.S., tailpipe SO_2 emissions have become negligibly small. As such, while SO_2 measurements were collected as a part of this study, they will not be reported or discussed because the sensor was not calibrated for SO_2 emissions.

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, engine size, 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 as demonstrated by Singer et al.[18] To calculate mass emissions as described below, the %HC values reported first have to be multiplied by 2.0 to account for these "unseen" hydrocarbons as shown below, assuming that the fuel used is regular gasoline. These percent emissions can be directly converted into mass emissions by the equations shown below.

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

These equations show that the relationships between emission concentrations and mass emissions are: (a) linear for NO_2 and NH_3, (b) nearly linear for CO and NO and (c) linear 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 emitted is close to 100% NO in the case of gasoline fueled vehicles.

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

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

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 (this translates to 860 gC/kg of 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.[18]

$$\text{gm CO/kg} = (28Q^{CO} / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \qquad (3a)$$
$$\text{gm HC/kg} = (2(44Q^{HC}) / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \qquad (3b)$$
$$\text{gm NO/kg} = (30Q^{NO} / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \qquad (3c)$$
$$\text{gm NH}_3\text{/kg} = (17Q^{NH3} / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \qquad (3d)$$
$$\text{gm NO}_2\text{/kg} = (46Q^{NO2} / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \qquad (3e)$$

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 in nitrogen, the second contains NH_3 and propane and the final cylinder contains NO_2 and CO_2 in air. 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 and PraxAir). These calibrations adjust 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.

Double blind 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 correct to within ±5% of the values reported by an on-board gas analyzer, and within ±15% for HC.[8, 19] The NO channel used in this study has been extensively tested by the University of Denver, but has not been subjected to an extensive double 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.[15] 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.[20] Appendix B gives a list of criteria for determining data validity.

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 two parallel 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 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 C defines the database format used for the data sets.

SAMPLING LOCATIONS

In December of 1989 the University of Denver collected the first on-road vehicle emission measurements in California at 6 different location in the South Coast Air Basin with 4 of those location located in the Lynwood, CA area.[8, 9] Figure 2 shows a current satellite image of Lynwood, CA with the four 1989 sampling locations marked. Site 1 was on Long Beach Blvd. near Norton Ave. Site 2 was located on the inside lane of the Imperial Highway just west of Long Beach Blvd. Sites 3 and 4 were located at the interchange of the Imperial Highway and the I-710 freeway with site 3 monitoring traffic downstream of the on-ramps from east and westbound Imperial Highway and site 4 was on the off-ramp from northbound I-710 to westbound Imperial Highway. Site 1 was also revisited in a 1991 study.[10]

For the follow up Lynwood, CA. measurements 29 years later in the spring of 2018 the desire was to repeat the measurements obtained at sites 1 and 4. Site 1 was on Long Beach Blvd. and was 2 lanes in 1989 and 1991 but in 2018 is now 3 lanes with large concrete planter medians installed between the south and northbound lanes making a safe remote sensing installation unlikely. Still desiring to monitor vehicles using Long Beach Blvd. it was decided to use the on-ramp from Long Beach Blvd. to eastbound I-105, which was constructed after the 1991 measurements. This would still allow vehicles using southbound Long Beach Blvd. to be monitored and was only 6 or 7 blocks south of the original site. Site 4, the off-ramp from northbound I-710 to westbound Imperial Highway, was still a single lane ramp enabling measurements for that location to be collected in the identical location used in 1989. Figure 3 shows a satellite image of the Los Angeles Basin with the two 2018 Lynwood sampling locations marked along with the location of the long-term sampling location in West Los Angeles for comparison.

Figure 4 is a satellite image showing the location of the Lynwood I-105 sampling location with a white arrow marking the approximate location of the remote sensing equipment. This site is a two-lane on-ramp with the outside lane being designated as a High Occupancy Vehicle (HOV) lane. Figure 5 is a photograph of the site with the equipment installed. Only emission measurements of vehicles using the inside lane of this ramp are included in the final database.

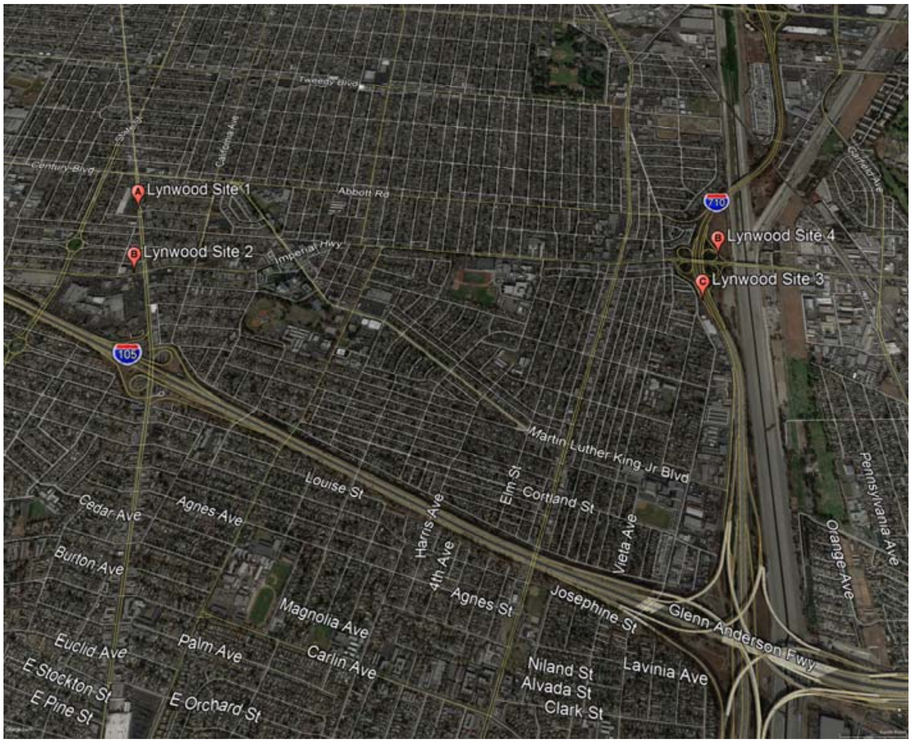

Figure 2. Satellite image of the Lynwood, CA area showing the locations of the sampling sites first used in the 1989 emission measurements.

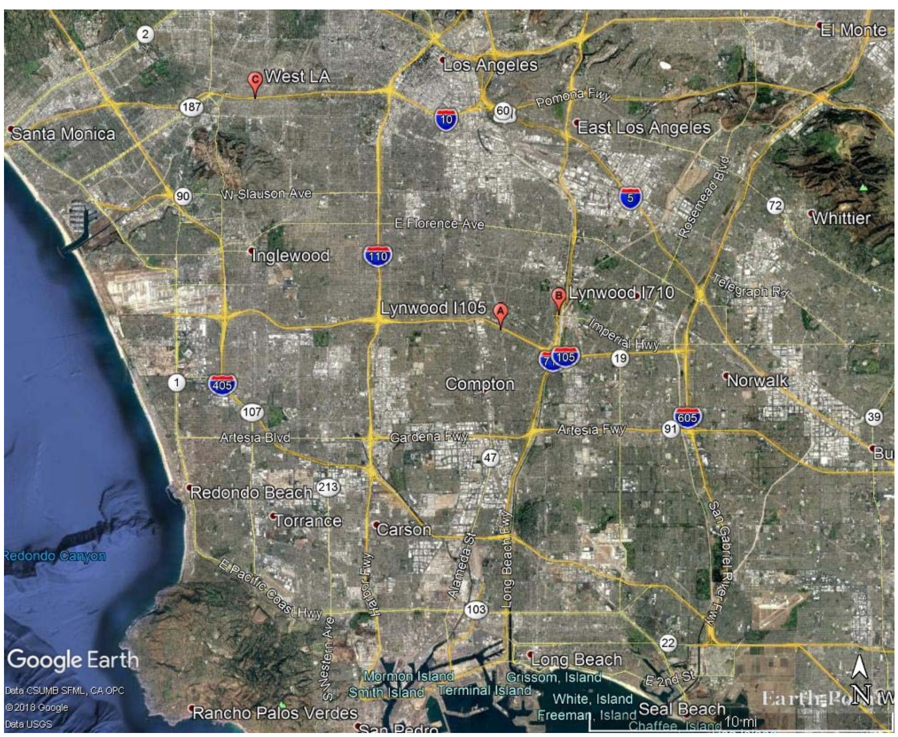

Figure 3. A satellite image of the Los Angeles basin with the location of the vehicle emission sampling sites for the Lynwood I-105 (site A), Lynwood I-710 (site B) and for comparison the West LA site (site C) and their relative locations within the basin.

Figure 4. Satellite image showing the location of the Lynwood I-105 emissions sampling site (arrow) located on the on-ramp from southbound Long Beach Blvd. to eastbound I-105 in Lynwood, CA.


Figure 5. Photograph of the remote sensing setup at the Lynwood I-105 sampling site. Measurements were only collected on the inside (non-HOV) lane.

Figure 6 is a satellite image showing the location of the Lynwood I-710 site within the Imperial Highway / I-710 interchange. Figure 7 is a photograph of the site with the equipment installed which is located in the identical location of the measurements collected at this site in 1989. This location was featured on the cover of the Journal of the Air & Waste Management Association (see Figure 8) detailing those first measurements and showing FEAT 1 located at the end of the concrete barrier as the current instrument was during the 2018 measurements.

RESULTS AND DISCUSSION

Measurements were made on three consecutive days at each of the two Lynwood sites. Measurements were collected between Monday May 7 through Wednesday May 9, 2018 between the hours of 8:00 and 17:30 on the on-ramp from southbound Long Beach Blvd. to eastbound I-105 (refer to Figures 3 and 4-5). This was followed with three additional days of measurements being collected between Thursday May 10 to Saturday May 12, 2018 also between the hours of 8:00 and 17:30 on the off-ramp from northbound I-710 to westbound Imperial Highway (refer to Figure 3 and 6-7).

The digital video images of the license plates were subsequently transcribed for license plate identification. California license plates were transcribed and submitted to the California Air Resources Board for matching against registration records for all non-personal vehicle information. The 2018 database for the Lynwood I-105 site contains 7,724 records with make and model year information and valid measurements for at least CO and CO_2. Most of these records also contain valid measurements for HC, NO, NH_3 and NO_2.

The validity of the attempted measurements from the I-105 site is summarized in Table 2. 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 closely following vehicle, that 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 absent (elevated, electric/hybrid engine off operation or rapid deceleration from foot off the throttle), or the reported error in the ratio of the pollutant to CO_2 exceeds a preset limit (see Appendix B). Additional data losses occur during the plate reading process, when out-of-state vehicles, vehicles with unreadable plates (obscured, missing, dealer placards, out of camera field of view) are omitted from the database. This step represents the largest loss of measurements as dealer placards and out of field of view among other factors combine to result in a more than 30% loss of data at the California sites. For example, California allows drivers to display dealer placards in lieu of a temporary license plate. We coded for these placards on 2 days at each site and found that they represented between 3.6 and 4.2% of a day's valid measurements and therefore accounted for a little more than a third of the unreadable plates. In addition at the Lynwood I-105 site, the measurement attempts included vehicles in the HOV lane, either by themselves or in combination with a vehicle in the inside lane, both

Figure 6. Satellite image showing the location of the Lynwood I-710 emissions sampling site (arrow) located on the off-ramp from northbound I-710 to westbound Imperial Hwy. in Lynwood, CA.

Figure 7. Photograph of the remote sensing setup at the Lynwood I-710 sampling site with the new and improved Winnie.

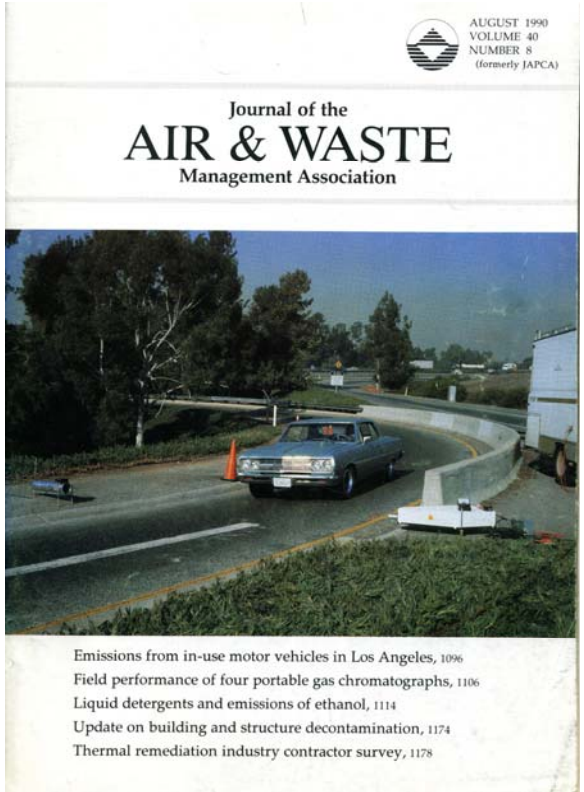

Figure 8. Cover of the August 1990 edition of the Journal of the Air & Waste Management Association showing FEAT 1 setup on the off-ramp from northbound I-710 to westbound Imperial Highway in 1989. If you compare this with Figure 7 you will notice that FEAT and the original Winnie are located in nearly identical locations.

Table 2. Validity summary for the Lynwood I-105 site.

	CO	HC	NO	NH_3	NO_2
Attempted Measurements	13,218				
Valid Measurements	11,772	11,650	11,771	11,754	11,712
Percent of Attempts	89.1%	88.1%	89.1%	88.9%	88.6%
Submitted Plates	7,880	7,804	7,879	7,872	7,847
Percent of Attempts	59.6%	59.0%	59.6%	59.6%	59.4%
Percent of Valid Measurements	67.0%	67.0%	67.0%	67.0%	67.0%
Matched Plates	7,724	7,649	7,723	7,717	7,691
Percent of Attempts	58.4%	57.9%	58.4%	58.4%	58.2%
Percent of Valid Measurements	65.6%	65.7%	65.6%	65.7%	65.7%
Percent of Submitted Plates	98.0%	98.0%	98.0%	98.0%	98.0%

instances were excluded during the plate matching process.

The 2018 database for the Lynwood I-710 site contains 14,302 records with make and model year information and valid measurements for at least CO and CO_2. The validity of the attempted measurements from this site is summarized in Table 3. These databases and all of the previous databases compiled for the CRC E-23 and E-106 campaigns can be found at www.feat.biochem.du.edu.

Table 3. Validity summary for the Lynwood I-710 site.

	CO	HC	NO	NH_3	NO_2
Attempted Measurements	21,050				
Valid Measurements	18,960	18,890	18,957	18,949	18,933
Percent of Attempts	90.1%	89.7%	90.1%	90.0%	89.9%
Submitted Plates	14,531	14,477	14,529	14,522	14,514
Percent of Attempts	69.0%	68.8%	69.0%	69.0%	69.0%
Percent of Valid Measurements	76.6%	76.6%	76.6%	76.6%	76.7%
Matched Plates	14,302	14,248	14,300	14,293	14,286
Percent of Attempts	67.9%	67.7%	67.9%	67.9%	67.9%
Percent of Valid Measurements	75.4%	75.4%	75.4%	75.4%	75.4%
Percent of Submitted Plates	98.4%	98.4%	98.4%	98.4%	98.4%

Plate capture rates were down at the I-105 site (7^{th} row of Table 2 and 3, I-105 ~67% of valid measurements and I-710 ~77% of valid measurements) with the difference reflecting the number of vehicles omitted due to the second lane at the I-105 site. As at the Long Beach Blvd. / I-105 site a similar number of dealer placarded vehicles were found on the I-710 ramp accounting for 10 to 12% of the valid measurements.

Table 4 provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured for the two Lynwood sites. Of the 7,724 records collected at the Lynwood I-105 site, 5,968 (77.3%) were contributed by vehicles measured only once, and the remaining 1,756 (22.7%) records were from vehicles measured at least twice. At the I-710 location a slightly higher number of repeat measurements were collected with 10,557 (73.8%) of the measurements contributed by vehicles measured only once and the remaining 3,745 (26.2%) contributed by vehicles measured at least twice.

Table 4. Number of measurements of repeat vehicles the two Lynwood sites.

Number of Times Measured	Number of Vehicles Lynwood I-105	Number of Vehicles Lynwood I-710
1	5,968	10,557
2	650	1,459
3	144	223
4	3	30
5	1	5
6+	1	2

Table 5 summarizes and compares the measurements collected at the two Lynwood sites. The average HC values have been adjusted individually for each site in this comparison 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 and that the median of these group's emissions distribution should be very close to zero but not negative. The lowest of either of these values is then chosen as the offset. The offset adjustment is subtracted (Lynwood I-710) or added (Lynwood I-105) to the individual hydrocarbon measurements. This normalizes each data set to a similar emissions zero point since it is assumed that the cleanest vehicles emit few hydrocarbons. Such an approximation will err only 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 adjustments have been performed where indicated in the analyses in this report and a detailed example of the calculation procedure is included in Appendix E.

The mean emission levels observed at the two sites are in general quite similar. The Lynwood I-710 fleet is slightly older (10.3 vs 10.1 years) but supports the idea that both sites are collecting a sample from the same parent population of vehicles. The Lynwood I-105 fleet does show slightly higher NO and NH_3 emissions than the fleet observed at the I-710 site, though median NO emissions are similar between the two locations. There were a few more diesel vehicles (1.7 vs 1.4% of the records) observed at the Lynwood I-105 site which may contribute to the increase in NO emissions but would work against the increased NH_3 emissions. Speeds are higher at the I-105 site as there is significantly more congestion at the I-710 site. Congestion at the I-105 site is regulated by a number of upstream traffic lights that control the vehicle flow along Long Beach Blvd and limit the number of vehicles reaching the on-ramp at a given time.

Fuel specific emissions of CO (top panel), HC (middle panel) and NO (bottom panel) versus model year are plotted for the two sites in Figure 9. Uncertainties are standard error of the mean calculated using the daily means. The HC data have been offset adjusted here for the comparison. When the measurements are aggregated by individual model year, there is increased uncertainty in the data, especially for the HC measurements due to the smaller number of records for each model year group. In addition, an increase in the measurement noise on the HC channel at the Lynwood I-105 site that is also a contributor. For some unexplained reason this instrument channel noise was a factor of three larger than normal and will be discussed later.

Table 5 also shows slightly higher mean CO emissions for the I-710 site compared to the I-105 location and the top panel in Figure 9 shows that this likely results from the differences in the newer model year vehicles that peak in model year 2014. Mean emission for HC were similar between the two sites and the significant noise observed in the model year measurements (middle panel) limit any additional conclusions. The Lynwood I-105 site had slightly higher mean NO emissions when compared with the I-710 site and the bottom panel shows that those differences appear to be in the older (pre-2005) model year vehicles.

Table 5. 2018 Lynwood Campaign Data Summary.

Study Year	Lynwood I-105	Lynwood I-710
Mean CO (%) (g/kg of fuel)	0.08 10.4	0.1 12.3
Median CO (%)	0.01	0.02
99th Percentile Contribution	41.2%	36.6%
Mean HC (ppm)[a] (g/kg of fuel)[a] Offset (ppm)	56 2.1 (-23)	52 2.0 (13)
Median HC (ppm)[a]	42	38
99th Percentile Contribution	29.6%	27.7%
Mean NO (ppm) (g/kg of fuel)	145 2.0	122 1.7
Median NO (ppm)	7.5	7.3
99th Percentile Contribution	24%	25.6%
Mean NH_3 (ppm) (g/kg of fuel)	77 0.62	54 0.43
Median NH_3 (ppm)	32	15
99th Percentile Contribution	11%	14.4%
Mean NO_2 (ppm) (g/kg of fuel)	1.3 0.03	1.6 0.03
Median NO_2 (ppm)	0.5	0.5
99th Percentile Contribution	75.5%	73.2%
Mean Model Year	2008.6	2008.4
Mean Fleet Age[b]	10.1	10.3
Mean Speed (mph)	25.9	20.3
Mean Acceleration (mph/s)	0.03	-0.7
Mean VSP (kw/tonne) Slope (degrees)	9.2 3.1°	3.9 3.4°

[a]Indicates values that have been HC offset adjusted as described in text.
[b]Assumes new vehicle model year starts September 1.

Following the data analysis and presentation format originally shown by Ashbaugh et al.,[21] the vehicle emissions data by model year for the two Lynwood sites were divided into quintiles and plotted. The results are shown in Figures 10 – 13 for the I-105 site and Figures 14 – 16 for the I-710 site. The bars in the top plot represent the mean emissions for each model year's quintile, but do not account for the number of vehicles in each model year. The middle graph shows the fleet fraction by model year for the newest 22 model years and illustrates the impacts of the last recession on car sales between 2009 and 2011 and the subsequent economic recovery. Model

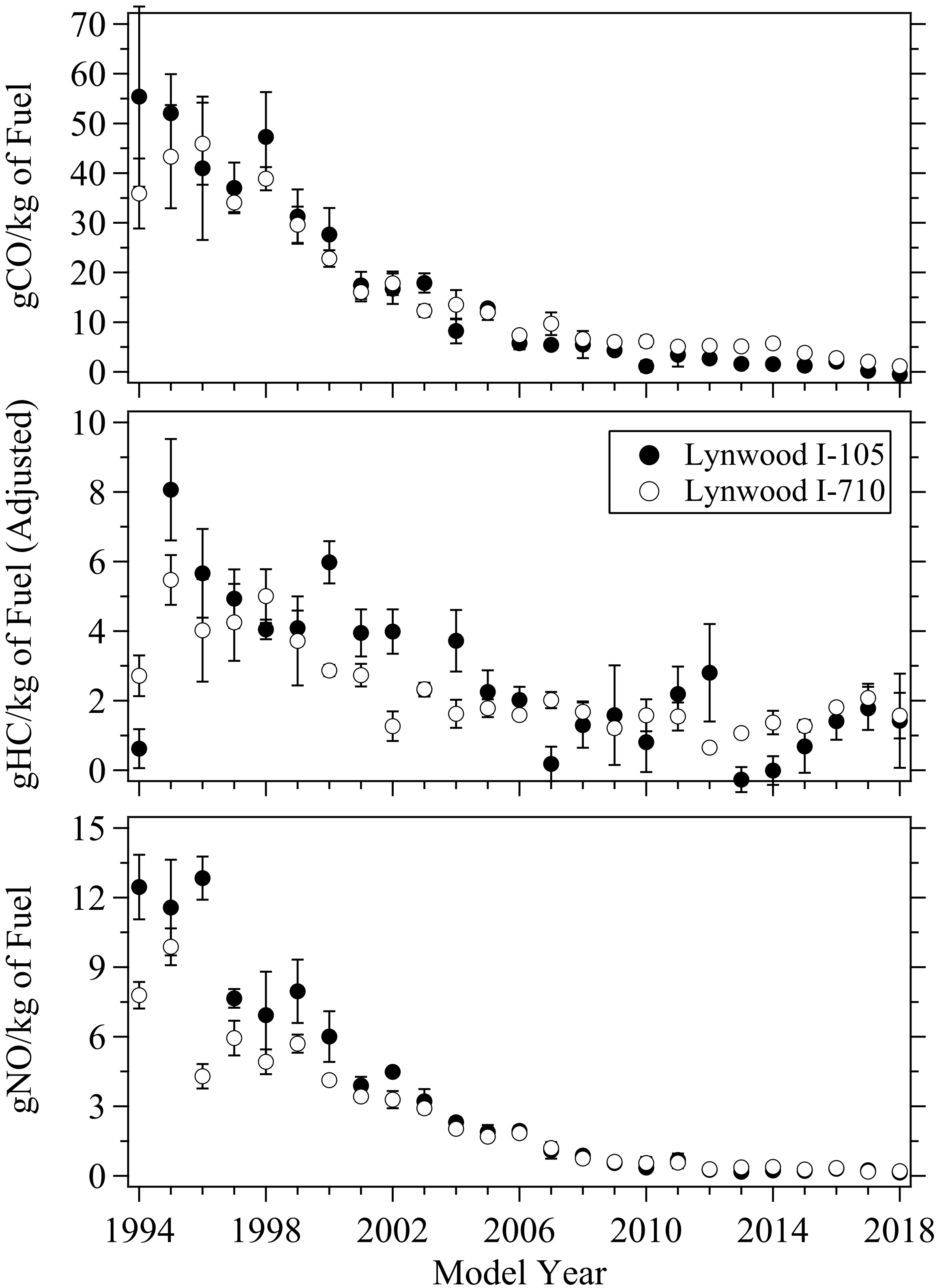

Figure 9. Fuel specific CO (top panel), HC (middle panel) and NO (bottom panel) emissions by model year for the Lynwood I-105 (●) and I-710 (○) sites. Uncertainties are standard error of the mean calculated using the daily means.

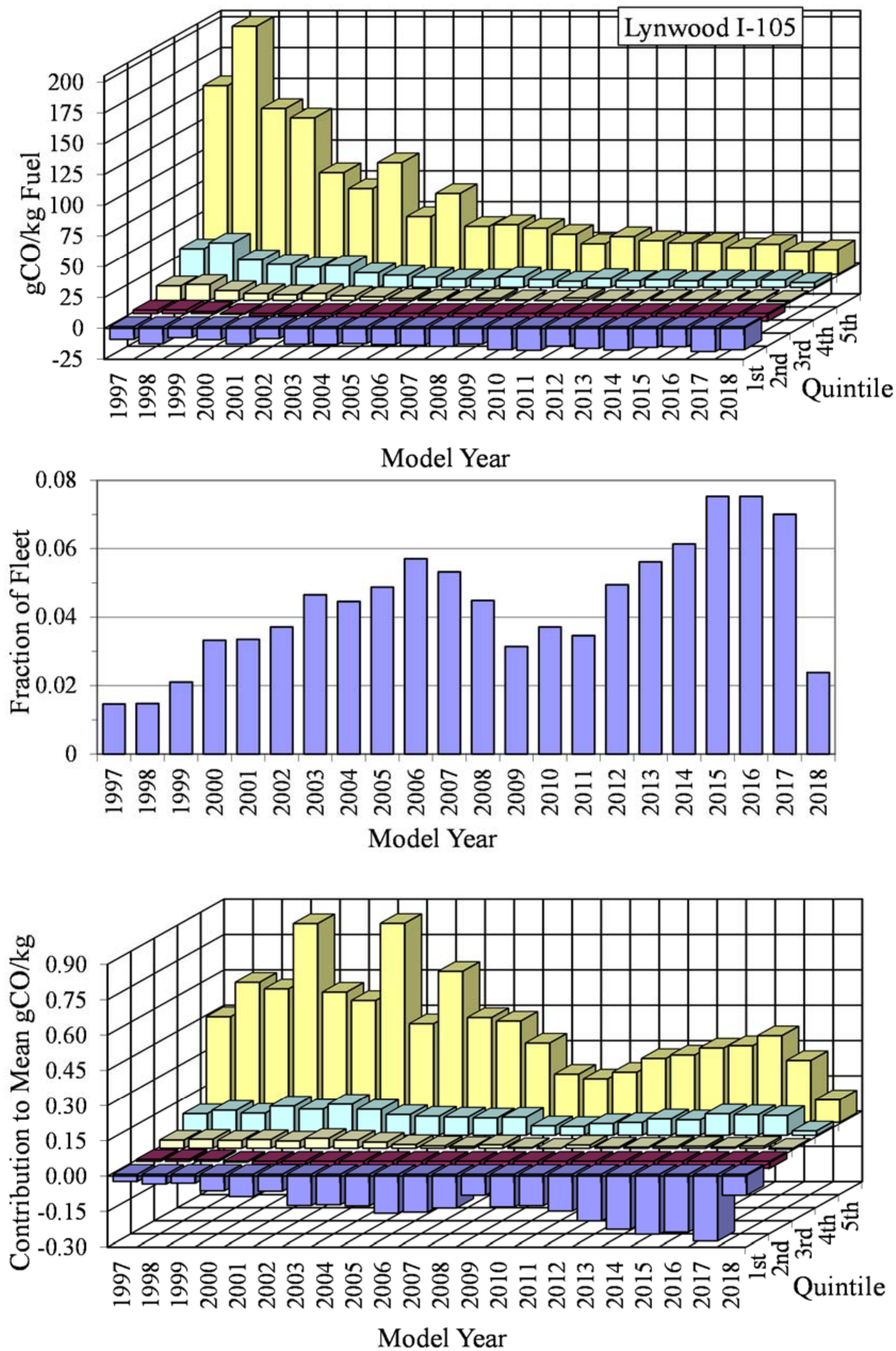

Figure 10. Mean gCO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gCO/kg of fuel emissions (10.4 ± 0.4) by model year and quintile (bottom) for the Lynwood I-105 site.

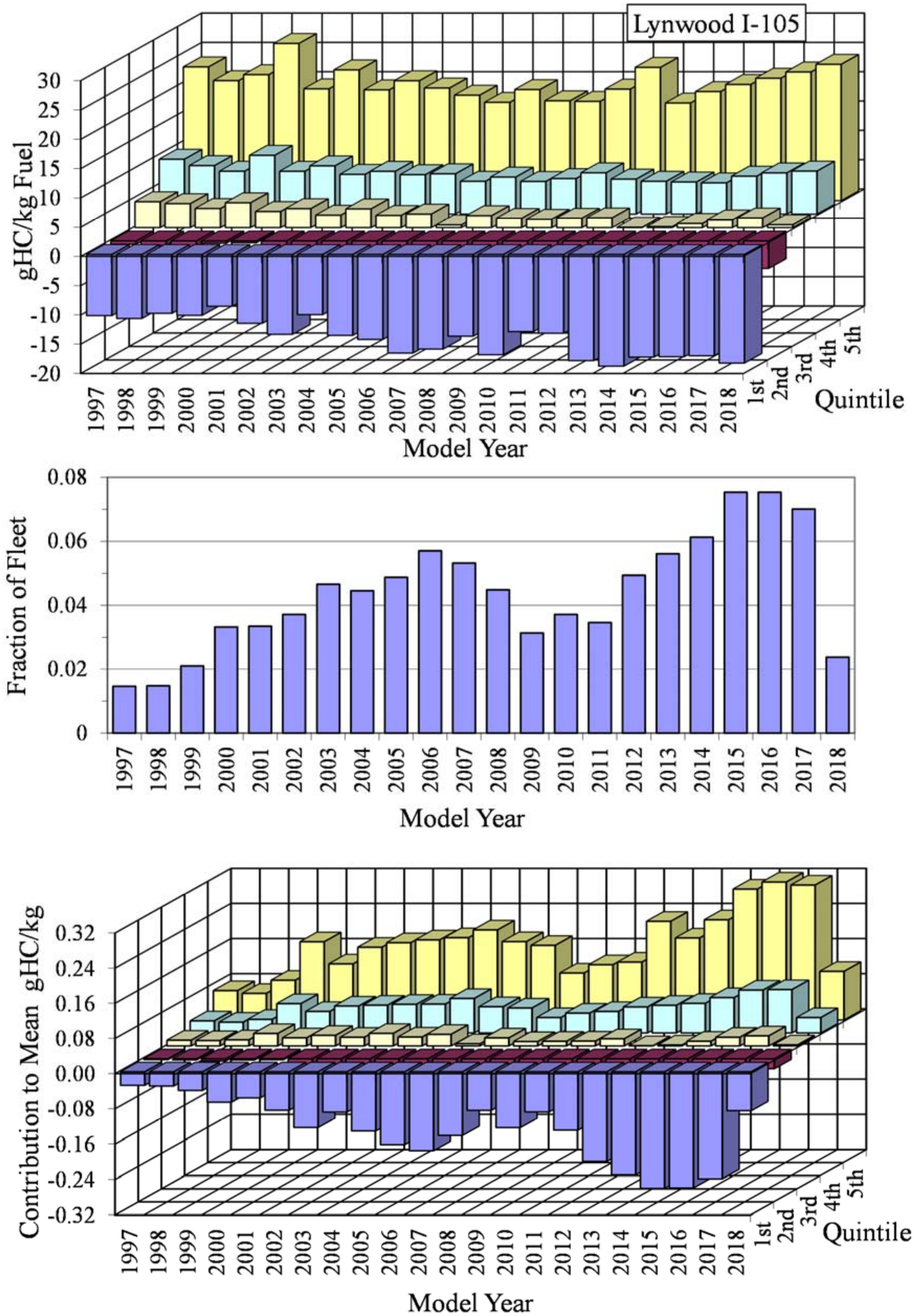

Figure 11. Mean gHC/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gHC/kg of fuel emissions (2.1 ± 0.3) by model year and quintile (bottom) for the Lynwood I-105 site.

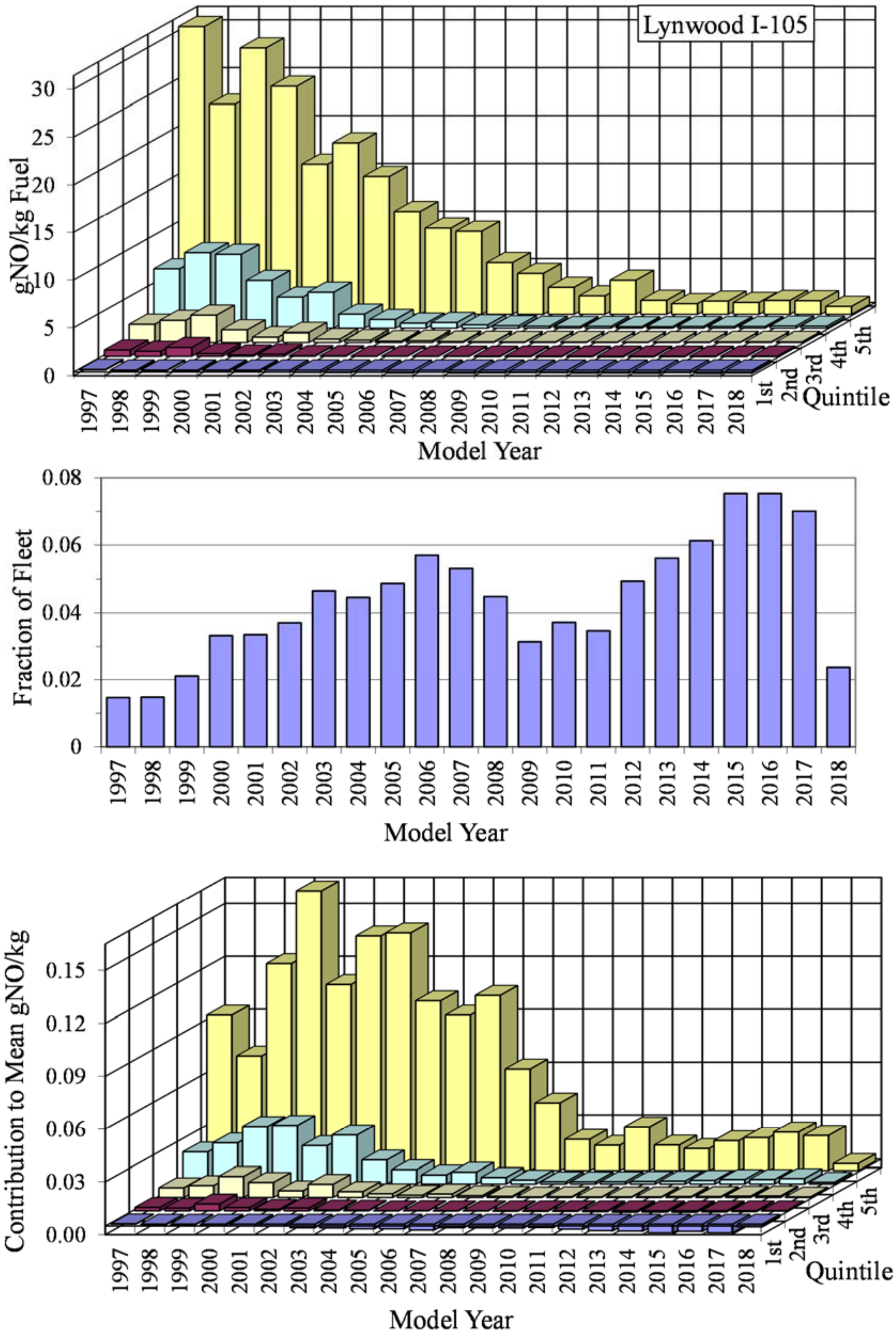

Figure 12. Mean gNO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gNO/kg of fuel emissions (2.28 ± 0.06) by model year and quintile (bottom) for the Lynwood I-105 site.

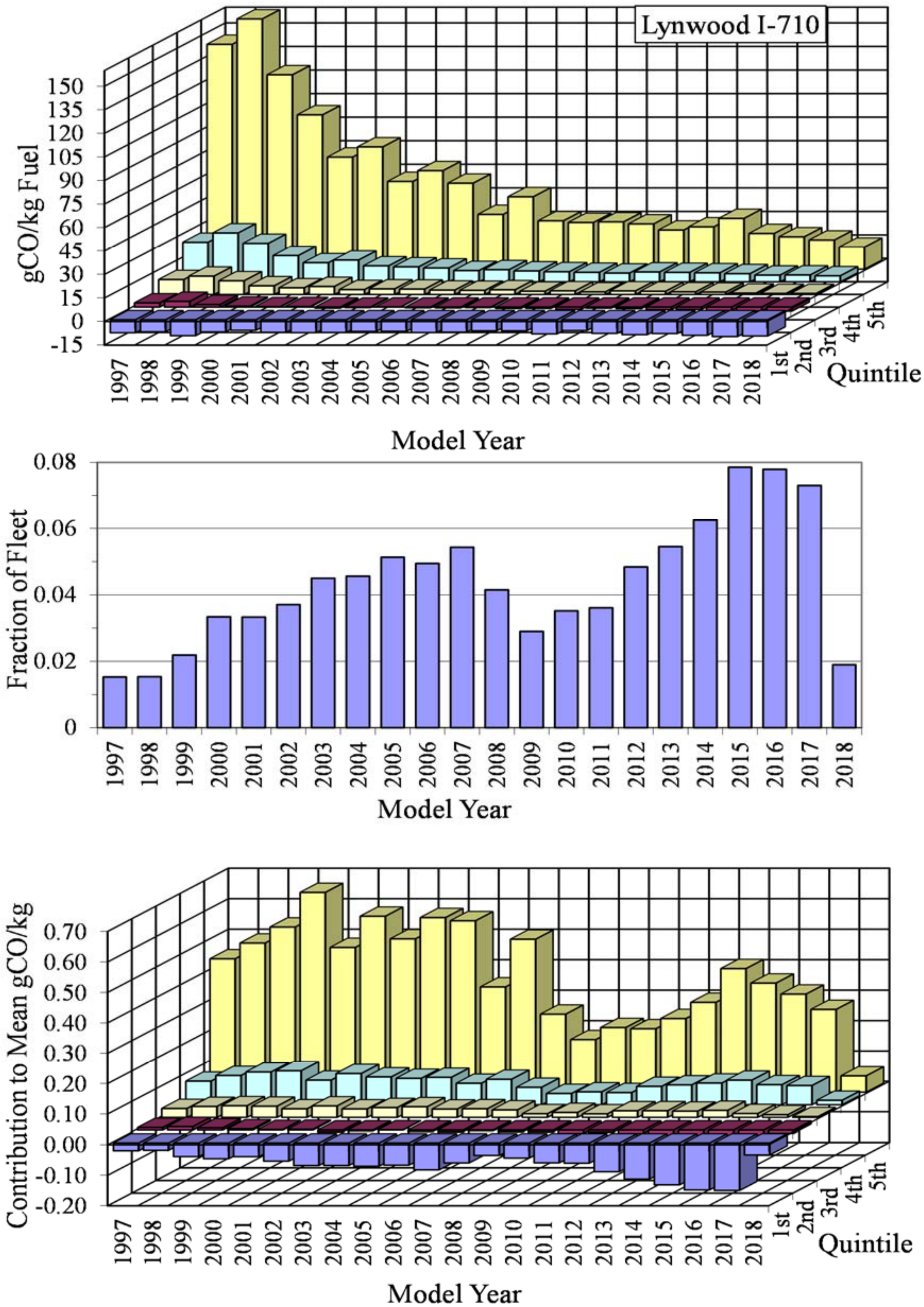

Figure 13. Mean gCO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gCO/kg of fuel emissions (12.4 ± 0.2) by model year and quintile (bottom) for the Lynwood I-710 site.

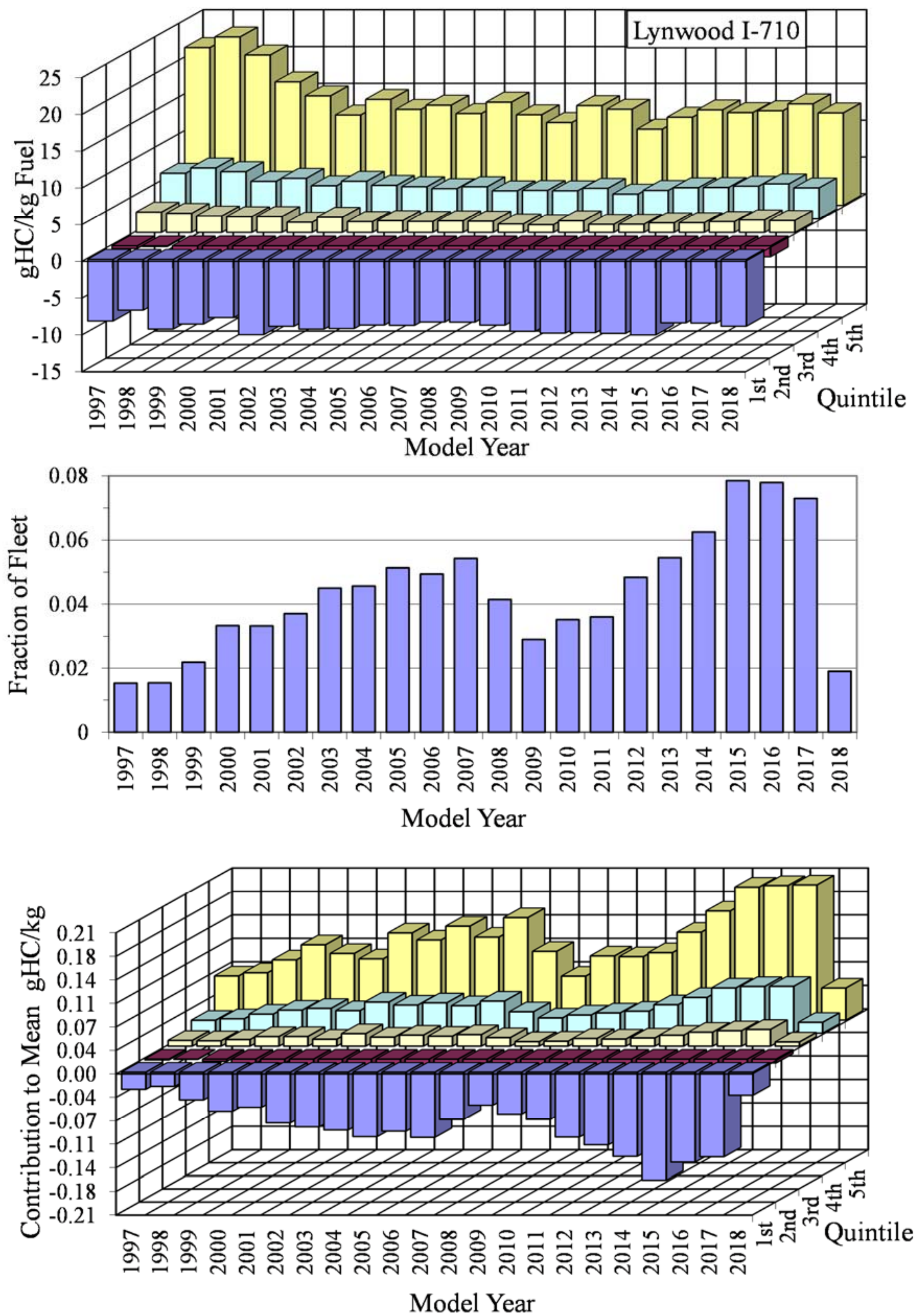

Figure 14. Mean gHC/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gHC/kg of fuel emissions (2.1 ± 0.2) by model year and quintile (bottom) for the Lynwood I-710 site.

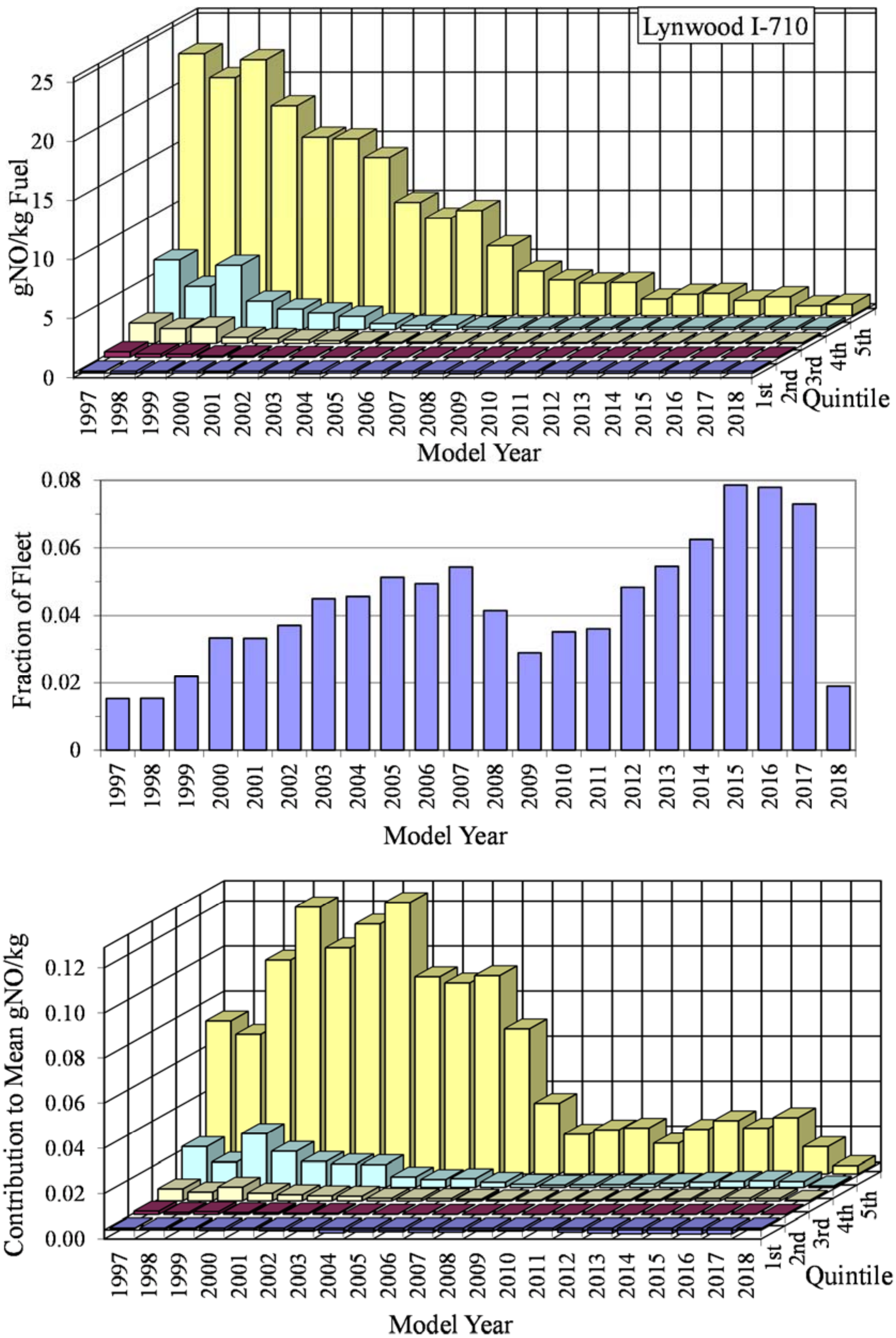

Figure 15. Mean gNO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gNO/kg of fuel emissions (1.79 ± 0.07) by model year and quintile (bottom) for the Lynwood I-710 site.

years older than 1997 and not graphed in Figures 10 -12 account for 3.6% of the measurements and contribute between 13.2% (HC) and 27.3% (CO) of the total emissions of the Lynwood I-105 data set. For the Lynwood I-710 site model years older than 1997 and not graphed in Figures 13-15 account for 4.3% of the measurements and contribute between 15.4% (HC) and 28.2% (CO) of the total emissions. The bottom graph for each species is the combination of the top and middle figures and shows the individual model year and quintile contribution to the fleet mean given in Table 5.

The middle graph in Figures 10 – 15 shows the fleet fractions by model year for the two Lynwood sites. The impact of the reduction in light-duty vehicle sales during the 2008 recession is still a prominent feature of these data sets.[22] At the West Los Angeles site the 2008 recession increased average fleet age from 7.4 years in 2008 to 8.9 years in 2015.[23] The two Lynwood fleets sampled are slightly more than a year older than observed in West Los Angeles (10.1 and 10.3 years at the I-105 and I-710 sites) which may still be tied to income differences.

There are only subtle differences between the magnitudes of the model year fleet fractions for the two Lynwood sites. The greater proportions of model year 2006 and 2018 vehicles at the I-105 site are the primary factors contributing to the 0.2 year lower average fleet age observed at this location. In comparison with a city such as Denver, the vehicle fleet impacts of the 2008 recession started sooner and recovered more slowly in Lynwood. This can be seen in the drop in the fraction of 2008 models and the recovery that did not begin in earnest until the 2012 model year. Figure 16 is a comparison between the fleet fractions observed at the Lynwood I-710 site and those observed in Denver in December 2017 and January 2018. The Denver fleet is 1.1 years younger on average with the largest differences occurring in model years 2008 and 2011 as the recession affected car sales later in Denver and then resumed sooner than in Lynwood.

The quintile plots in Figures 10 through 15 illustrate that the lowest emitting 60% of the on-road Lynwood fleet, regardless of model year, make an essentially negligible contribution to the overall fleet mean emissions. The accumulations of negative emissions in the first two quintiles are the result of ever decreasing emission levels. Our instrument is designed such that when measuring true zero emission plumes (a ratio of zero), approximately half of the readings will be negative and half will be positive. As the lowest emitting segments of the fleets continue to trend toward zero emissions, the negative emission readings will continue to grow toward half of the measurements. This is evident for approximately the first 10 model years for HC (bottom panel Figures 11 and 14) where the negative height of the first quintile is generally equal to the positive height of the last quintile.

As emissions have been drastically reduced over the past two decades, generally the majority of the contributions to the overall means are found in the last or fifth quintile (as shown in the bottom graphs of Figures 10 - 15). For the two Lynwood sites the CO and HC contributions of the last quintile to the fleet mean emissions generally follows the pattern of the fleet fractions. The CO contributions for the model year vehicles that are older than 2008 outweigh their numbers as represented by fleet registration fractions by model year (middle panels) due to the influence of the increasing mean emission factors for these model years. The contributions of the last (fifth) quintile to the mean NO emissions generally follows the emission factor trends seen in

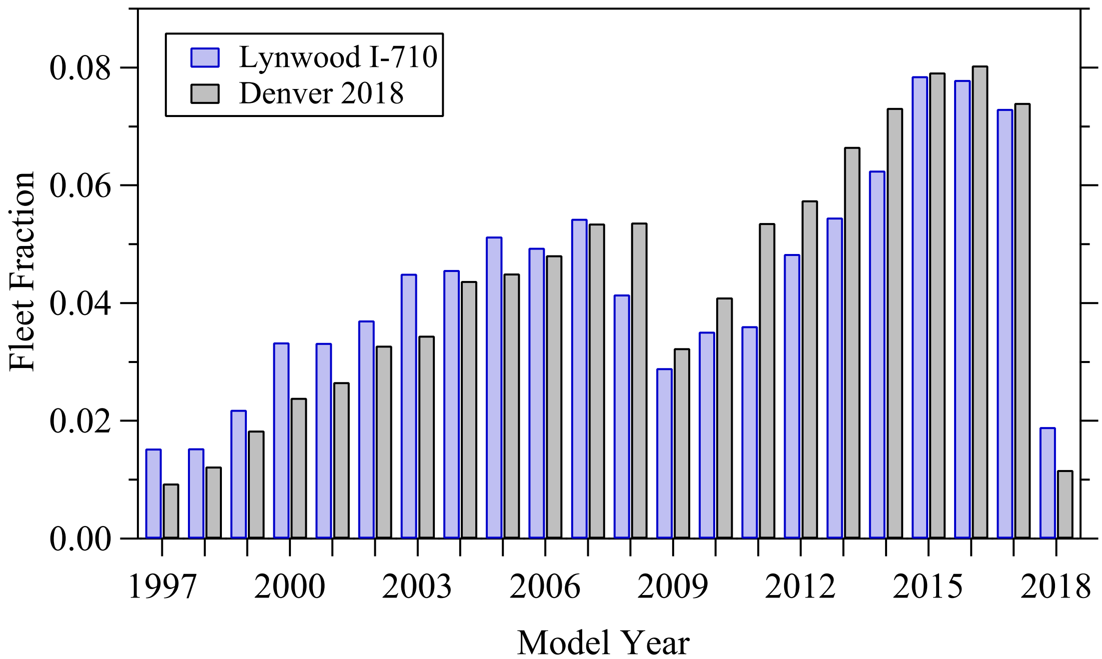

Figure 16. Fleet fraction versus model year comparison between the Lynwood I-710 fleet and the 2018 Denver fleet measured at the I-25 and 6th Avenue ramp.

the top panel. Consistently lower NO emissions from LEV II vehicles have shifted the bulk of the contributions to the mean to 2008 and older models (see the bottom graph of Figures 12 and 15).

An equation for determining the instantaneous power of an on-road vehicle by Jimenez takes the form

$$VSP = 4.39 \cdot \sin(slope) \cdot v + 0.22 \cdot v \cdot a + 0.0954 \cdot v + 0.0000272 \cdot v^3 \qquad (4)$$

where VSP is the vehicle specific power in KW/metric ton, *slope* is the slope of the roadway (in degrees), *v* is vehicle speed in mph, and *a* is vehicle acceleration in mph/s.[24] 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 equation 4, VSP was calculated for all measurements in the two Lynwood 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 graphed in Figure 17 for the Lynwood I-105 (●) and I-710 (○) sites. Each of the specific power bins contains at least 119 measurements, except for VSP bin 20 for the Lynwood I-710 site that only contains 88 measurements, and the HC data have been offset adjusted for this comparison. The uncertainty bars included in the plot are standard error of the mean calculated using the daily means (see Appendix A). The dashed (I-105 site) and solid (I-710 site) lines in the bottom graph are the frequency count distributions of vehicles in the two Lynwood datasets sorted by specific

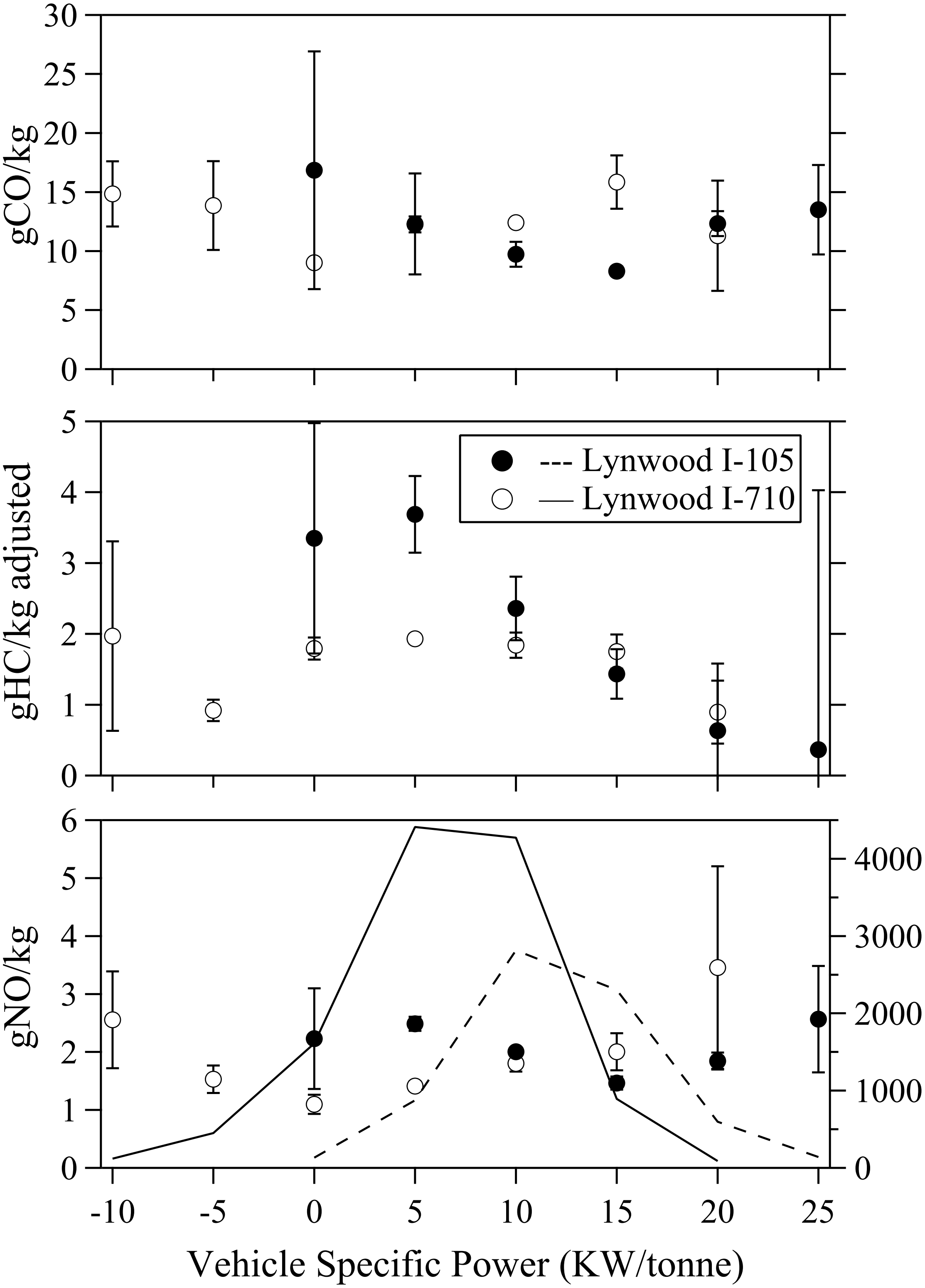

Figure 17. Fuel specific emissions for CO (top panel), HC (middle panel) and NO (bottom panel) as a function of vehicle specific power for the Lynwood I-105 (●) and Lynwood I-710 (○) data sets. Uncertainties plotted are standard error of the mean calculated using the daily samples. The solid (I-710) and dashed (I-105) lines in the bottom graph are the vehicle count profiles for the data sets.

power bin.

The smaller overall size of the two databases introduces more uncertainty when evaluating the overall VSP trends. The end points of all three plots at both sites suffer from higher uncertainties as indicated by the size of the uncertainty bars, especially for the HC data. The CO and NO trends versus VSP are generally flat across the load ranges observed that indicates little dependency of VSP on emissions. This result has been observed at other U.S. sites.[13] Keep in mind that the lack of an influence of VSP for CO and NO are for fuel specific emissions and is likely not the case for distance specific emissions as the fuel economy changes by a factor of 3 or more across the range of VSP's plotted. HC emissions at the I-105 site do show increasing emissions with decreasing VSP though the uncertainties expressed in the data points of that plot are significant. At the I-710 site the HC trend appears to follow the CO and NO trends with little influence of VSP on emissions.

While NH_3 is not a regulated pollutant, it is a necessary precursor for the production of ammonium nitrate and sulfates which are often a significant component of secondary aerosols found in urban areas.[25] Ammonia is most often associated with farming and livestock operations but it can also be produced by 3-way catalyst equipped gasoline and natural gas vehicles.[26] The production of exhaust NH_3 emissions is contingent upon the vehicle's ability to produce NO in the presence of a catalytic convertor that has enough hydrogen available to reduce the NO to NH_3. The absence of either of these species precludes the formation of exhaust NH_3. Dynamometer studies have shown that the hydrogen stores can be increased when acceleration events are preceded by a deceleration event though not necessarily back to back.[27] 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 our E-106 sites in Denver and Tulsa and by Kean et al in 1999 and 2006 from the Caldecott tunnel near Oakland.[28-31] The University of Denver collected NH_3 measurements at three California, (San Jose, Fresno and West LA) sites in 2008 and from a Van Nuys, California site in 2010.[32, 33] In addition air borne measurements of ammonia were collected in 2010 over the South Coast Air Basin as part of the CalNex campaign.[34] Most recently we have reported on ammonia emissions collected in 2013 from West LA, Tulsa and this Denver site.[35]

The production of tailpipe NH_3 also provides an estimate of catalytic activity, a necessary component in the reduction reaction, and therefore provides a gauge of converter lifetimes. Figure 18 graphs the gNH_3/kg of fuel emissions collected at the two Lynwood sites versus model year. The uncertainties plotted are standard error of the mean determined using the daily means (see Appendix A). As noted in Table 5 the mean fuel specific NH_3 emissions at the I-105 location were 30% higher (0.62 ± 0.01 versus 0.43 ± 0.03) than for a similar fleet measured at the I-710 site. This difference appears to be a result of the vehicles measured at the I-105 site being simply offset to a higher NH_3 emissions level than similarly aged vehicles measured at the I-710 site. To test this hypothesis, the correlation graph inset into the upper right corner of Figure 18 shows the individual model year gNH_3/kg of fuel means from the I-710 site plotted against the same model year means from the I-105 site. The correlation is quite good with a slope of 0.96 $\pm$ 0.09, intercept of -0.16 $\pm$ 0.06 and an R^2 of 0.86. The two model years which obviously fall

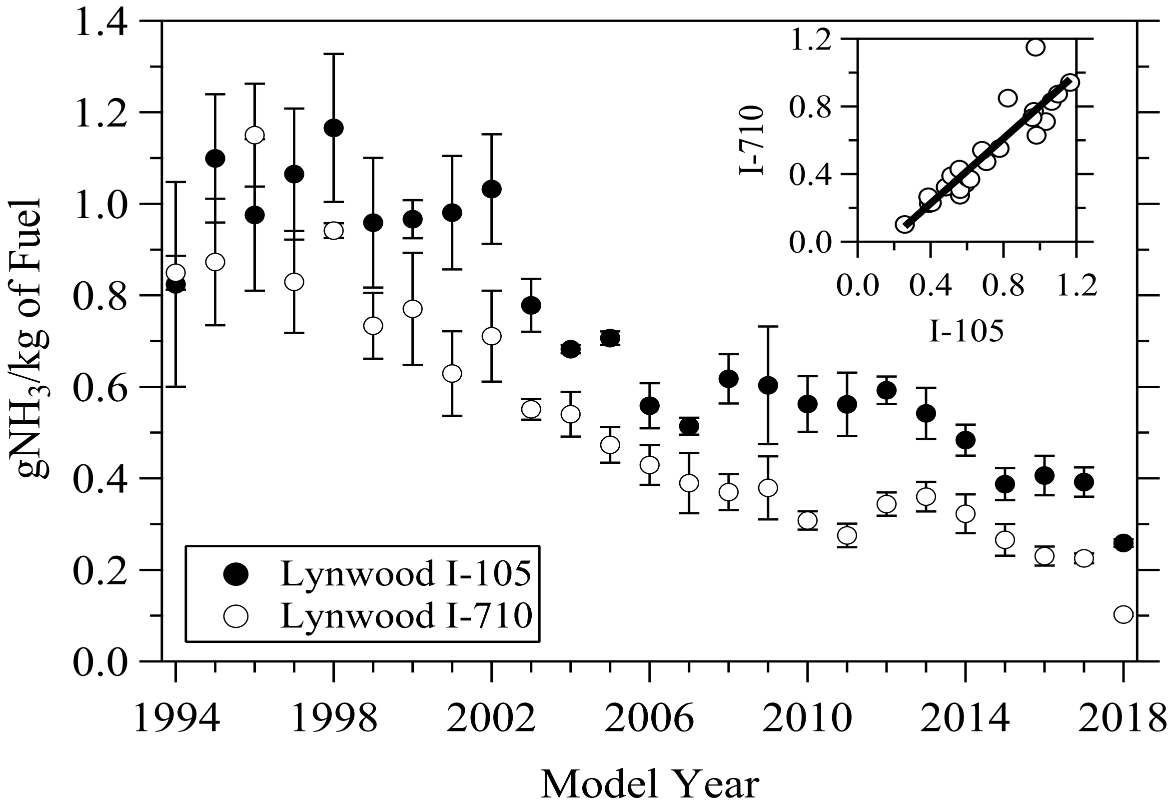

Figure 18. Mean gNH_3/kg of fuel emissions plotted against vehicle model year for the Lynwood I-105 (●) and I-710 (○) measurement sites. Uncertainties plotted as standard error of the mean determined using the daily means. The inset graph is the correlation between the fuel specific NH_3 emissions for the I-710 model year means versus the I-105 model year means. The slope of the correlation is 0.96 ± 0.09.

above the line are the model years of 1994 and 1996.

Figure 19 is a plot of fuel specific NH_3 emissions as a function of VSP for the Lynwood I-105 (●) and I-710 (○) sites. The uncertainties plotted are standard error of the mean determined from the daily means. As with the emission versus model year plot the differences in NH_3 emissions, after accounting for VSP, appear to be offset to a higher emissions level for the Lynwood I-105 site. While there may be an increasing emissions trend with VSP at the I-710 site there is not one at the I-105 site. The differences observed in the NH_3 means are found between VSP bins 0 to 15 where gNH_3/kg of fuel emissions are 0.62 ± 0.01 at the I-105 site and 0.43 ± 0.03 at the I-710 location, which are the overall means. A slightly smaller difference in fuel specific NO emissions exists in the same VSP range (see Figure 17) where the mean at the I-105 site is 1.87 ± 0.02 and 1.6 ± 0.1 at the I-710 site. Fleet age for both of these comparisons is not a factor as the difference in the flee age for the 0 to 15 VSP bin range is less than 0.1 model years (2008.64 vs. 2008.68). As previously mentioned dynamometer studies have indicated that decelerations followed by accelerations can increase the amounts of hydrogen stored on 3-way catalytic converters increasing the availability of hydrogen, a potentially limiting reagent in the reduction of NO to NH_3.[27] One major difference between the two sites is the upstream traffic conditions. The I-105

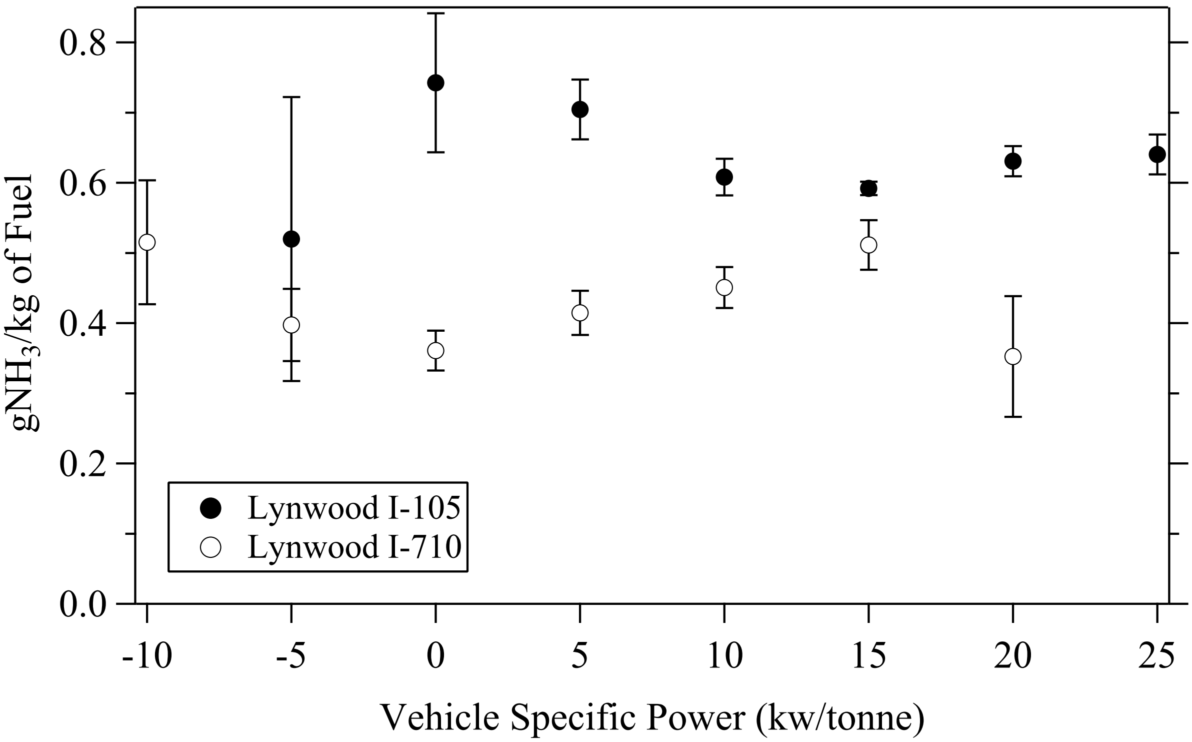

Figure 19. Fuel specific NH_3 emissions as a function of vehicle specific power for the Lynwood I-105 (●) and Lynwood I-710 (○) data sets. Uncertainties plotted are standard error of the mean calculated using the daily samples.

site collects traffic off of a major surface street that is traffic light controlled at all of the major cross streets which forces stop and go driving by these vehicles before they reach the on-ramp. The I-710 location samples vehicles coming directly from the freeway and while stop and go freeway traffic is common on LA freeways it is not as regular as traffic lights on Long Beach Blvd. The model year NH_3 emission differences between the two sites may be the consequence of the upstream driving patterns at the two sites and that stop and go driving along Long Beach Blvd. provides more hydrogen for NO reduction.

Figure 20 compares fuel specific NH_3 emissions from the two Lynwood data sets to the 2015 West Los Angeles data, which is the most recent publicly available, by vehicle age where year 0 year vehicles are model year 2018 for the Lynwood sites and 2015 for the West Los Angeles site.[23] The uncertainties plotted are standard error of the mean calculated from distributing the daily means for each year's data (see Appendix A). The West Los Angeles measurement site is a traffic light controlled on-ramp to eastbound I-10 that is fed by traffic from southbound La Brea Ave., a traffic light-controlled surface street. The Lynwood I-105 site shows higher emissions than the Lynwood I-710 location and generally follows the 2015 West Los Angeles data, especially for the first 9 model years, before diverging and falling below the West Los Angeles trend. This again suggests that the upstream stop and go traffic pattern created on Long Beach Blvd. may be involved in the elevated NH_3 emissions when compared to the I-710 site.

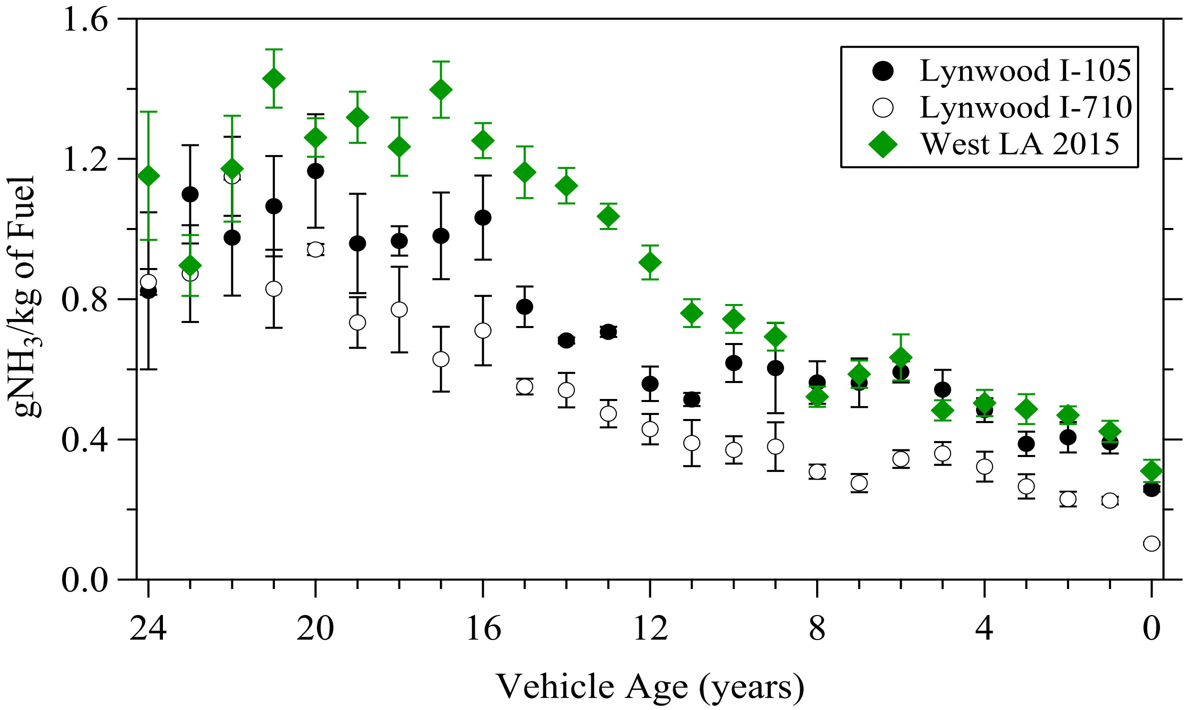

Figure 20. Fuel specific NH_3 emissions plotted against vehicle age in years for the 2018 Lynwood I-105 (●), Lynwood I-710 (○) sites and the 2015 West Los Angeles (◆) data. Uncertainties are standard error of the mean calculated using the daily means. Zero year vehicles are model year 2018 for the Lynwood data and 2015 for the West Los Angeles data.

The production of exhaust NH_3 results when engine-out NO emissions are reduced on a catalytic convertor with available hydrogen. Its presence in the exhaust requires a functioning catalytic converter as NH_3 levels decrease as a catalyst loses its ability to reduce NO and indirectly provides a gauge to estimate converter lifetimes. Peak NH_3 emissions and therefore converter lifetimes have been increasing since our first NH_3 measurements on Tulsa, OK and Denver, CO fleets in 2005 when peak NH_3 emissions were found from 10 to 12 year old vehicles.[30] Figure 20 shows peak NH_3 emissions, which corresponds to the point after which catalyst activity starts to decline, occurs in 17 to 21 year old vehicles for the 2015 West Los Angeles data. Both Lynwood sites show peak NH_3 emissions that are comparable (~20 to 22 year old vehicles). This is an important finding and it demonstrates that catalyst durability in the Lynwood fleet is at least on par with that observed at the West Los Angeles site.

The total fixed nitrogen in g/kg of fuel (◆, right axis) for the two Lynwood measurement sites is shown in Figure 21 with the molar percent composition distributed between NH_3 (●, left axis) and the NO_x (▲, left axis) component versus model year for non-diesel vehicles. The total fixed nitrogen calculation neglects any unmeasured nitrous oxide (N_2O) and nitrous acid (HONO) that may account for a few percent of the total. Total fixed nitrogen emissions have been on a steep decline since the mid-nineties in the gasoline fleet and are continuing to show decreases in the newest model years in this data as well. For the two Lynwood sites the percent of fixed nitrogen made up of NH_3 has continued to rise since the introduction of Lev II vehicles and is now the dominant reactive nitrogen species in exhaust. This is in contrast to the NH_3/NO_x ratio in the

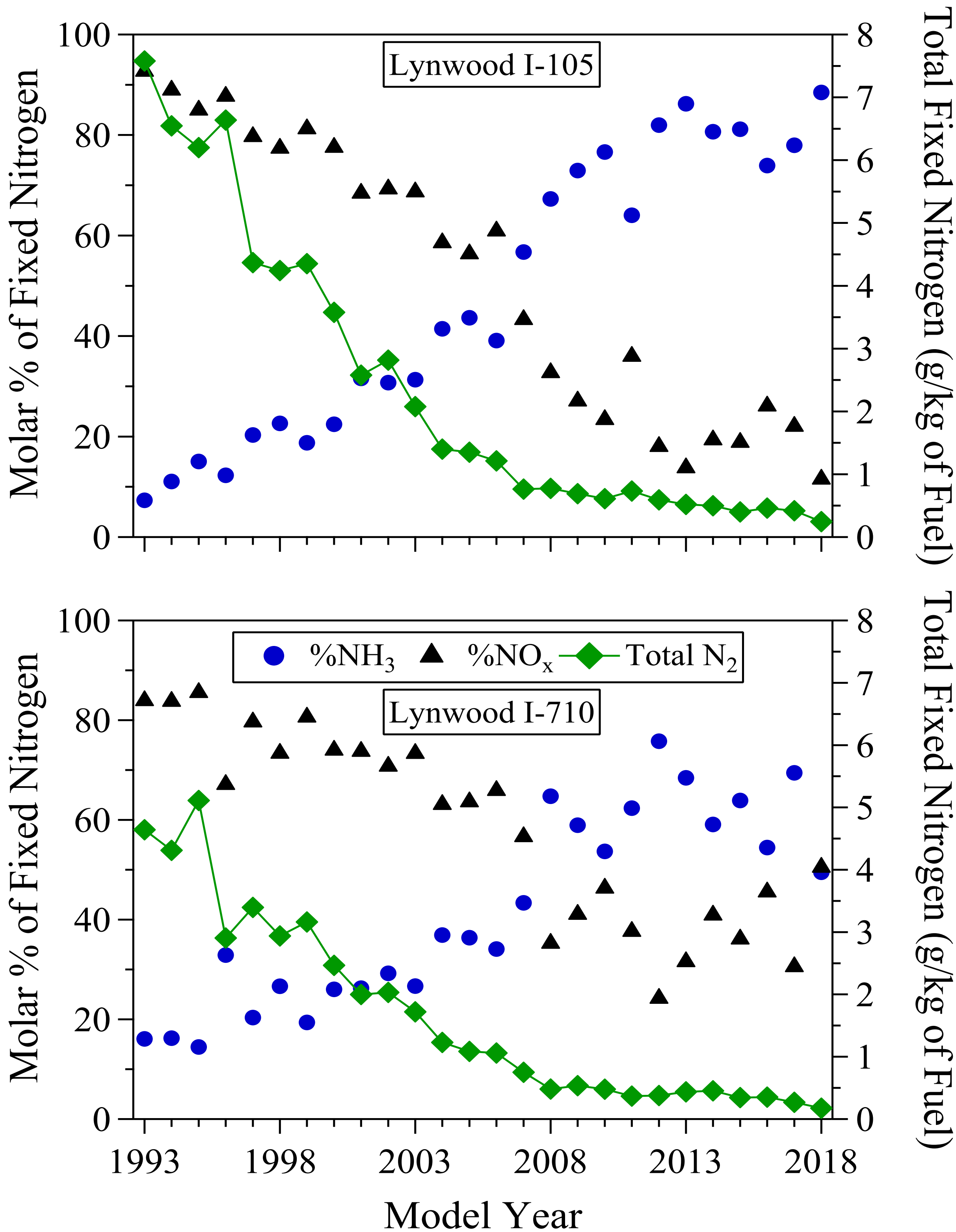

Figure 21. Total fixed nitrogen in g/kg of fuel (◆, right axis) with the molar percent composition distributed between the NH_3 (●, left axis) and NO_x (▲, left axis) component versus model year for non-diesel vehicles at the Lynwood I-105 (top panel) and I-710 (bottom panel) sites.

newest model year vehicles in the 2017 Denver, CO measurements where NH_3 percentages have leveled out and started declining with newer models favoring NO_x production.[36] It is known that catalyst formulation, in regards to the amount and type of precious metals employed, can influence reduction (NH_3) or oxidation (NO_x) of the NO exhaust stream in addition to the control of the air to fuel ratio with slightly rich lambda settings producing NH_3 and slightly lean settings favoring NO_x formation.[37-39] In addition as shown with the differences between the I-105 and I-710 site as part of this study the driving mode prior to the measurement could also be a factor in the observed differences between the two locations.

As previously detailed in Tables 2 and 3, the process of matching the vehicle license plates associated with valid measurements to state vehicle registration data led to larger than normal reductions in the final databases for both of the Lynwood sites. The Lynwood I-105 site experienced decreases of 34% and the I-710 site saw a 25% reduction in this step. Both of these values exceed those previously found in data sets of remote sensing measurements collected at other sites. As briefly discussed, the largest contributor to these decreases were unreadable plates, either because they are out of the field of view (second lane at the I-105 site) or have no visible license plate. Provided these losses are random, the final sample of matched plates should still faithfully describe the emissions distributions at the sites. Table 6 compares the mean emissions at each site for the original data set that contains all of the valid vehicle emission measurements and the final matched license plate database. The uncertainties are standard error of the mean calculated from the daily measurements.

Table 6. Fuel specific mean and standard error of the mean uncertainty comparison for the original valid measurements and the license plate matched databases for the Lynwood sites.

Location	Lynwood I-105		Lynwood I-710	
	All Valids (records)	Matched Plates (records)	All Valids (records)	Matched Plates (records)
gCO/kg of Fuel	10.9 ± 0.1 (11,772)	10.4 ± 0.4 (7,724)	12.4 ± 0.2 (18,960)	12.3 ± 0.2 (14,302)
gHC/kg of Fuel[a]	2.4 ± 0.4 (11,650)	2.1 ± 0.3 (7,649)	2.1 ± 0.2 (18,890)	2.0 ± 0.2 (14,248)
gNO/kg of Fuel	2.28 ± 0.06 (11,771)	2.05 ± 0.04 (7,723)	1.79 ± 0.07 (18,957)	1.72 ± 0.08 (14,300)
gNH_3/kg of Fuel	0.59 ± 0.01 (11,754)	0.62 ± 0.01 (7,717)	0.42 ± 0.03 (18,949)	0.43 ± 0.03 (14,293)
gNO_2/kg of Fuel	0.04 ± 0.003 (11,712)	0.03 ±0.005 (7,691)	0.04 ± 0.004 (18,933)	0.03 ± 0.007 (14,286)
gNO_x/kg of Fuel	3.54 ± 0.09 (11,711)	3.17 ± 0.06 (7,690)	2.79 ± 0.11 (18,930)	2.67 ± 0.12 (14,284)

[a]HC data have been offset adjusted as described in the text.

With the exception of the NH_3 measurements, all of the mean emission values are larger for the original databases. However, only the CO, NO and NO_x mean values at the Lynwood I-105 site fall outside the estimated uncertainties. Because the fleet emissions distributions are skewed, it is more difficult to represent the extremes of the emissions distributions of smaller samples, and the final sample at the Lynwood I-105 site is only about half of the size of the database collected at the I-710 site. Figures 22 and 23 are log-normal plots of the probability distributions of the fuel specific CO, HC and NO emissions factors comparing the distribution between the all valid measurements and the license plate matched databases for the two Lynwood sites. These plots represent the probability for each data set that a vehicle will have an emission factor that is less than the value indicated on the y-axis. Data originating from a lognormal distribution would plot as straight diagonal lines.

As with the comparison of the mean emission data, when comparing the fuel specific emission distributions for CO, HC and NO the differences between the "all valid" and the "matched plates" databases, are small. However, for HC and to a smaller degree CO, there are differences at the very top of the emissions distribution (>99th probability). What this reveals is that the plate matched database does not completely capture the highest emitting HC and CO vehicles in the fleet; however, as shown in Table 6 the differences created are not large. For HC there were 12 and 22 measurements with fuel specific HC emissions greater than 100gHC/kg of fuel at the I-105 and I-710 sites respectively. In both cases only about half of those measurements ended up in the plate matched database. The reason for this most often was that the license plate was not visible in the digital plate image (4 of 6 at the I-105 site and 6 of 11 at the I-710 site). At the I-105 site the remaining two missing plates were due to a dealer placard displayed instead of a license plate and a trailer hitch blocked the view of the second plate. At the I-710 site the 5 unrecovered vehicles plates were 1 unmatched plate (transcribed correctly but did not return a registration record), 1 motorcycle and 3 heavy-duty trucks.

For CO the differences are significantly smaller and only occur beyond the 99.9th probability, which only represents the contribution of 1 or 2 vehicles. For NO the differences lie in the top third of the distribution and not at the very top as seen for CO an HC. The I-105 site shows the larger of the two differences with the differences between the "all valid" and "matched plates" databases extending down to the median. This may be an unintended consequence of monitoring a two lane ramp where all of the valid measurements captured from the outside lane are excluded in the matched database.

Historical Comparison

The University of Denver previously collected measurements in the Lynwood area in south Los Angeles in 1989 and 1991 (see Table 1).[8-11] In the spring of 2018 we revisited two of those sites, one near the original Long Beach Blvd. site and the other on the off-ramp from northbound I-710 to westbound Imperial Highway. Table 7 summarizes the fleet fuel specific emission means from these three campaigns along with the mean model year and age of the vehicle fleet observed. The uncertainties are standard error of the mean determined from the daily means for the multi-day measurements. For the measurements collected on a single day, the 1989 measurements at the I-710 off-ramp and the 1991 measurements on Long Beach Blvd., resampling statistics were used to estimate the standard error of the mean. Fuel specific CO emissions show decreases of

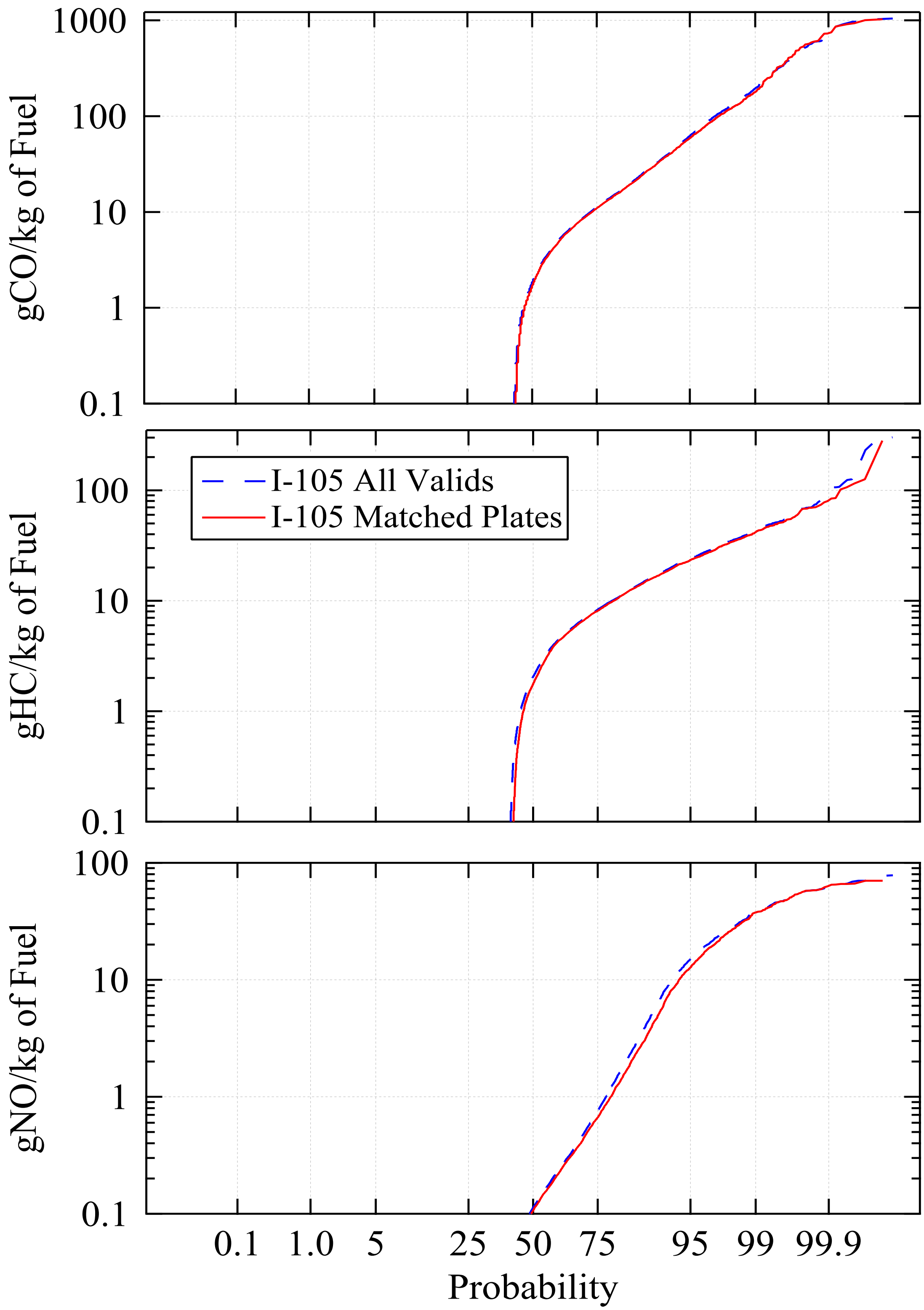

Figure 22. Lognormal probability plots comparing the emissions distribution of the Lynwood I-105 all valid data set (blue dashed line) against the license plate matched (red line) data set for fuel specific CO (top panel), HC (middle panel) and NO (bottom panel).

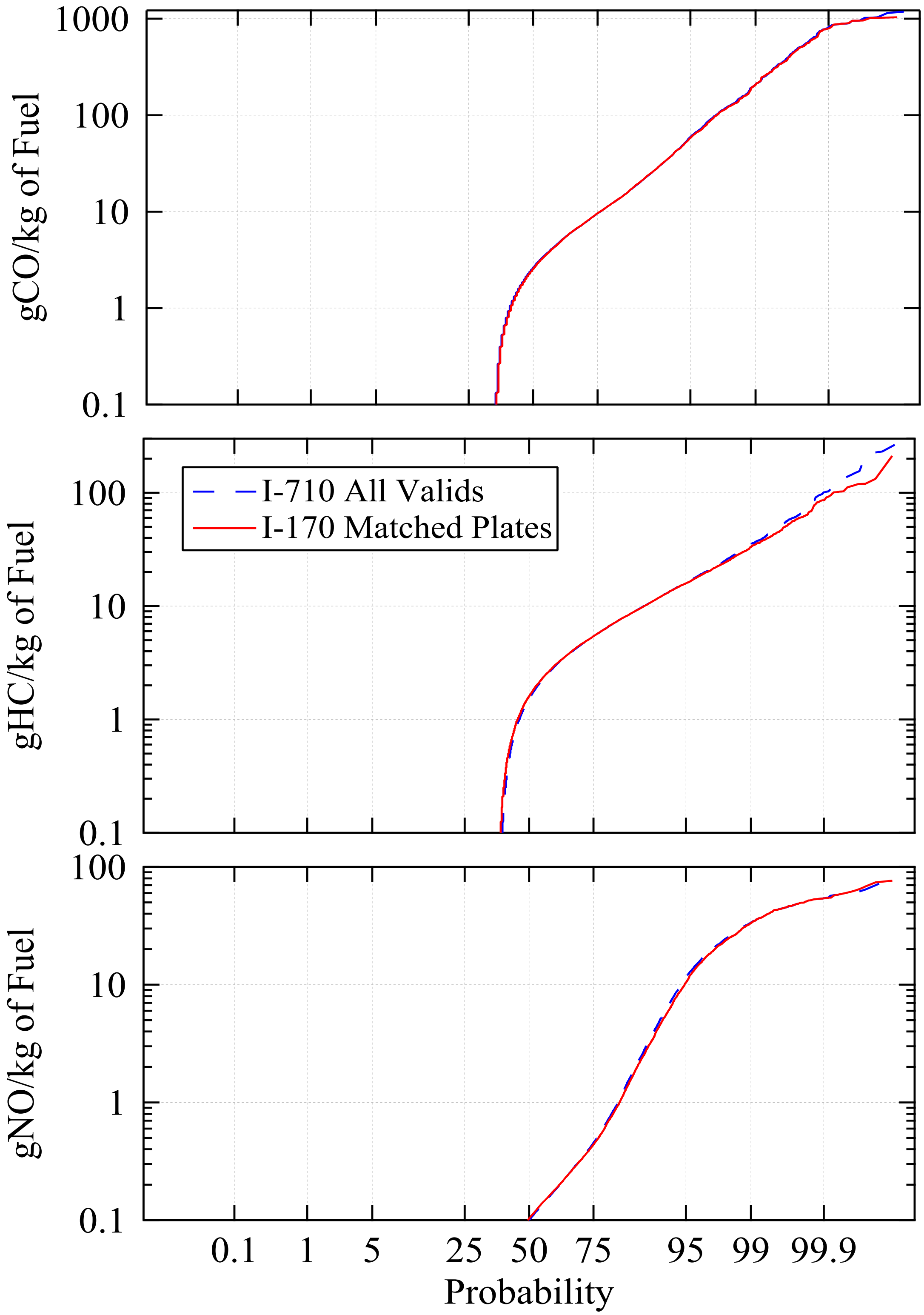

Figure 23. Lognormal probability plots comparing the emissions distribution of the Lynwood I-710 all valid data set (blue line) against the license plate matched (red line) data set for fuel specific CO (top panel), HC (middle panel) and NO (bottom panel).

Table 7. Mean emission comparison by site for the 1989, 1991 and 2018 Lynwood measurements. Uncertainties are standard error of the mean.

	1989	1991		2018	
	Mean gCO/kg of Fuel	Mean gCO/kg of Fuel	Mean gHC/kg of Fuel	Mean gCO/kg of Fuel	Mean gHC/kg of Fuel
Long Beach Blvd. / I-105	210 ± 8	191.9 ± 13.6[a]	50.3 ± 3.9[a]	10.4 ± 0.4	2.1 ± 0.3
Mean Model Year (Age)[b]	1980.6 (9.7)	1981.7 (10.1)		2008.6 (10.1)	
I-710 Off-ramp	120.2 ± 7.6[a]	N.A.	N.A.	12.3 ± 0.2	2.0 ± 0.2
Mean Model Year (Age)[b]	1982.9 (7.4)	N.A.		2008.4 (10.3)	

[a] Single day of measurements. SEM estimated using resampling statistics.
[b] Mean model year calculated excluding unidentified model years and fleet age is calculated assuming the new model year starts September 1.

approximately factors of 10 and 20 at the I-710 and Long Beach Blvd. sites respectively. Fuel specific HC emission show decreases of a factor of 25 from the 1991 measurements collected along Long Beach Blvd. Fleet age has changed little at the Long Beach Blvd. site but increased significantly at the I-710 off-ramp from the 1989 measurements matching those observed along Long Beach Blvd.

Despite the similar fleet ages between the 1989, 1991 and 2018 measurements, there are differences in the composition of the observed fleets. Figure 24 plots fleet percentage by age for the 1989 (blue bars) and 2018 (green bars) measurements in the top panel. Zero year old vehicles in 1989 represent 1990 model year vehicles and in 2018 they represent 2018 model year vehicles and the 25 year old category aggregates vehicles which are 25 years old and older. The bottom panel shows the differences between the 2018 fleet and the 1989 fleet percentage highlighting where the largest changes have occurred. The 2018 Long Beach Blvd. fleet has more 0 to 4 year old vehicles and in general more 15 year old and older vehicles, though the differences in 0 year old vehicles is heavily influenced by the fact that the 2018 measurements were collected 5 months later than the 1989 measurements. Both age distributions are bi-modal with 2 and 12 year old vehicles representing the tops of the two peaks. This is in part a fortuitous coincidence of two economic recessions, one in 1980-81 (~9 years before the 1989 measurements) and the other in 2008 – 2010 (~10 years before the 2018 measurements). Both decreased the fleet representation of 7 to 10 year old vehicles in the two data sets. The 2008 recession impacted the 2018 fleet to a larger degree than did the 1980 recession and accounts for the differences in the fleet age distribution between the two data sets. In 1989, the most common vehicles at this site were 11 and 12 year old models which accounted for 15.9% of the total. In 2018 those ages only represented 11% of the total, replaced in importance by 2 and 3 year old vehicles which accounted for 15% of the 2018 fleet.

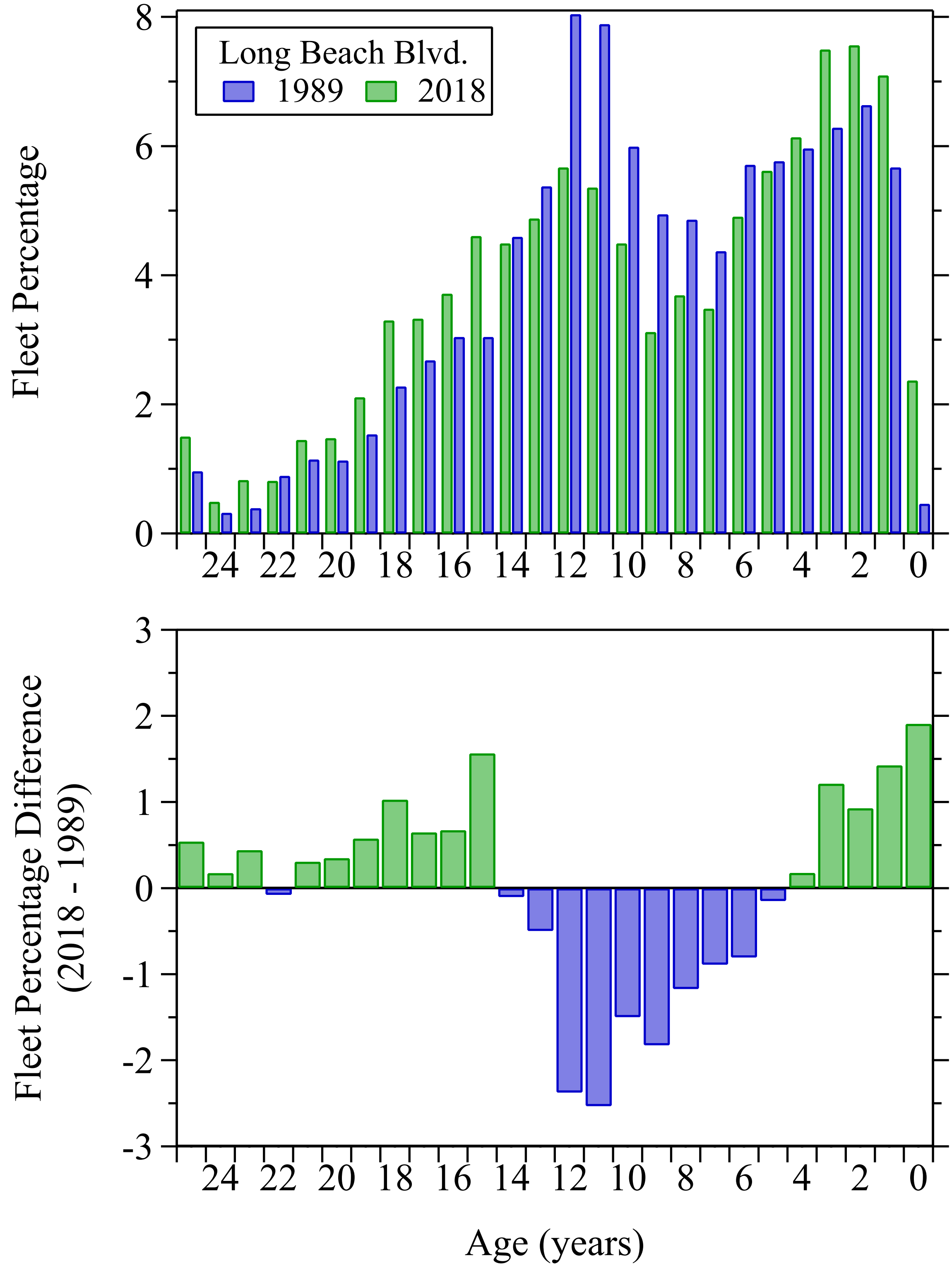

Figure 24. Fleet percentage by vehicle age for the 1989 Long Beach Blvd. (blue bars) and 2018 Long Beach Blvd. / I-105 (green bars) measurements (top panel) and the fleet percentage difference (bottom panel, 2018 – 1989). The 25 year old category includes 25 year old and older vehicles.

Figure 25 is a similar type plot comparing the fleet age distribution between the 1989 (blue bars) and 1991 (grey bars) measurements on Long Beach Blvd. The 1991 data set was a single day of measurements collected in June and includes only 1807 measurements that increases the scatter between the individual age groups. The majority of the differences between the 1989 and 1991 data sets are within ±1% (20/25 age groups) of each other. The 1991 data has a smaller number of 1 to 4 year old vehicles and while the older vehicles still peak at 12 year old vehicles, the 1991 measurements include more 13 year old vehicles both of which are reflected in the slight increase in fleet age (see Table 7).

The largest changes in fleet age were found at the I-710 off-ramp site where fleet age increased by almost 3 years (2.9 years) between 1989 and 2018. Figure 26 compares the differences between the age distribution for the 1989 (blue bars) and 2018 (green bars) measurements at the I-710 off-ramp. At this site, there is a notable shift from 1 to 10 year old vehicles to 13 year old and older vehicles which is responsible for the increase in fleet age.

Figure 27 compares the fleet percentages by model year for the 2018 measurements at the two Lynwood sites. Unlike in 1989, the fleet age distributions for the 2018 measurement are very similar between the two Lynwood sites that are also reflected in their similar fleet age. This was not unexpected as both sites should measure vehicles from the same geographic area; however, as shown this was for some unknown reason not the case in 1989. For comparison, the fleet age measured at the West Los Angeles site in 2015 was 8.9 years.

Comparing the emissions distributions between the two years at each site emphasizes the large emission changes that have taken place despite the fleet age increasing. Figure 28 is a lognormal probability plot comparing the log of the fuel specific CO emissions in gCO/kg of fuel for the 1989 (red ▲) and 2018 (blue ●) measurements against the probability for each measurement value occurring in the data set. The top panel of the figure compares the two Long Beach Blvd. sites and the bottom panel compares the data obtained at the I-710 off-ramp location. The mean values for each of the distributions have been added to the plot as open symbols. These plots present the probability that a vehicle will have a CO emission rate that is less than or equal to the value on the y-axis. If the underlying data represented a lognormal distribution, then it would plot as a straight diagonal line. The breaks present in the 1989 data occur because the CO measurements, which are recorded in percent space, were only recorded to two digits after the decimal point and the gaps correspond to the distance in gCO/kg of fuel space for a 0.01% change in %CO.

The CO distributions for the 1989 and 2018 data sets shown in Figure 28 converge to a similar value at or slightly above 1000 gCO/kg of fuel at the very top of the distribution that is above the 99.9th probability. The percent change between the two distributions, as a percent of the 1989 CO values, is reasonably constant between the 50th and the 95th probability level indicating a constant reduction in emissions. For the I-105 site, this reduction is ~95% reduction and it is ~92% at the I-710 site. Above the 95th probability, the distributions converge and the percent emissions reduction decreases. However, the age of the fleet at the top of the distributions is markedly different between 1989 and 2018. The average age of the 99th probability and above vehicles for the 1989 Long Beach Blvd. and I-710 off-ramp sites were 13.7 (1976.6) and 11.5 (1978.8) years

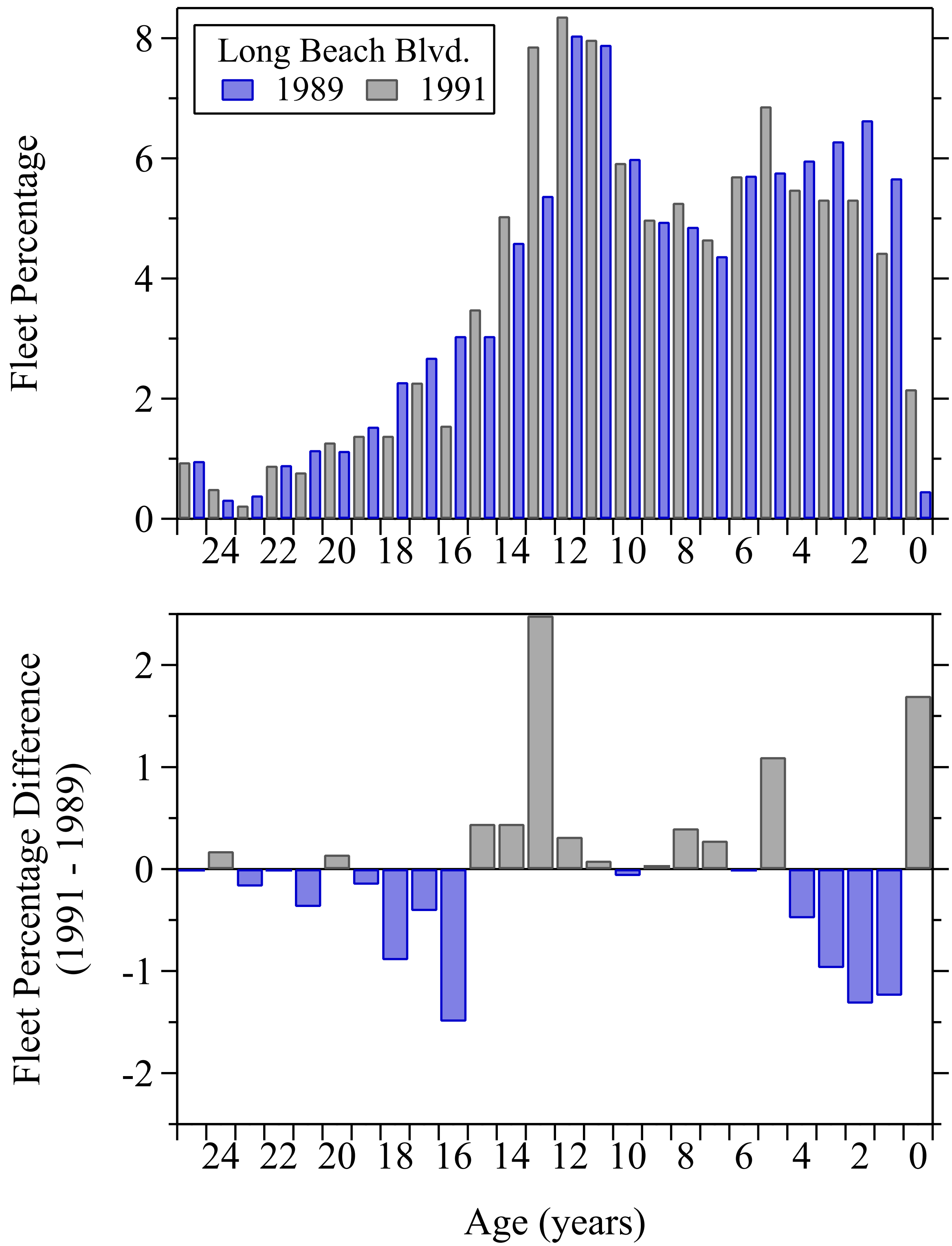

Figure 25. Fleet percentage by vehicle age for the 1989 (blue bars) and 1991 (grey bars) Long Beach Blvd. measurements (top panel) and the fleet percentage difference (bottom panel, 1991 – 1989). The 25 year old category includes 25 year old and older vehicles.

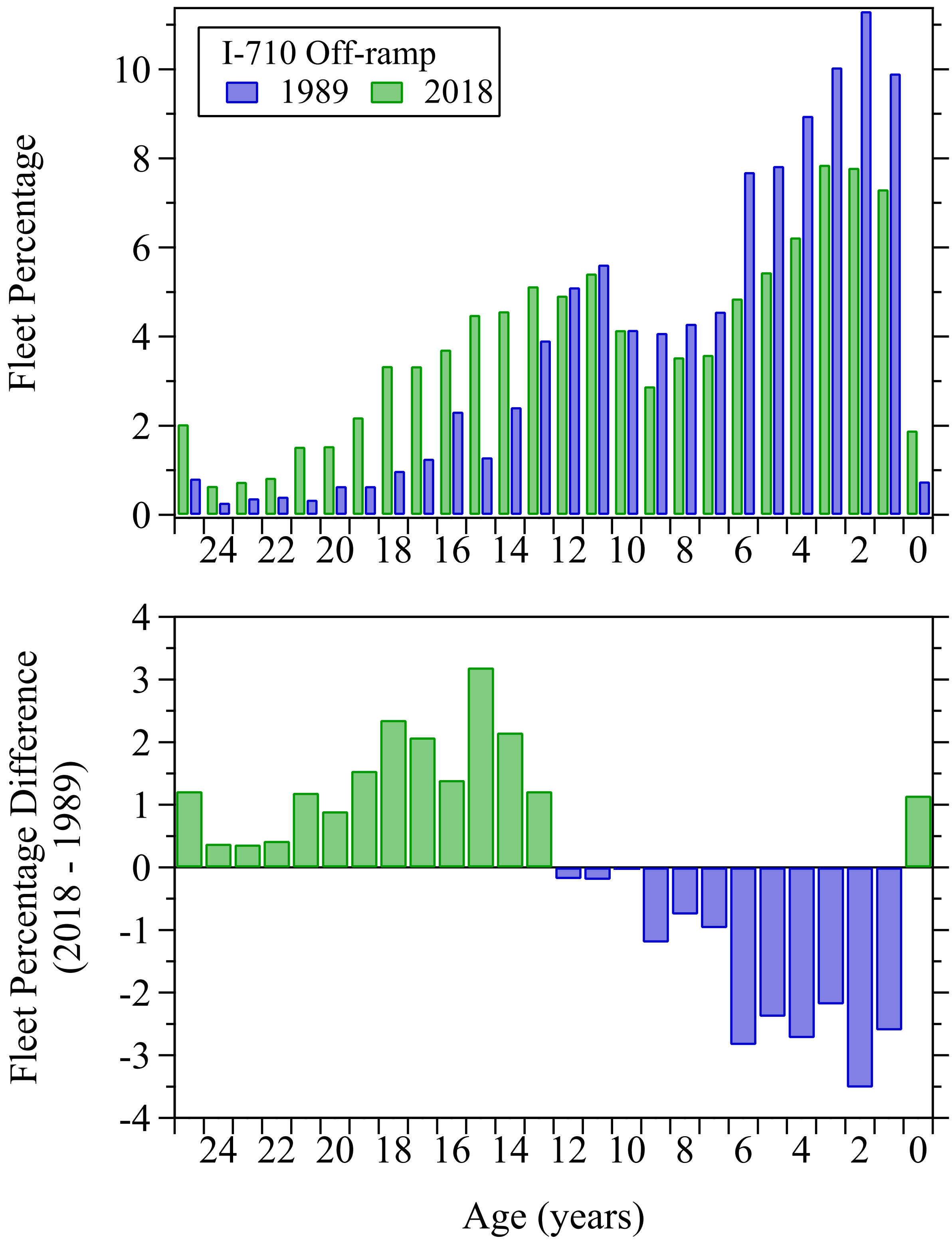

Figure 26. Fleet percentage by vehicle age for the 1989 (blue bars) and 2018 (green bars) I-710 off-ramp measurements (top panel) and the fleet percentage difference (bottom panel, 2018 – 1989). The 25 year old category includes 25 year old and older vehicles.

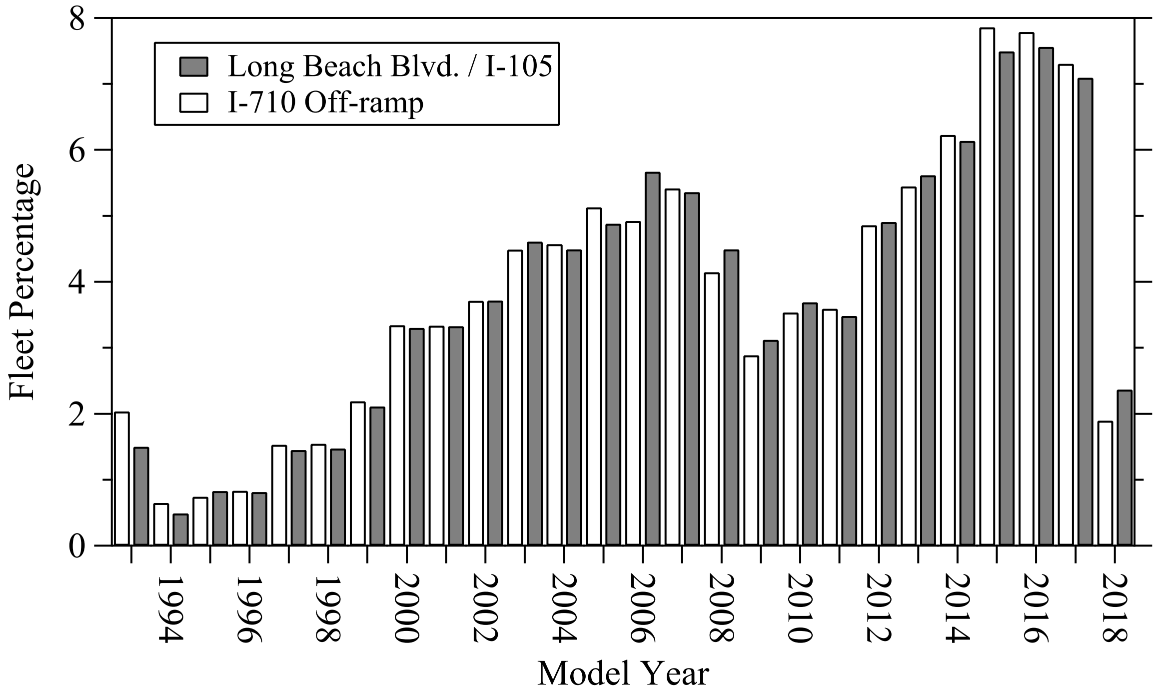

Figure 27. Fleet percentage by model year for the 2018 measurements collected at the Long Beach Blvd. / I-105 (dark bars) and the I-710 off-ramp (white bars) sites. The 1993 model year bars include 1993 and older model year vehicles.

old while the 2018 ages for the comparable sites were 21.7 (1997) and 23.8 (1994.9) or approximately double the age of the 1989 group. The comparison between the 1991 Long Beach Blvd. emissions distribution and the 2018 measurements is very similar to that shown for the 1989 data set.

Figure 29 is a lognormal probability plot comparing the log of the fuel specific HC emissions for the 1991 (red ▲) and 2018 (blue ●) measurements against the probability for each measurement value occurring in the data set. The mean value for each of the distributions has been added to the plots as an open symbol. Differences in the fuel specific HC emissions show consistent reductions across all of the distribution, even for probabilities above the 99.9th probability line with the two distributions generally not converging. The ages of the vehicles above the 99th percentile are 14.8 (1977) years old for the 1991 data set and 10.4 years old for the 2018 measurements.

Figures 10 – 16, previously presented, show the 2018 emissions data by model year and quintiles for fuel specific CO, HC and NO for the two Lynwood sites. Figures 30 – 32 follow this format for the 1989 Long Beach Blvd. fuel specific CO emission measurements (Figure 30), the 1989 I-710 off-ramp fuel specific CO emission measurements (Figure 31) and the 1991 Long Beach Blvd. fuel specific HC emission measurements (Figure 32). The bars in the top plot represent the mean emissions for the quintiles of each model year, but do not account for the number of vehicles in each model year. The middle graph provides the fleet fraction by model year for the newest 22 model years. The bottom graph in each series is the combination of the top and middle

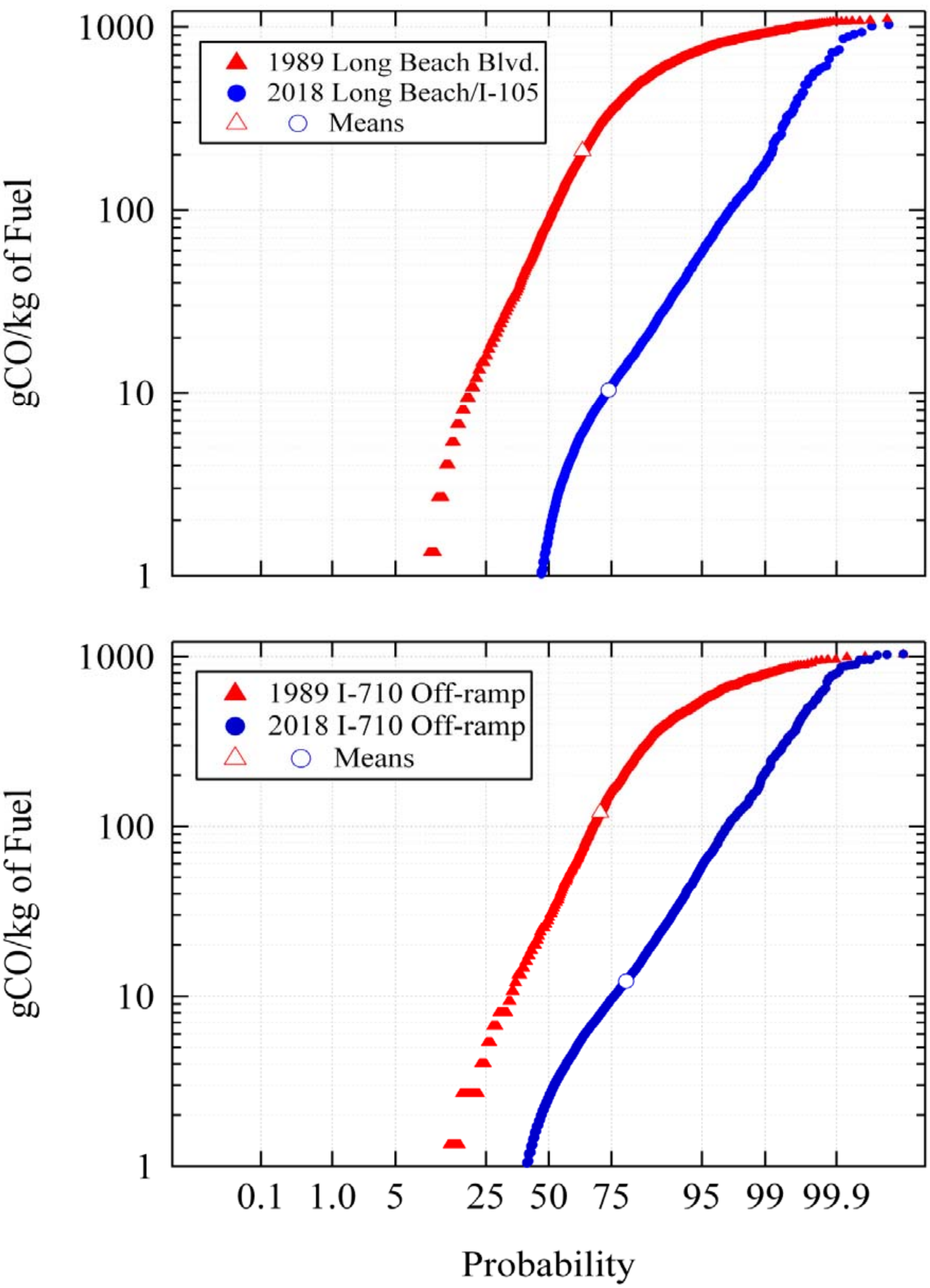

Figure 28. Lognormal probability plots comparing the fuel specific CO emission distributions for the 1989 (red ▲) and 2018 (blue ●) measurements at the Long Beach Blvd. sites (top panel) and the I-710 off-ramp site (bottom panel). Open symbols are the respective means for each distribution.

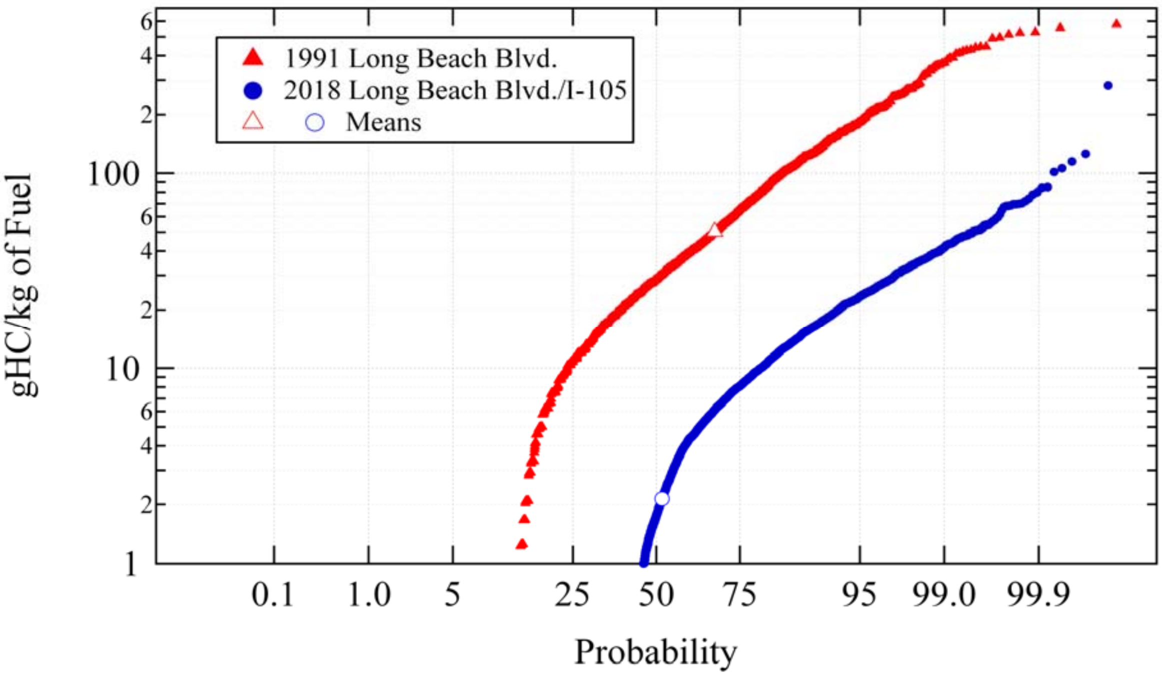

Figure 29. Lognormal probability plot comparing the fuel specific HC emission distributions for the 1989 (red ▲) and 2018 (blue ●) measurements at the Long Beach Blvd. site. Open symbols are the respective means for each distribution.

figures and shows the individual model year and quintile contribution to the overall fleet mean given in Table 7.

In general, rapidly increasing model year emissions combined with a significant fraction of the fleet occurring in the first 11 model years results in the emissions contributions (bottom panel in each graph) being front weighted by age. Because the fleet at Long Beach Blvd. has a larger fraction of 11 to 13 year old vehicles (1979 – 1977 for the 1989 measurements and 1980 – 1978 for the 1991 measurements) than that observed at the I-710 location, this “front-weighting” effect is stretched out further not reaching its peak until these older models. For the 1989 Long Beach Blvd. measurements the 1977 - 1979 model year vehicles account for 25% of the total fuel specific CO and in 1991 the 1978 – 1980 model year vehicles account for 30% of the total fuel specific HC emissions. In all of the plots of the 1989 and 1991 data shown in Figures 30 – 32, only the first and perhaps the second quintiles could be considered as negligible contributors to the overall fleet totals unlike the modern fleet where the mean emissions is now really only determined by the contribution of the last (fifth) quintile.

To emphasize this last point, Figure 33 reproduces the top panels from Figures 30 – 32 of emissions by model year using the comparable 2018 data set but keeping the y-axis range as established by the 1989 and 1991 data plots. The top panel represents the fuel specific CO emissions from the 2018 Long Beach Blvd. / I-105 measurements (see top panel of Figure 10 for comparison). The middle panel is fuel specific CO emissions from the 2018 I-710 Off-ramp measurements (see top panel of Figure 13 for comparison). The bottom panel is fuel specific HC

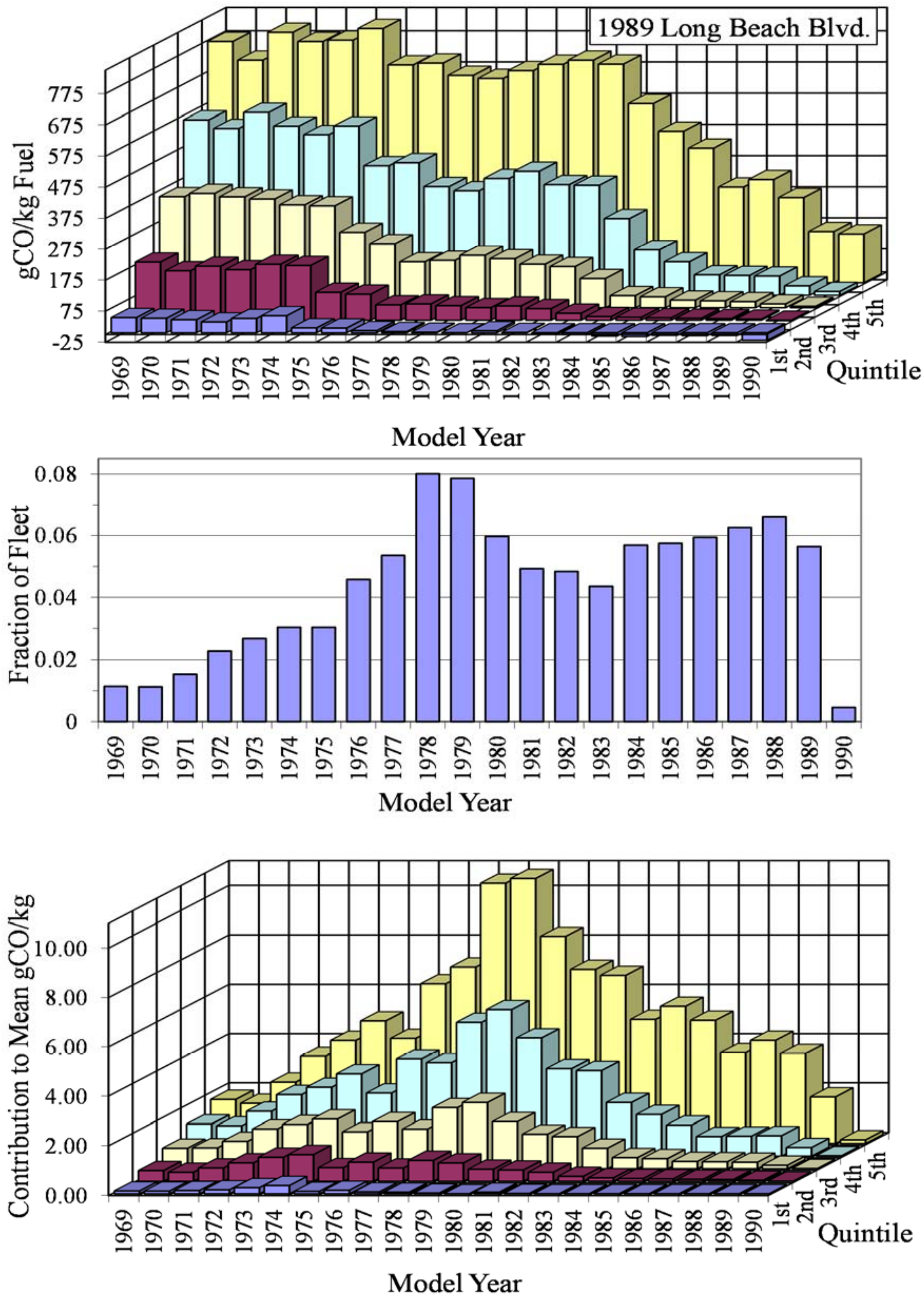

Figure 30. Mean gCO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gCO/kg of fuel emissions (210 ± 8) by model year and quintile (bottom) for the 1989 Lynwood Long Beach Blvd. measurements.

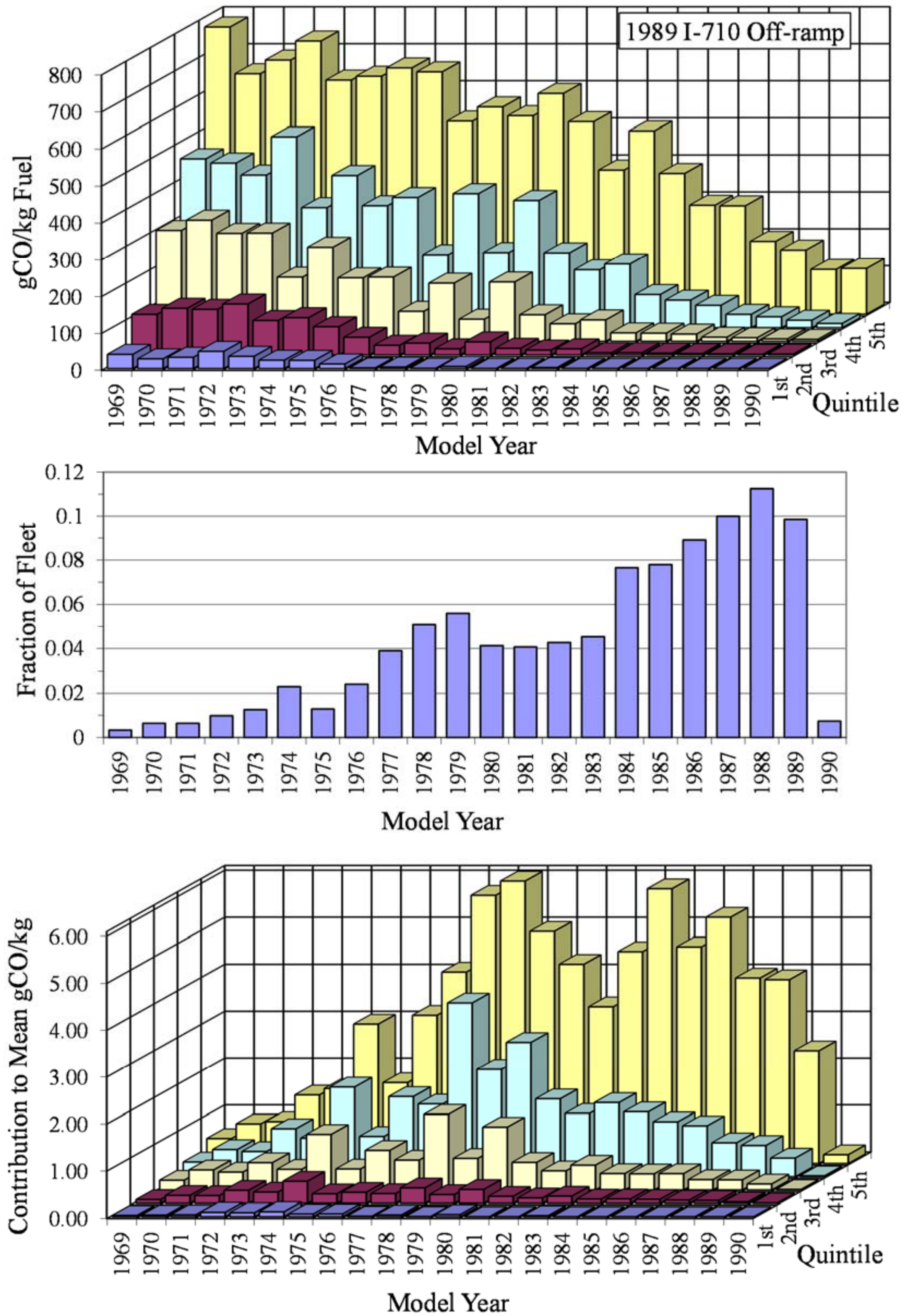

Figure 31. Mean gCO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gCO/kg of fuel emissions (120.2 ± 7.6) by model year and quintile (bottom) for the 1989 I-710 off-ramp measurements.

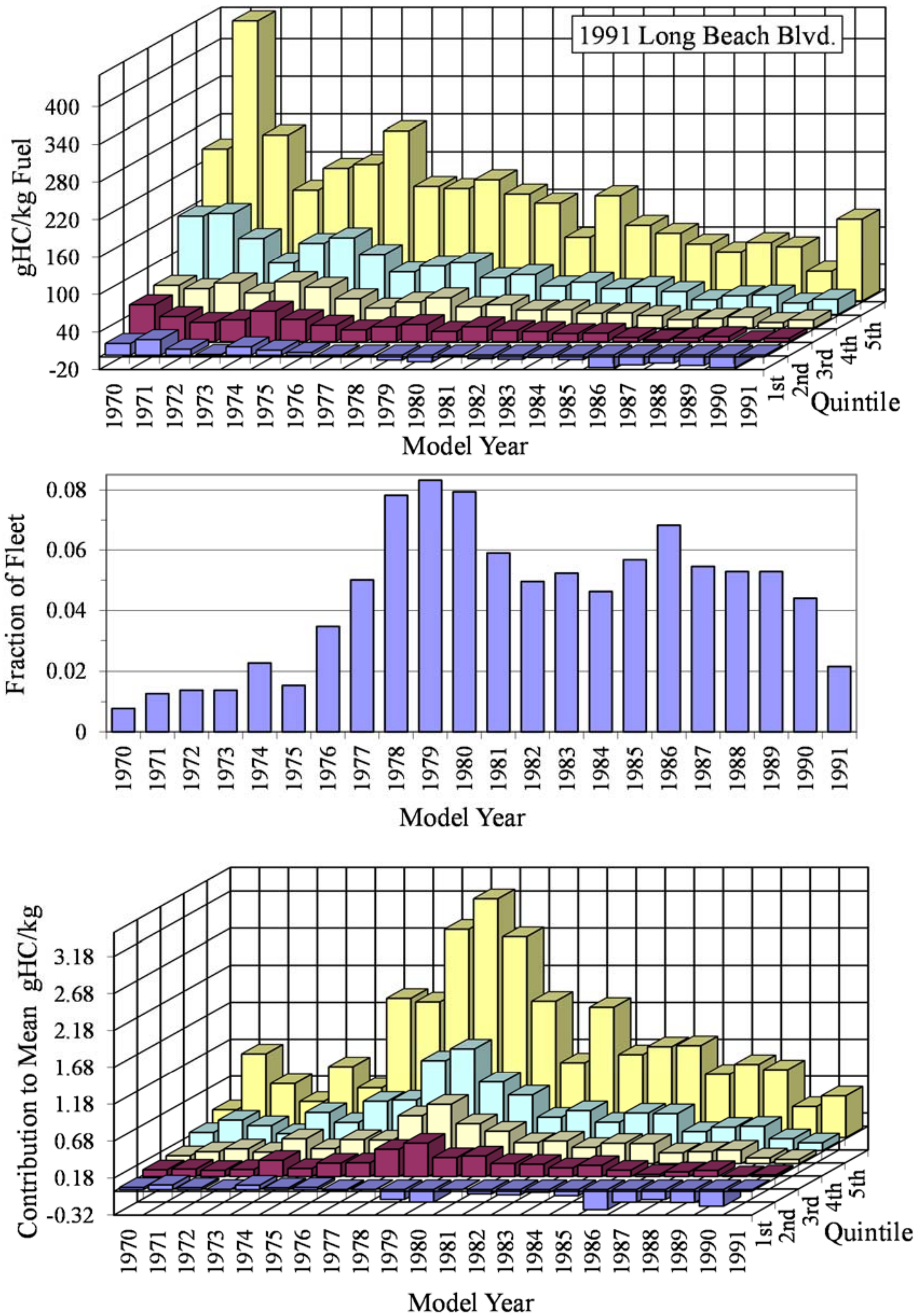

Figure 32. Mean gHC/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gHC/kg of fuel emissions (50.3 ± 3.9) by model year and quintile (bottom) for the 1991 Lynwood Long Beach Blvd. measurements.

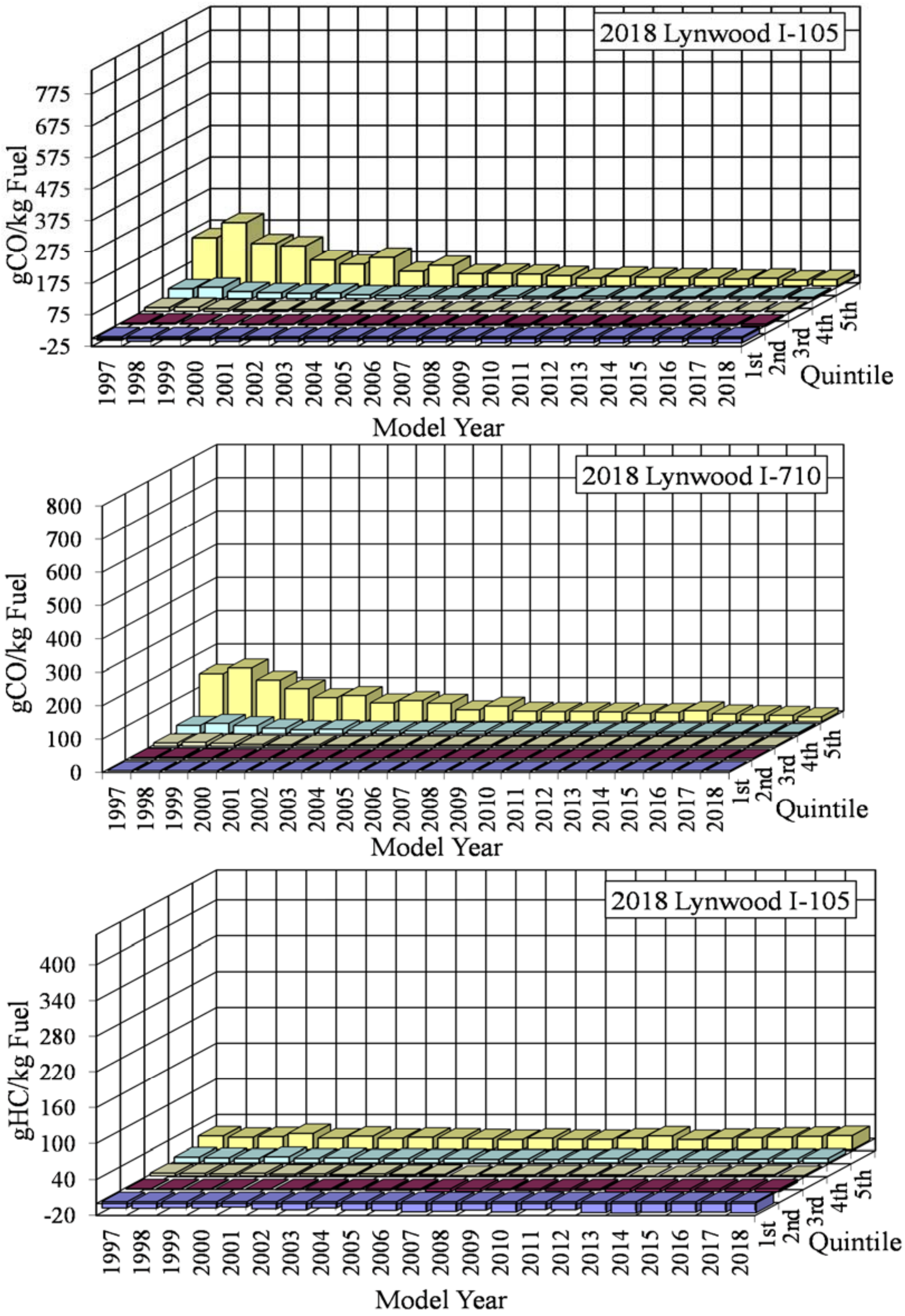

Figure 33. Fuel specific CO emissions by model year and quintile for the 2018 Long Beach Blvd. / I-105 measurements (top), 2018 I-710 off-ramp measurements (middle) and the 2018 Long Beach Blvd. / I-105 fuel specific HC emission measurements. The y-axis for each plot has been set to match the axis values for the top plots in Figures 30 – 32.

emissions from the 2018 Long Beach Blvd. / I-105 measurements (see top panel of Figure 11 for comparison). Using the y-axis ranges established by the 1989 and 1991 measurements, the changes in the fleet emissions over the last 29 years are dramatic with only the oldest 8 or 9 model years in the last quintile of the CO emissions plots having emission levels one can see. For the HC emissions, the bottom panel in Figure 33 highlights the low and consistent emission levels found now in modern fleets sampled in Lynwood.

Instrument noise was measured by looking at the slope of the negative portion of the log plots in the same manner as described in the Phoenix, Year 2 report.[40] Such plots were constructed for all of the measured species (not shown) at both Lynwood measurement sites. Linear regression gave best-fit lines with slopes corresponding to the inverse of the Laplace factor, which describes the noise present in the measurements for a zero measurement. This factor must be viewed in relation to the average measurement for the particular pollutant to obtain a description of noise. Table 8 list the Laplace factors for each species and the resulting standard deviation for a single measurement (1σ) and 100 measurements (0.1σ) for the fuel specific and concentration values (the standard deviation is reduced by the square root of the number of measurements). All but the noise for the HC channel are consistent with noise values observed at previous measurement sites. The Laplace factor for CO is also higher at the Long Beach Blvd. site but its value is still in line with a range of values (4 to 9) that have been previously observed within the last two years of measurements. However, for some unexplained reason the noise for the HC channel was not typical at the Long Beach Blvd. site and it was ~3 times higher than normally observed.

Table 8. Laplace factors and resulting standard deviation calculations for the Lynwood sites.

Species	Long Beach Blvd. / I-105			I-710 and Imperial Highway		
	Laplace Factor	1 σ g/kg / [ ]	0.1 σ g/kg / [ ]	Laplace Factor	1 σ g/kg / [ ]	0.1 σ g/kg / [ ]
CO	8.8	12.4 / 0.09%	1.2 / 0.009%	4.9	6.9 / 0.05%	0.7 / 0.005%
HC	8.9	12.6 / 289ppm	1.3 / 30ppm	4.9	6.9 / 163ppm	0.7 / 16ppm
NO	0.3	0.48 / 64ppm	0.05 / 6ppm	0.3	0.43 / 51ppm	0.04 / 5ppm
NH_3	0.03	0.04 / 6ppm	0.004 / 0.6ppm	0.014	0.02 / 3ppm	0.002 / 0.3ppm
NO_2	0.2	0.3 / 15ppm	0.03 / 2ppm	0.15	0.2 / 10ppm	0.02 / 1ppm

For the three days of measurements collected after the Long Beach Blvd. measurements at the I-710 off-ramp site, the noise observed on the HC channel decreased significantly (almost a factor of 2). Following the Lynwood measurements, an additional week of work was carried out at the West Los Angeles site and the Laplace factor for the HC channel for those measurements decreased an additional 20% to 4. This suggests some type of temporary problem occurred that only effected the HC detector. This unfortunately has increased the uncertainty levels for the Long Beach Blvd. HC measurements that were already larger because of the smaller size of the database. The increased noise on the HC channel is only an issue for analyzing the model year or VSP segregated data as the uncertainties, increased by the combination of the increased noise and a smaller sample size, works to obscure some of the trends. For evaluating the differences in mean values between the 2018 and 1991 data sets the increased uncertainties are not a factor as the standard deviation is decreased by approximately a factor of 70 for the Long Beach Blvd. data set.

CONCLUSIONS

The University of Denver carried out six days of remote sensing measurements at two locations in the Lynwood, CA area in May of 2018. Measurements were collected between Monday, May 7 through Wednesday May 9, 2018 between the hours of 8:00 and 17:30 on the on-ramp from southbound Long Beach Blvd. to eastbound I-105. This was followed with three additional days of measurements collected between Thursday May 10 and Saturday, May 12, 2018 during similar hours on the off-ramp from northbound I-710 to westbound Imperial Highway. Databases were compiled for each site with the Long Beach Blvd. / I-105 site containing 7,724 records and the I-710 / Imperial Highway location having 14,302 records for which the California Air Resources Board provided vehicle registration information. All of these records contained valid measurements for at least CO and CO_2, and most records contained valid measurements for the other species as well. The database, as well as others compiled by the University of Denver, can be found at www.feat.biochem.du.edu.

The 2018 mean CO, HC, NO, NH_3 and NO_2 emissions for the fleet measured at the Long Beach Blvd. / I-105 location were 10.4 ± 0.4 g/kg of fuel (0.08%), 2.1 ± 0.3 g/kg of fuel (56 ppm), 2.05 ± 0.04 g/kg of fuel (145 ppm), 0.62 ± 0.01 g/kg of fuel (77 ppm) and 0.03 ± 0.01 g/kg of fuel (1.3 ppm) respectively. The average fleet model year was 2008.6 for an approximate age of 10.1 years (assuming a September 1 starting point for new models). At the I-710 / Imperial Highway location the measured means were 12.3 ± 0.2 gCO/kg of fuel (0.1%), 2.0 ± 0.2 gHC/kg of fuel (52 ppm), 1.72 ± 0.08 g/kg of fuel (122 ppm), 0.43 ± 0.03 g/kg of fuel (54 ppm) and 0.03 ± 0.01 g/kg of fuel (1.6 ppm). The mean fleet model year of 2008.4 and age of 10.3 years old was slightly older than the fleet at the Long Beach Blvd. site. The 2018 Lynwood emission means are generally consistent with the last measurements collected at the West Los Angeles site in 2015 and now appear to be more in line with other locations across the basin. However, the two Lynwood sites still have a fleet that is more than a year older than the West Los Angeles site.

When compared with the previous measurements from 1989, there are dramatic decreases for mean CO (g/kg of fuel) of factors of 10 (Long Beach Blvd. site) and 20 (I-710 site). For fuel specific HC emissions, there is a reduction of a factor of 25 from the 1991 Long Beach Blvd. measurements. Fleet age has changed little at the Long Beach Blvd. site (9.7 years old in 1989 and 10.1 years old in 1991 to 10.1 years old in 2018) but increased significantly at the I-710 off-ramp from the 1989 measurements (7.4 years old to 10.3 years old) matching the age now observed along Long Beach Blvd. Despite similar average fleet ages between the 1989 and 2018 Long Beach Blvd. measurements, the age distribution has changed since 1989. Because of the 2008 recession, the 2018 measurements contain fewer 7 to 10 year old vehicles (model years 2011 to 2008) and increased numbers of 15 year old and older vehicles (model years 2003 and older). A notable characteristic of the 1989 Long Beach Blvd. fleet was the large percentage of 11 and 12 year old vehicles (model years 1979 and 1978, ~16% of total) which have seen a reduction to 11% of the total in 2018, replaced in importance by 2 and 3 year old vehicles (15%).

The CO distributions for the 1989 and 2018 data sets converge to a similar value at or slightly above 1000 gCO/kg of fuel at the very top of the distribution that is above the 99.9th probability. The change between the two distributions, as a percent of the 1989 CO values, is reasonably constant between the 50th and the 95th probability level of a ~95% reduction for the Long Beach Blvd. comparison. Above the 95th probability, the distributions converge and the percent reduction in emissions decreases. However, the ages of the two fleets at the top of the distribution are markedly different. The average age of the 99th percentile and above vehicles for the Long Beach Blvd. and I-710 off-ramp sites were 13.7 (1976.6) and 11.5 (1978.8) years old in 1989 while the 2018 ages for the comparable sites were 21.7 (1997) and 23.8 (1994.9) or approximately double the age of the 1989 group. Differences in the fuel specific HC emissions also show consistent reductions across all of the distribution, even for probabilities above the 99.9th probability line with the two distributions generally not converging. The ages of the vehicles found above the 99th probability line for these data sets are 14.8 (1977) years old for the 1991 data and 10.4 years old for the 2018 measurements.

Mean fuel specific NH_3 emissions for the 2018 Lynwood I-105 measurements were found to be ~30% higher (0.62 ± 0.01 versus 0.43 ± 0.03) than the similar fleet measured at the I-710 site. This difference appears to be a result of the vehicles measured at the I-105 site being simply offset to a higher NH_3 emissions level than similarly aged vehicles measured at the I-710 site. Speeds and acceleration rates were higher at the I-105 site but that does not help to explain the difference. Comparisons with the 2015 measurements from the West Los Angeles site show that the Long Beach Blvd. / I-105 measurements have similar NH_3 emission levels, especially for the first 9 model years. The West Los Angeles measurement site is a traffic light controlled on-ramp to eastbound I-10 that is fed by traffic from southbound La Brea Ave., a traffic light controlled surface street.

Dynamometer studies have shown that decelerations followed by accelerations can increase the amounts of hydrogen stored on 3-way catalytic converters increasing the availability of hydrogen, a potentially limiting reagent in the reduction of NO to NH_3. One major difference between the Long Beach Blvd. and I-710 sites is the upstream traffic conditions. The I-105 site collects traffic off of a major surface street that is traffic light controlled at all of the major cross streets which forces stop and go driving by these vehicles before they reach the on-ramp. The I-710 location samples vehicles coming directly from the freeway and while stop and go freeway traffic is common on LA freeways it is not as regular as traffic lights on Long Beach Blvd. The model year NH_3 emission differences between the two sites may be the consequence of: (a) the upstream driving patterns at the two sites and (b) the stop and go driving along Long Beach Blvd. that provides more hydrogen for NO reduction.

Total fixed nitrogen emissions have been on a steep decline since the mid-nineties in the gasoline fleet and are continuing to show decreases in the newest model years in the Lynwood data as well. However, the percent of fixed nitrogen made up of NH_3 has continued to rise at the two Lynwood sites since the introduction of LEV II vehicles and NH_3 is now the dominant reactive nitrogen species in exhaust. This is in contrast to the NH_3/NO_x ratio in the newest model year vehicles in the most recent Denver, CO measurements where NH_3 percentages have leveled out and started declining with newer model year vehicles now favoring NO_x production. It is known that catalyst formulation, in regards to the amount and type of precious metals employed, can influence reduction (NH_3) or oxidation (NO_x) of the exhaust stream in addition to the control of the air to fuel ratio with slightly rich lambda settings producing NH_3 and slightly lean settings favoring NO_x formation. The differences in the NH_3/NO_x ratios in the exhaust may be related to this fact or be influenced by driving mode.

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APPENDIX A: How standard error 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 calculation that may not be familiar to many readers. 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 usually 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 error 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 2018 Lynwood Long Beach Blvd. / I-105 gCO/kg of fuel and gNO/kg of fuel for matched plate 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.

Lynwood 2018

Date	Mean gCO/kg of fuel	Counts	Mean gNO/kg of fuel	Counts
5/7/18	10.35	2474	2.00	2473
5/8/18	9.63	2604	2.02	2604
5/9/18	11.10	2646	2.12	2646
Average for Daily Means	10.36		2.04	
Standard Error for the daily means	0.43		0.04	
Weighted Fleet Mean	10.36		2.05	
Standard Error calculated for the fleet means	0.43		0.04	
As reported in Table 6	10.4 ± 0.4		2.05 ± 0.04	

APPENDIX B: 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 ±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 ±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 ±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 ±50ppm.

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

10) Excessive error on NO_2/CO_2 slope, equivalent to ±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 C: Explanation of the Lynwd105_18.dbf and Lynwd710_18.dbf databases.

The Lynwood databases 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 this database:

License	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.
PercentSO2	Sulfur dioxide concentration, in percent (NOT CALIBRATED).
SO2_err	Standard error of the sulfur dioxide 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”.
CO2_max	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	10 –digit vehicle identification number stem.
Make	Manufacturer of the vehicle.
Year	Model year.
Series	DMV model information
Model	DMV model designation.
Fuel	Fuel type G (gasoline), D (diesel), N (natural gas) and Q (hybrid).
Gvw_code	DMV gross vehicle weight code
Unladen_wt	DMV unladen vehicle weight in lbs.
Disp_ci	DMV engine displacement in cubic inches.
County	California county number where vehicle is registered.
Zipcode	Registrant's 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	Percent hydrocarbon concentration 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 calculated using the equation provided in the report. KW/metric ton

APPENDIX D: Temperature and Humidity Data from Los Angeles International Airport

Lynwood I-105 Temperature and Humidity Data

5/7 Time	5/7 °F	5/7 %RH	5/8 Time	5/8 °F	5/8 %RH	5/9 Time	5/9 °F	5/9 %RH
7:53	62	78	7:53	61	84	7:53	64	73
8:53	65	66	8:53	65	73	8:53	67	68
9:53	70	53	9:53	67	68	9:53	67	68
10:53	68	61	10:53	65	70	10:53	67	68
11:53	68	61	11:53	66	68	11:53	68	65
12:53	67	63	12:53	67	66	12:53	68	65
13:53	66	65	13:53	68	63	13:53	68	65
14:53	66	68	14:53	67	68	14:53	66	70
15:53	66	68	15:53	66	70	15:53	64	75
16:53	65	70	16:53	64	75	16:53	65	73
17:53	62	80	17:53	63	78	17:53	62	80

Lynwood I-710 Temperature and Humidity Data

5/10 Time	5/10 °F	5/10 %RH	5/11 Time	5/11 °F	5/11 %RH	5/12 Time	5/12 °F	5/12 %RH
7:53	64	75	7:53	62	70	7:53	61	70
8:53	65	73	8:53	63	68	8:53	62	70
9:53	68	68	9:53	63	70	9:53	61	72
10:53	67	68	10:53	64	65	10:53	61	75
11:53	67	68	11:53	64	70	11:53	63	68
12:53	68	65	12:53	65	68	12:53	63	70
13:53	66	70	13:53	65	68	13:53	66	63
14:53	65	73	14:53	65	66	14:53	66	61
15:53	65	73	15:53	63	68	15:53	65	63
16:53	64	68	16:53	63	68	16:53	63	68
17:53	63	70	17:53	62	70	17:53	62	70

APPENDIX E: 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 E1. 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 E1. 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 F: Field Calibration Record.

Lynwood I-105						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
5/7	8:30	3.10	3.03	2.42	0.75	2.26
5/7	9:30	2.77	2.76	2.32	0.82	1.97
5/7	12:00	2.48	2.49	2.12	0.85	1.75
5/7	15:00	2.37	2.40	1.97	0.84	1.72
5/8	7:30	3.11	3.26	2.79	0.83	2.61
5/8	9:40	2.67	2.85	2.42	0.87	2.12
5/8	12:00	2.33	2.62	2.24	0.93	1.81
5/8	15:00	2.36	2.39	2.07	0.93	1.68
5/9	8:20	2.79	2.86	2.30	0.90	2.43
5/9	10:05	2.53	2.72	2.16	0.93	2.06
5/9	12:15	2.35	2.48	1.96	0.95	1.78
5/9	15:00	2.36	2.48	2.00	0.94	1.87

Lynwood I-710						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
5/10	8:00	2.23	2.32	1.93	0.85	1.88
5/10	10:00	2.00	2.13	1.79	0.88	1.70
5/10	12:25	1.82	1.92	1.59	0.92	1.45
5/11	7:35	2.35	2.38	2.10	0.89	2.05
5/11	9:30	2.15	2.18	1.99	0.94	2.00
5/11	12:00	2.12	2.13	1.89	0.95	1.85
5/11	14:15	2.11	2.16	2.02	0.93	1.97
5/12	7:35	2.27	2.26	1.97	0.82	2.11
5/12	9:30	2.22	2.26	1.94	0.86	1.98
5/12	12:00	2.14	2.16	1.89	0.89	1.85
5/12	14:45	2.07	2.13	1.84	0.91	1.75