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Gary A. Bishop

Molly J. Haugen

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On-Road Remote Sensing of Automobile Emissions in the Chicago Area: Fall 2016

Gary A. Bishop and Molly J. Haugen

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

Prepared for:

Coordinating Research Council, Inc.
5755 North Point Parkway, Suite 265
Alpharetta, Georgia 30022
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EXECUTIVE SUMMARY

The University of Denver has completed the ninth year of a multi-year remote sensing study in the Chicago area, with measurements made in Septembers of 1997 through 2000, 2002, 2004, 2006, 2014 and 2016. The remote sensor used in the 2016 study measured the ratios of CO, HC, NO, SO_2, NH_3 and NO_2 to CO_2 in motor vehicle exhaust. Mass emissions per mass or volume of fuel are determined from these ratios and are the units used for the major results in this report. From these ratios, we can also 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 air. The system used in this study was configured to determine the speed and acceleration of the vehicle, and was accompanied by a video system to record the license plate of the vehicle and, from this record, the vehicle's model year. Since fuel sulfur has been nearly eliminated in US fuels, SO_2 emissions are generally below detection limits. While vehicle SO_2 measurements are routinely collected and archived for each data campaign, since 2012 we have not calibrated these measurements and they are not included in the discussion of the results.

The ninth campaign of this study involved fieldwork on September 12 - 21, 2016, conducted at the on-ramp from Algonquin Rd. to eastbound I-290 in northwest Chicago. This year's data collection is larger than in the past as a result of an extra three days of measurements collected in support of an instrument inter-comparison with the EDAR system developed by HEAT. For the 2016 measurements, a database was compiled containing 30,062 records for which the State of Illinois provided make and model year information. All of these records contain valid measurements for at least CO and CO_2, and most records contain valid measurements for the other species. The database, as well as others compiled by the University of Denver, can be found at www.feat.biochem.du.edu.

The CO, HC, NO, NH_3 and NO_2 mean and standard errors of the mean emissions for the fleet measured in this study were 10.9 ± 0.4 gCO/kg of fuel (0.09 ± 0.01 %), 1.8 ± 0.1 gHC/kg of fuel (46 ± 3 ppm), 1.2 ± 0.1 gNO/kg of fuel (84 ± 7 ppm), 0.64 ± 0.02 gNH_3/kg of fuel (79 ± 2 ppm) and 0.1 ± 0.01 gNO_2/kg of fuel (5 ± 0.5 ppm) respectively. When compared with the measurements from 2014 both the CO (+16%) and HC (+38%) emissions have increased, and NO (-20%) and NH_3 (-10%) mean emissions have decreased. This is the first time in our history of measurements taken at this site that the CO and HC emissions have not decreased but they follow a similar pattern of the 2015 measurements made in both Tulsa and Denver. However, the Denver interchange ramp was rebuilt prior to the 2015 measurements significantly changing the driving mode by increasing the fraction of higher speed deceleration events and may not be representative. The emissions measurements in this study exhibit a gamma distribution and the 99^{th} percentile for the 2016 measured fleet is responsible for 27%, 25%, 31% and 10% of the CO, HC, NO and NH_3 total fleet-wide emissions, respectively. The age of the average vehicle in the 2016 measured fleet remained constant at the 2014 level of 7.5 years old.

Figure E1 is a historical summary of the fuel specific mean emissions for all the Chicago light-duty measurements to date as well as the mean emissions for the other E-23 and E-106 sites

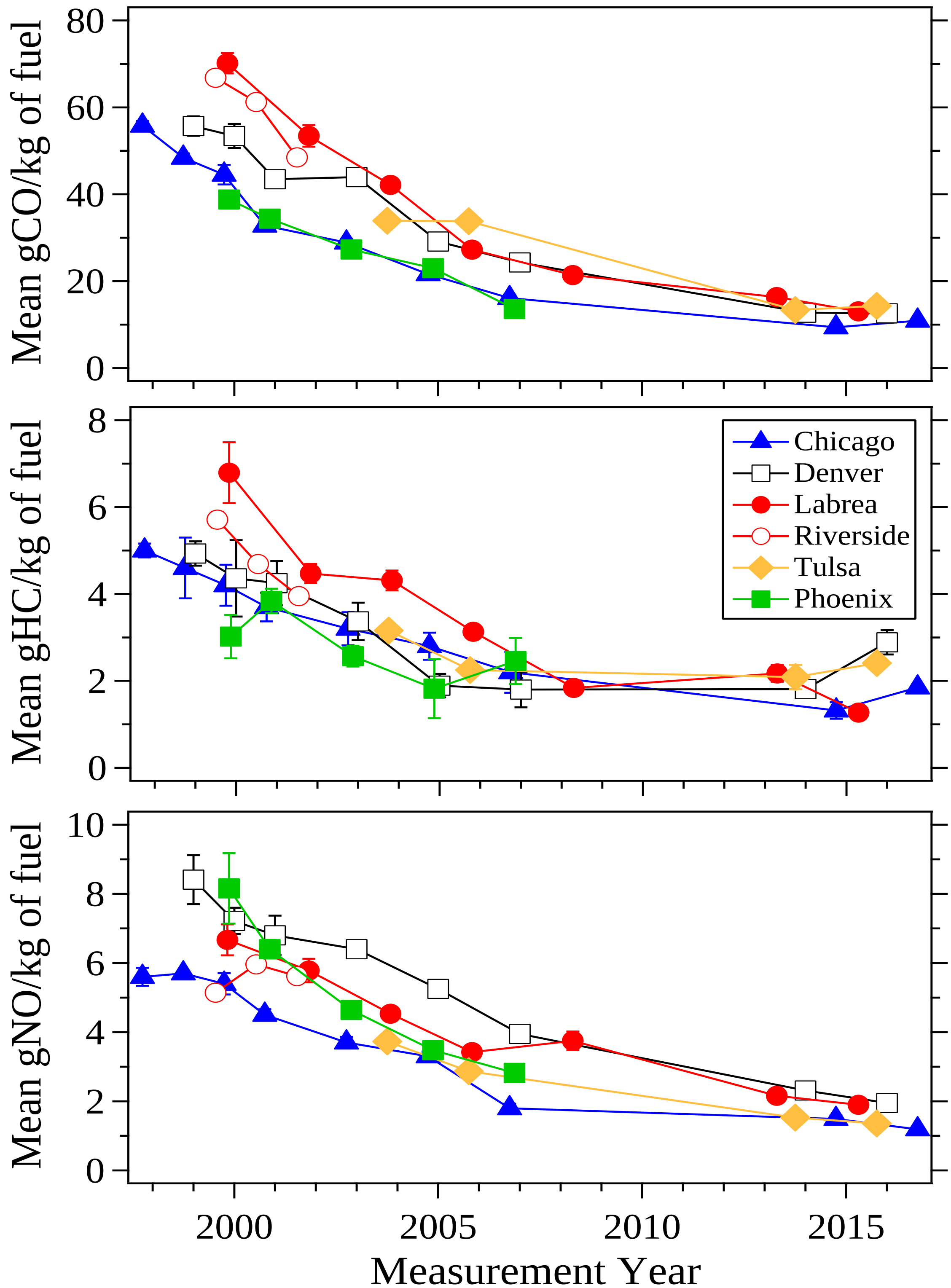


Figure E1. Historical fuel specific mean emission for CO (top), HC (middle) and NO (bottom) for all of the E-23 and E-106 light-duty measurements to date. Uncertainties are standard errors of the mean determined from the daily measurements. HC means have been offset adjusted as described in the text.

(Omaha is the exception). All of the sites tell a similar story with large reductions in emissions of all three species during the first decade of measurements. The trend, since the resumption of measurements in 2013, has been a slowdown in the absolute reduction of emissions over time. The most recent measurements in Chicago, Denver and Tulsa have shown mean emissions to increase slightly for CO and HC. In addition, the increases in HC emissions observed at the Denver site in 2015 were definitely influenced by the new driving mode introduced by the reconstruction of the roadway ramp as made evident by an increase in the number of negative VSP measurements.

Several factors have likely contributed to the slowdown in the reduction in the mean emissions. Due to the recession of 2008 and 2009 the average age of the fleet has increased 1.5 model years from around 6 years old in 2006 to 7.5 years old in the 2014 and 2016 measurements. An additional factor can be seen in Figure E2 which compares the fuel specific emissions by vehicle age for CO, HC and NO for the original data set collected in 1997 and the most recent measurements collected in 2016. The mean CO and HC emissions for the average 20 year old vehicle measured in 2016 are similar to those of the average 5 and 7 year old vehicles measured in 1997. In 2016, both CO and HC emissions show little change in mean emissions for the first 10 to 12 model years, unlike in the 1997 data set. NO is the only species where 20 year old vehicles in 2016 have similar emissions to 20 year old vehicles measured in 1997. However, it is only since the model year 2004 – 2009 phase-in of Tier 2 emissions compliant light-duty vehicles that NO emissions have been aggressively targeted for reduction. In the bottom panel one can see that mean on-road fuel specific NO emissions are now being well controlled as it is not until model year 2009 (i.e., 9 year or older vehicles in 2016) that the age-based mean emissions begin to rise. It is this lack of significant emission deterioration which also contributes to the slowing of the fleet mean reductions from fleet turnover over time since a new vehicle purchased today will most likely replace a vehicle with emissions that are, on average very similar.

NH_3 measurements (0.64 ± 0.02 gNH_3/kg of fuel) in 2016 represent almost a 10% reduction from the mean observed in 2014. Emissions reductions observed from the 2016 and 2017 models measured in 2016, which account for 9% of the total fleet, are a major factor in the 10% reduction in mean emissions observed since 2014 despite some increases in a few later model year vehicles. Other differences between the two measurement years include an unexplained increase in model year 2009 emissions observed in 2014 which was not present in the 2016 study. The total fixed nitrogen species have continued to decrease and the percent contributed by ammonia has steadily increased and now dominates the small amount of fixed nitrogen being emitted by the newest model year vehicles. Ammonia dominates NO_x emissions from vehicles up to 10 years of age in Chicago in the 2016 measurements, the same as observed in 2014.

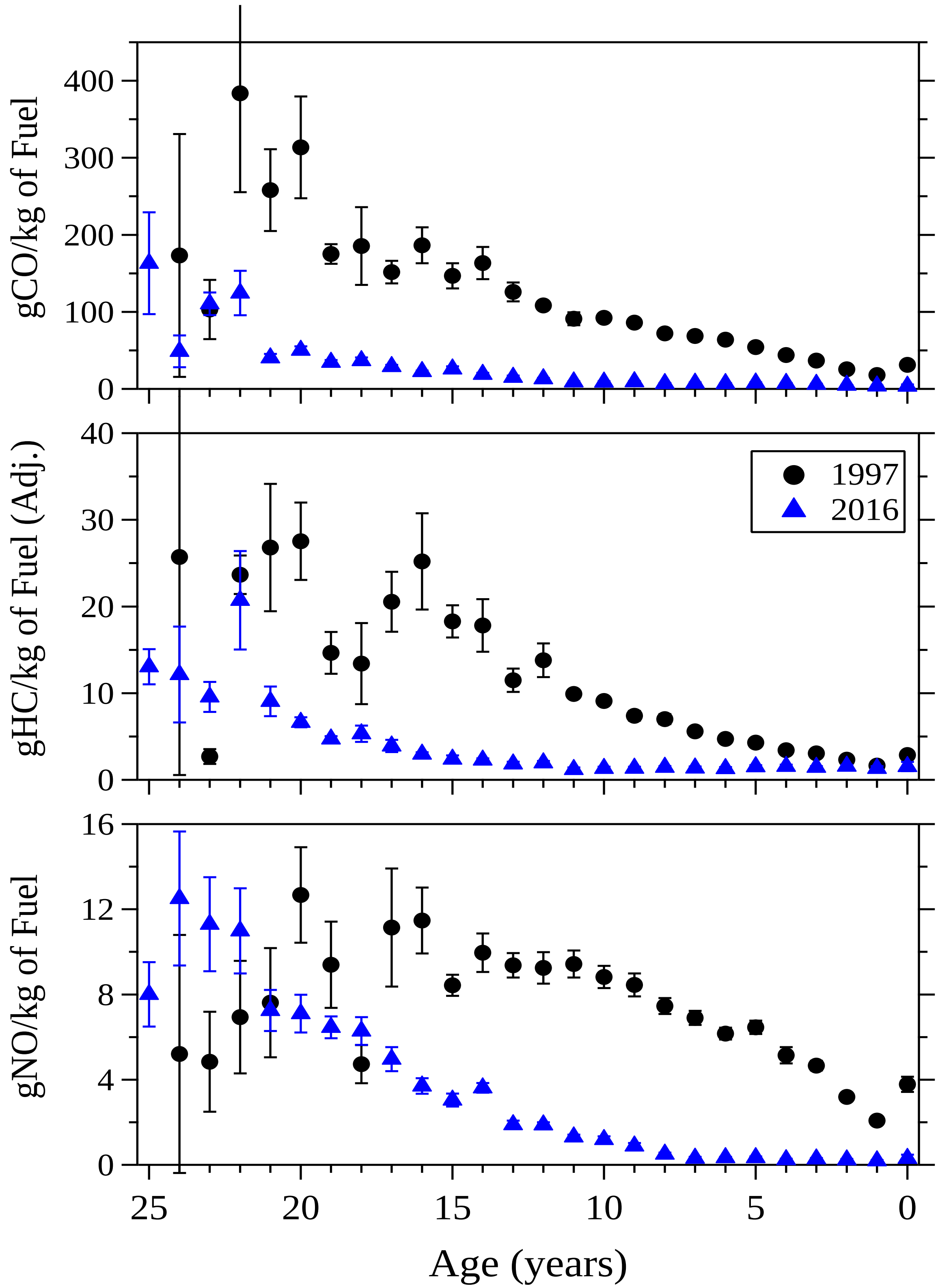


Figure E2. Mean fuel specific emissions by vehicle age for the 1997 (circles) and 2016 (triangles) Chicago data sets for CO (top), HC (middle) and NO (bottom). Uncertainties are standard error of the means calculated from the daily samples.

INTRODUCTION

Since the early 1970's, many heavily populated U.S. cities have violated the National Air Quality Standards (NAAQS) established by the Environmental Protection Agency (EPA) pursuant to the requirements of the Federal Clean Air Act.[1, 2] Carbon monoxide (CO) levels become elevated primarily due to direct emission of the gas, and ground-level ozone, a major component of urban smog, is produced by the photochemical reaction of nitrogen oxides (NO_x) and hydrocarbons (HC). Ambient levels of particulate emissions can result either from direct emissions of particles or semi-volatile species or from secondary reactions between gaseous species, such as ammonia and nitrogen dioxide. 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 VOC's, 3% of the NH_3 and 36% of the NO_x to the national emission inventory.[3]

The use of the internal combustion engine (and its combustion of carbon-based fuels) as a primary means of transportation, makes it a significant contributor of species 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, 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 is difficult to quantify. Many areas remain in non-attainment for ozone. The further tightening of the federal eight-hour ozone standards (first introduced by the EPA in 1997 and subsequently lowered in 2008) means that many new locations are likely to have difficulty meeting the standards in the future.

In 1997, the University of Denver began conducting on-road tailpipe emission surveys at a site northwest of Chicago IL, in Arlington Heights to follow long term emission trends. Since 1997, measurements have also been collected in Los Angeles CA, Denver CO, Omaha NE, Phoenix AZ, Riverside CA, and Tulsa OK.[5] Following a protocol established by the Coordinating Research Council (CRC) as part of the E-23 program, the data collected have provided valuable information about the changes in fleet average on-road emission levels. The data have also been used by many researchers to study fleet emission trends and construct emission inventories.

Reflecting a desire to continue evaluation of historical and recent emissions trends, several of the E-23 sites have been chosen for additional data collection. This report describes the on-road emission measurements taken in the Chicago IL area in the fall of 2016, under CRC Contract No. E-106. Measurements were made on parts of eight weekdays, from Monday, September 12, to Wednesday, September 21 (note data were not collected on Saturday or Sunday) between the hours of 9:00 and 18:30 on the on-ramp from Algonquin Rd. to southbound I-290/SH53. The additional days were included as part of an inter-comparison with the EDAR remote sensor developed by HEAT. Since the measurements were collected at the same sampling site we have taken advantage of that and combined them to create a larger data set. Measurements have previously been collected eight times at this same location in 1997, 1998, 1999, 2000, 2002, 2004, 2006 and 2014.

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; it has been extensively discussed in the literature.[6-8] The instrument consists of a non-dispersive infrared (NDIR) component for detecting CO, CO_2, and HC and twin dispersive ultraviolet (UV) spectrometers (0.26 nm/diode resolution) for measuring oxides of nitrogen (NO and NO_2), SO_2 and NH_3. The source and detector units are positioned on opposite sides of a single lane road in a bi-static arrangement. Collinear beams of infrared (IR) and UV light are passed across the roadway into the IR detection unit then focused through a dichroic beam splitter, which separates 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 beam splitter and focused onto the end of a quartz fiber bundle mounted to a coaxial connector on the side of the detector unit. The quartz fibers in the bundle are divided in half to carry the UV signal to two separate spectrometers. The first spectrometer's wavelength ranges from 227nm down to 198nm to measure the species of NO, SO_2 and NH_3. 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 to obtain the vehicle emissions. The second spectrometer measures only NO_2 by measuring an absorbance band at 438nm in the UV spectrum and comparing it to a calibration spectrum in the same region.[9] All species are sampled at 100Hz. Since the removal of sulfur from US gasoline and diesel fuel, SO_2 emissions have become negligibly small. 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 depend on, 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 measures directly only 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; they are useful parameters for describing a hydrocarbon combustion system. This study reports measured emissions as grams/kilogram of fuel (g/kg of fuel) or 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. 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.[10] To calculate mass emissions as described below, the %HC values reported are first multiplied by 2.0 as shown below to account for these "unseen" hydrocarbons, assuming that the fuel used is regular gasoline. These percent emissions can be directly converted into mass emissions by the following equations.

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

These equations 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 nearly 100% NO in the case of gasoline-fueled vehicles.

The major relationship reported here is the direct conversion from the measured pollutant ratios to g/kg of fuel. This is achieved by first converting the pollutant ratio readings to moles of pollutant per mole of carbon in the exhaust using the following equation:

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

Next, moles of pollutant are converted to grams by multiplying by molecular weight (e.g., 44 g/mole for HC since propane is measured), and the moles of carbon in the exhaust are converted to kilograms by multiplying (the denominator) by 0.014 kg of fuel per mole of carbon in the 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.[10]

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

Quality assurance calibrations are performed twice daily in the field unless observed voltage readings or meteorological changes are judged to warrant additional calibrations. The multi-species instrument used in this study requires three calibration cylinders. The first contains 6% CO, 6% CO_2, 0.6% propane and 0.3% NO; the second contains 0.1% NH_3 and 0.6% propane and the final cylinder contains 0.05% NO_2 and 15% CO_2. A puff of gas is released into the instrument's path, and the measured ratios from the instrument are compared to those certified by the cylinder manufacturer (Air Liquide). These calibrations account for day-to-day variations in instrument sensitivity and variations in ambient CO_2 levels caused by local sources, atmospheric pressure and instrument path length. Since propane is used to calibrate the instrument, all hydrocarbon measurements reported by the remote sensor are reported as propane equivalents.

Studies sponsored by the California Air Resources Board and General Motors Research Laboratories have shown that the remote sensor is capable of CO measurements that are correct to within ±5% of the values reported by an on-board gas analyzer, and within ±15% for HC.[11, 12] The NO channel used in this study has been extensively tested by the University of Denver, but we are still awaiting the opportunity to have it independently validated in an extensive blind study and instrument intercomparison. 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.[7] A list of criteria for determining data validity is shown in Appendix A.

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 and a time and date stamp are 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 0.1 mph) 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. Acceleration is calculated (reported to 0.001 mph/sec) from these two speeds and the time difference between the two speed measurements. Appendix B defines the database format used for the data set.

RESULTS AND DISCUSSION

Following the eight days of data collection in September of 2016, the digital images were transcribed for license plate identification. Plates that appeared to be in state and readable were sent to the State of Illinois to be matched against the state non-personal vehicle registration information. The resulting database contained 30,062 records with make and model year information and valid measurements for at least CO and CO_2. The database and all previous databases compiled for CRC E-106 and CRC E-23-4 campaigns can be found at www.feat.biochem.du.edu. The majority of these records also contain valid measurements for HC, NO, NH_3 and NO_2.

The data reduction process of the measurements is summarized in Table 1. The table details the steps beginning with the number of attempted measurements and ending with the number of records containing both valid emissions measurements and vehicle registration information. An

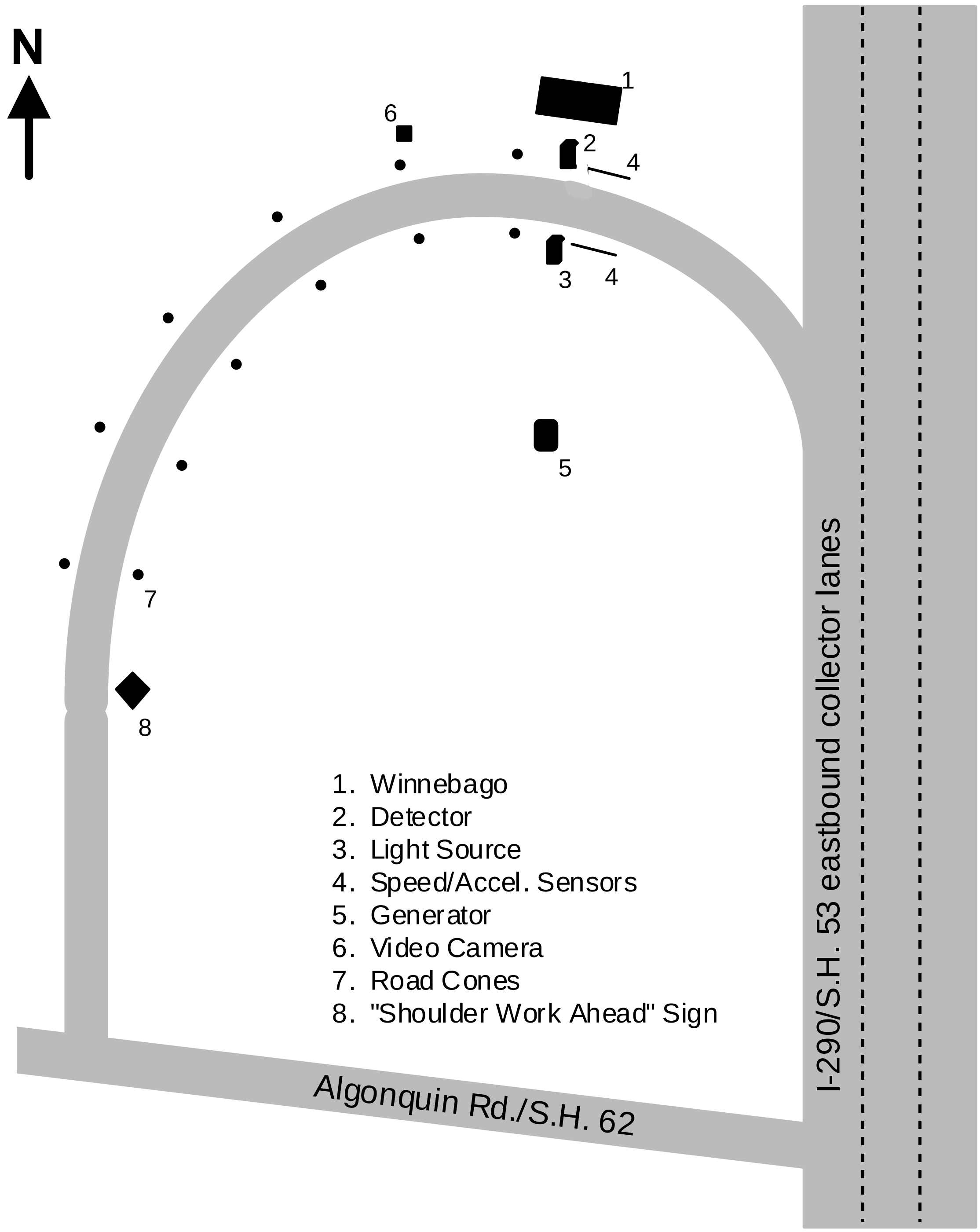


Figure 1. Area map of the on-ramp from Algonquin Road to eastbound I-290 in northwest Chicago, showing remote sensor configuration and safety equipment.


Figure 2. A photograph looking east at the Algonquin Rd. monitoring site and 2014 remote sensing setup.

Table 1. Validity Summary.

	CO	HC	NO	NH_3	NO_2
Attempted Measurements	40,602				
Valid Measurements	35,786	35,759	35,784	35,741	35,402
Percent of Attempts	88.1%	88.1%	88.1%	88.0%	87.2%
Submitted Plates	30,370	30,354	30,368	30,332	30,087
Percent of Attempts	74.8%	74.8%	74.8%	74.7%	74.1%
Percent of Valid Measurements	84.9%	84.9%	84.9%	84.9%	85.0%
Matched Plates	30,062	30,046	30,060	30,024	29,781
Percent of Attempts	74.0%	74.0%	74.0%	73.9%	73.3%
Percent of Valid Measurements	84.0%	84.0%	84.0%	84.0%	84.1%
Percent of Submitted Plates	99.0%	99.0%	99.0%	99.0%	99.0%

attempted measurement is defined as a beam block followed by a half second of data collection. If the data collection period is interrupted by another beam block from a close following vehicle, the measurement attempt is aborted and a new attempt is made to measure the second vehicle. In this case, the beam block from the first vehicle is not recorded as an attempted measurement. The first significant data losses occur from invalid measurement attempts when the vehicle plume misses the sampling beam, is highly diluted or the reported error in the ratio of the pollutant to CO_2 exceeds a preset limit (See Appendix A). The second significant loss of data occurs during the plate reading process, when out-of-state vehicles and vehicles with unreadable plates (obscured, rusted, missing, dealer, out of camera field of view) are omitted from the database.

Table 2 provides an analysis of the number of vehicles that were measured repeatedly and the number of times they were measured. Of the 30,062 records used in this analysis, 14,148 (47%) were contributed by vehicles measured once, and the remaining 15,914 (53%) records were from vehicles measured at least twice.

Table 2. Number of measurements of repeat vehicles.

Number of Times Measured	Number of Vehicles
1	14,148
2	2,467
3	1,242
4	739
5	461
6	205
7	69
>7	32

Table 3 provides the data summary for 2016 and also includes summaries of all previous remote sensing databases collected by the University of Denver at the I-290 and Algonquin Rd. site. These other measurements were conducted in September of 1997, 1998, 1999, 2000, 2002, 2004, 2006 and 2014. For the first time since measurements began at the Algonquin Rd. site, the mean fleet emissions for CO and HC increased slightly while those for NO and NH_3 means continued to show decreases. The fleet age remained unchanged at 7.5 years – still high relative to that observed before the 2008 - 2009 recession. The percentage of emissions contributed by the 99^{th} percentile decreased for CO and HC and increased for NO and NH_3. The decreases indicate a less skewed CO and HC emission distribution. These small changes between 2014 and 2016 raise the question: have we reached the limit of emissions reductions gained through vehicle emission improvements? Certainly the reductions in mean NO emissions reflect the growing number of Tier II vehicles that occupy a larger fraction of the fleet. Traffic volumes in 2016 were slightly larger than seen in the previous year measurements. Afternoon stop-and-go driving brought about by congestion downstream on the freeway was similar.

Table 3. Historical data summary.

Study Year	1997	1998	1999	2000	2002	2004	2006	2014	2016
Mean CO (%) (g/kg of fuel)	0.45 (55.8)	0.39 (49.0)	0.35 (44.2)	0.26 (32.8)	0.23 (28.9)	0.17 (21.5)	0.13 (16.1)	0.074 (9.4)	0.085 (10.9)
Median CO (%)	0.14	0.15	0.09	0.05	0.07	0.04	0.02	0.011	0.023
Percent of Total CO from the 99th Percentile	13.9%	14.6%	16.5%	19.6%	20.4%	22.3%	26.3%	34.4%	27.1%
Mean HC (ppm)[a] (g/kg of fuel)[a] Offset (ppm)	130 (5.3) 80	130 (5.3) 120	109 (4.5) 70	94 (3.9) 60	80 (3.2) 10	72 (2.8) 20	58 (2.2) 10	35 (1.3) 12.5/30[b]	46 (1.8) 25
Median HC (ppm)[a]	50	50	50	40	40	30	30	9	22
Percent of Total HC from the 99th Percentile	21.0%	26.7%	22.8%	22.2%	21.9%	24.8%	33.9%	42.5%	24.5%
Mean NO (ppm) (g/kg of fuel)	400 (5.5)	405 (5.7)	378 (5.3)	316 (4.5)	262 (3.7)	236 (3.3)	125 (1.8)	105 (1.5)	84 (1.2)
Median NO (ppm)	160	140	121	79	52	39	14	5	3
Percent of Total NO from the 99th Percentile	8.7%	8.1%	9.7%	11.2%	13.2%	13.5%	18.8%	24.9%	30.8%
Mean NH_3 (ppm) (g/kg of fuel)								89 (0.71)	79 (0.64)
Median NH_3 (ppm)								43	38
Percent of Total NH_3 from the 99th Percentile								10.3%	10.4%
Mean NO_2 (ppm) (g/kg of fuel)								-1.5 (-0.04)	5 (0.1)
Median NO_2 (ppm)								-3.6	2
Percent of Total NO_2 from the 99th Percentile								N.A.	36.6%
Mean Model Year	1992.7	1993.6	1994.3	1995.5	1997.4	1999.2	2001.0	2007.5	2009.6
Mean Fleet Age[c]	5.3	5.4	5.7	5.5	5.6	5.8	6	7.5	7.5
Mean Speed (mph)	25.1	24.7	25.8	24.5	24.2	24.3	23.9	24.0	24.1
Mean Acceleration (mph/s)	0.1	0.8	0.2	0.5	-0.4	0.4	0.4	0.2	0.5
Mean VSP (kw/tonne) Slope (degrees)[d]	5.3 1.5°	9.3 1.5°	6.0 1.5°	7.9 1.5°	-6.9 1.0°	6.0 1.0°	5.9 1.0°	4.8 1.0°	6.7 1.0°

[a]Indicates values that have been HC offset adjusted as described in text.
[b]Different offset values applied to the first 3 and last 3 days due to weather change.
[c]Assumes new vehicle model year starts September 1.
[d]Roadway was repaved between 2000 and 2002, which caused a slight change in the slope.

The mean HC values have been adjusted to remove a systematic offset in the measurements. This offset, restricted to the HC channel, has been reported in previous CRC reports. 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, using the lowest of either of these values as the offset. The offset adjustment subtracts this value from all of the hydrocarbon data. For the 2016 Chicago data this process was done using all eight days of measurements. Since it is assumed that the cleanest vehicles emit little hydrocarbons, this approximation will only err slightly towards clean because the true offset will be a value somewhat less than the average of the cleanest model year and make. Unless otherwise stated, the analysis of the HC measurements in this report uses the offset adjusted data.

The inverse relationship between vehicle emissions and model year is shown in Figure 3 for data collected during each of the eight campaigns. The HC data have been offset adjusted as previously described. As previously mentioned the mean CO (+16%) and HC (+38%) emissions increased between the 2014 measurements and the 2016 measurements. Mean emission increases have also been observed in the most recent 2015 measurements in Denver and Tulsa. These increases are generally concentrated in emission increases in the first fifteen model year vehicles for both CO and HC. Since the fleet fractions in Chicago are dominated by the first ten model years (~70% of the fleet) emission changes in this group will be strongly reflected in the mean emissions. However, emission model year trends observed in 2016 are nearly identical to those observed in 2014 with little change in mean CO and HC emissions over the first 10 to 12 model years. NO emissions continued to expand on the number of model years observed in 2014 with very low and stable fuel specific NO emissions with no statistical differences in mean gNO/kg of fuel emissions now for the first 8 or 9 model years.

As originally presented by Ashbaugh et al., vehicle emissions by model year, with each model year divided into emission quintiles, were plotted for data collected in 2016.[13] This resulted in the plots shown in Figures 4 - 6. The bars in the top graphs represent the mean emissions for each quintile. The middle graphs give the fraction of the fleet for each model year. The impact of the reduction in light-duty vehicle sales due to the economic recession is still clearly evident in the fleet model year fraction beginning in 2009 and continuing through 2012. The bottom graphs, which are a product of the first two graphs, display the fraction of the total emissions by quintiles and model year. Model years older than 1996 and not graphed account for only ~0.7% of the measurements and contributes between 6.2% (HC) to 7.7% (CO) of the emissions. The bottom graphs for each species illustrates that the first three quintiles of the measurements (60%), regardless of model year; make an essentially negligible contribution to the total emissions. For CO and HC only the last quintile now contributes significant amounts to the total. The large accumulations of negative emissions in the first two quintiles are the result of ever decreasing emission levels. The instrument is designed such that when measuring a zero emission plume, half of the readings will be negative and half will be positive. As the lowest emitting segments of the fleets continue to dive toward zero emissions, the negative emission readings will continue to grow toward half of all the measurements. The newest model years are at that stage now for all species.

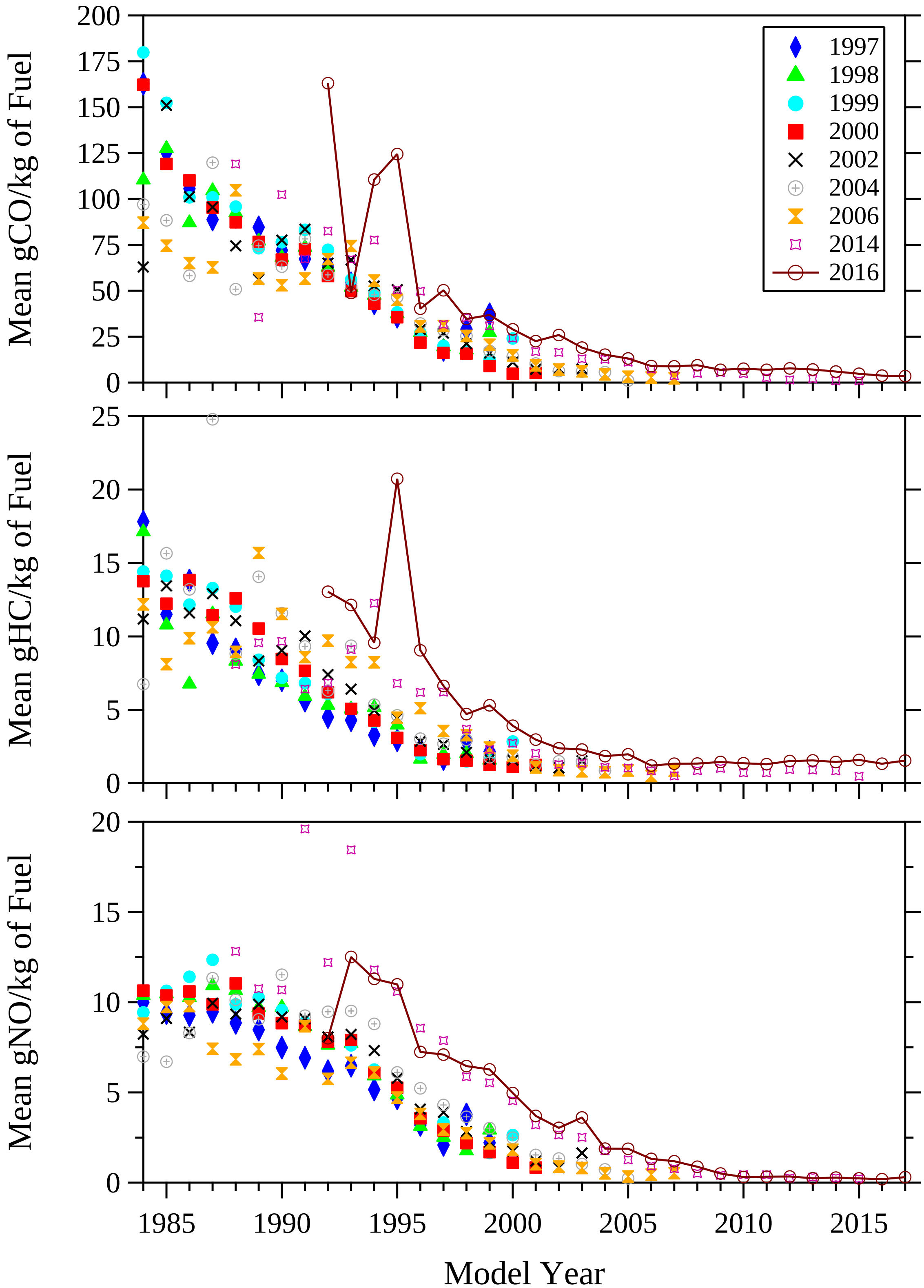
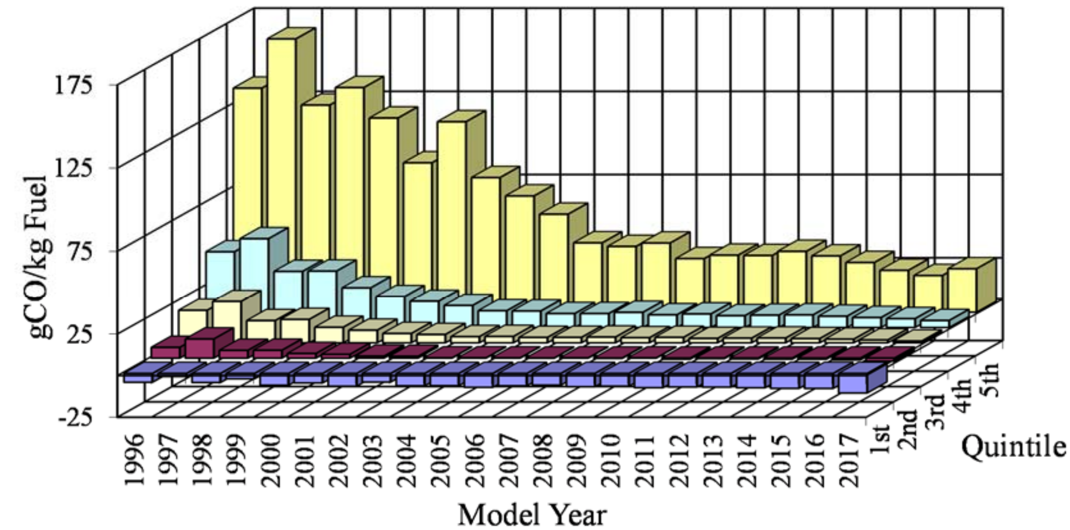
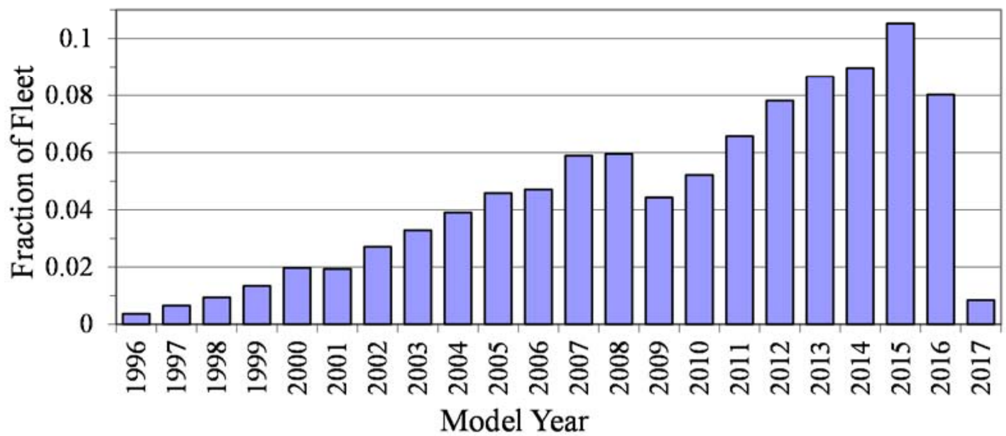


Figure 3. Chicago historical fuel specific mean vehicle emissions plotted as a function of model year. HC data have been offset adjusted as described in the text.





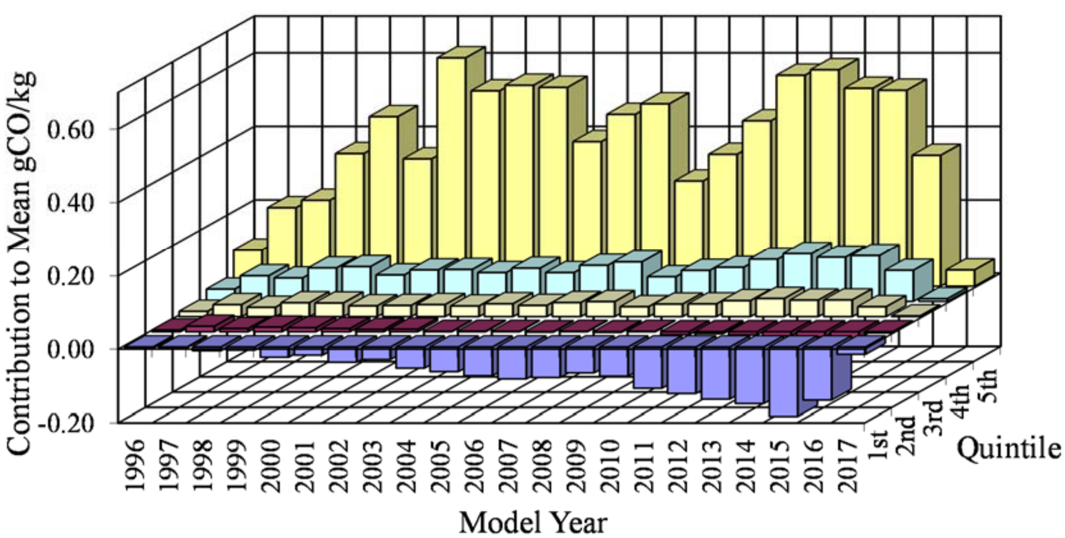


Figure 4. 2016 CO emissions by model year and quintile (top), fleet distribution (middle) and their product showing the total fractional CO emissions by model year and quintile (bottom).

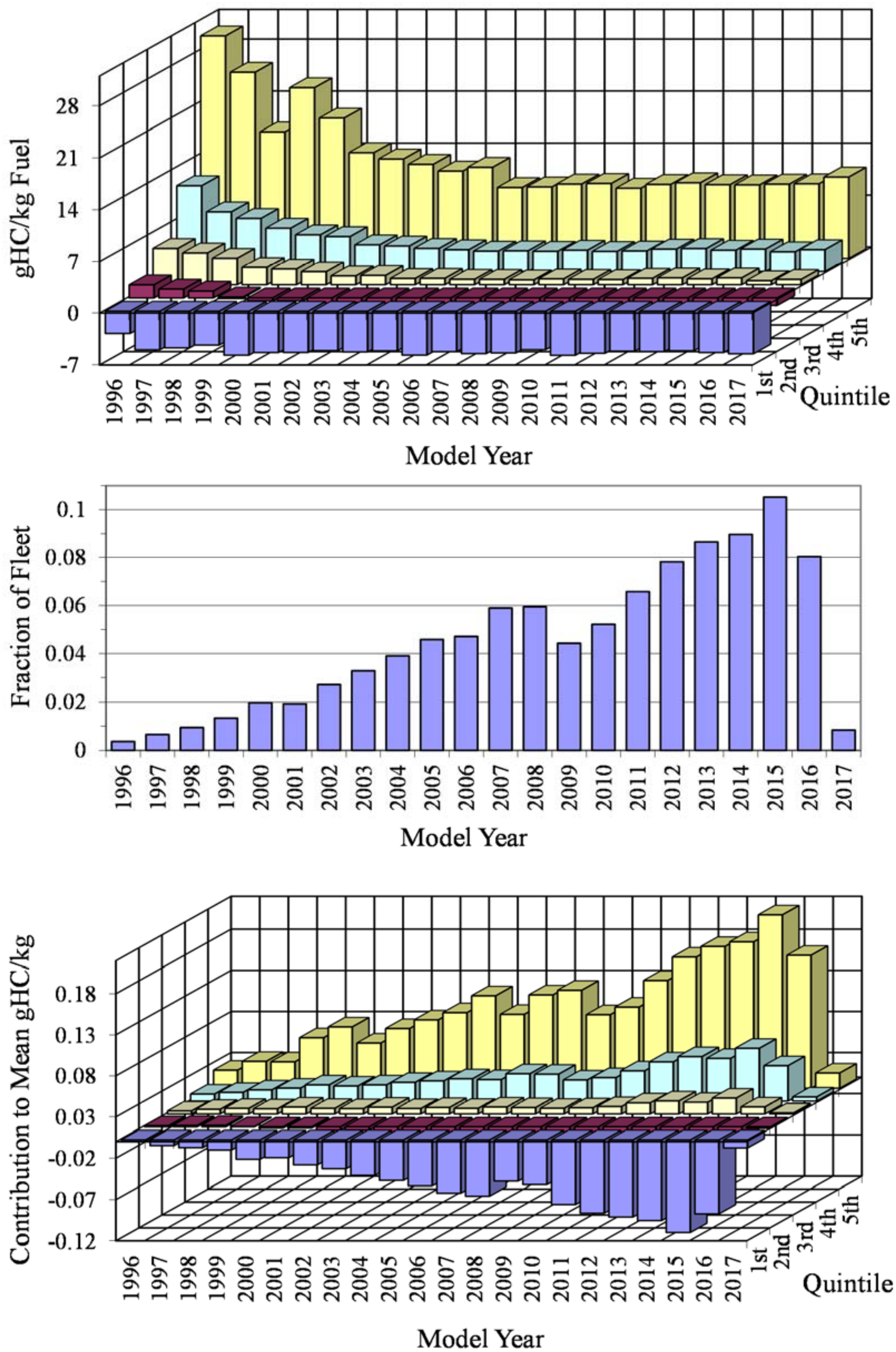


Figure 5. 2016 HC emissions by model year and quintile (top), fleet distribution (middle) and their product showing the total fractional HC emissions by model year and quintile (bottom).

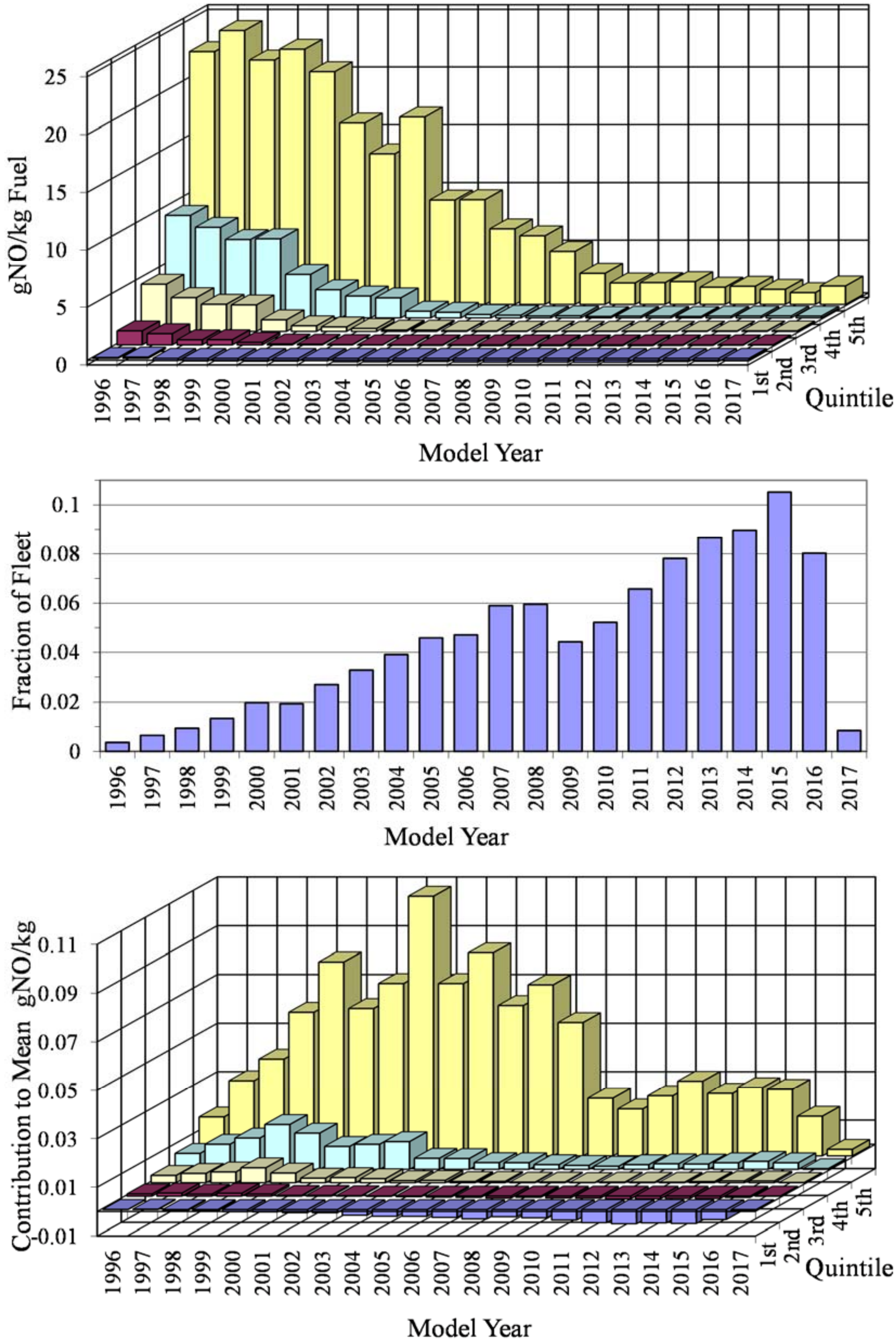


Figure 6. 2016 NO emissions by model year and quintile (top), fleet distribution (middle) and their product showing the total fractional NO emissions by model year and quintile (bottom).

The impact of the economic recession on depressing the contribution of model year 2009 vehicles (relative to other model years) to the overall size of the fleet of vehicles measured is shown in the middle plots. The 2009 models were only reduced by 26% at the Chicago site as measured in 2014, a smaller contraction than those observed in Denver (35%), Los Angeles (38%) or Tulsa (40%).[14] The Denver and Tulsa fleet saw a disproportionate reduction in trucks, which were the majority segment of both of those fleets. Passenger vehicles are still the largest segment of the Chicago site's fleet (55% in 2014), and the 2009 passenger model year vehicles saw only a 19% drop in 2014. In 2006 the fleet percentage contribution for 1 to 5 year old vehicles averaged 9.9% (half of the total fleet) a level that has only recently been surpassed by the 2015 model year vehicles in the 2016 measurements. In the 2016 measurements the percentage contribution for 1 to 5 year old vehicles average 8.8% (44% of the total fleet). The end result is that the recession increased the age of the Chicago site's fleet; Table 3 shows that the fleet is ~0.5 model year older than the 2006 data set, which at the time was significantly older than the previous six data sets (they ranged from 5.3 to 6.1 years old). This smaller age increase than previously observed at the other sites may also be a product of the later sampling data which has allowed fleet turnover to catch up and reduce the age of the Chicago area fleet.

An equation for determining the instantaneous power of an on-road vehicle proposed by Jimenez[15], takes the form

$$\text{VSP} = 4.39 \bullet \sin(slope) \bullet v + 0.22 \bullet v \bullet a + 0.0954 \bullet v + 0.0000272 \bullet v^3 \quad (4)$$

where VSP is the vehicle specific power in kW/metric tonne, *slope* is the slope of the roadway (in degrees), v is vehicle speed in mph, and a is vehicle acceleration in mph/s. This equation is derived from dynamometer studies and is 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. This equation was used to calculate vehicle specific power for all measurements in each of the nine years' databases. This equation, like all dynamometer studies, does not include any load effects arising from road curvature. The emissions data, binned according to vehicle specific power, are graphed in Figure 8. All of the specific power bins contain at least 100 measurements and the HC data have been offset adjusted.

All of the species show reduced emissions when compared with previous data sets. All three species emissions also show less and less dependence on vehicle specific power than previous years' data. The error bars included in the plot are standard errors of the mean calculated from the daily averages. These uncertainties were generated for these γ-distributed data sets by applying the central limit theorem. Each day's average emission for a given VSP bin was assumed to be an independent measurement of the average emissions at that VSP. Normal statistics were then applied to these daily averages. Only the influence of decelerations which increases HC emissions remains as a significant driving mode factor for mean emissions.

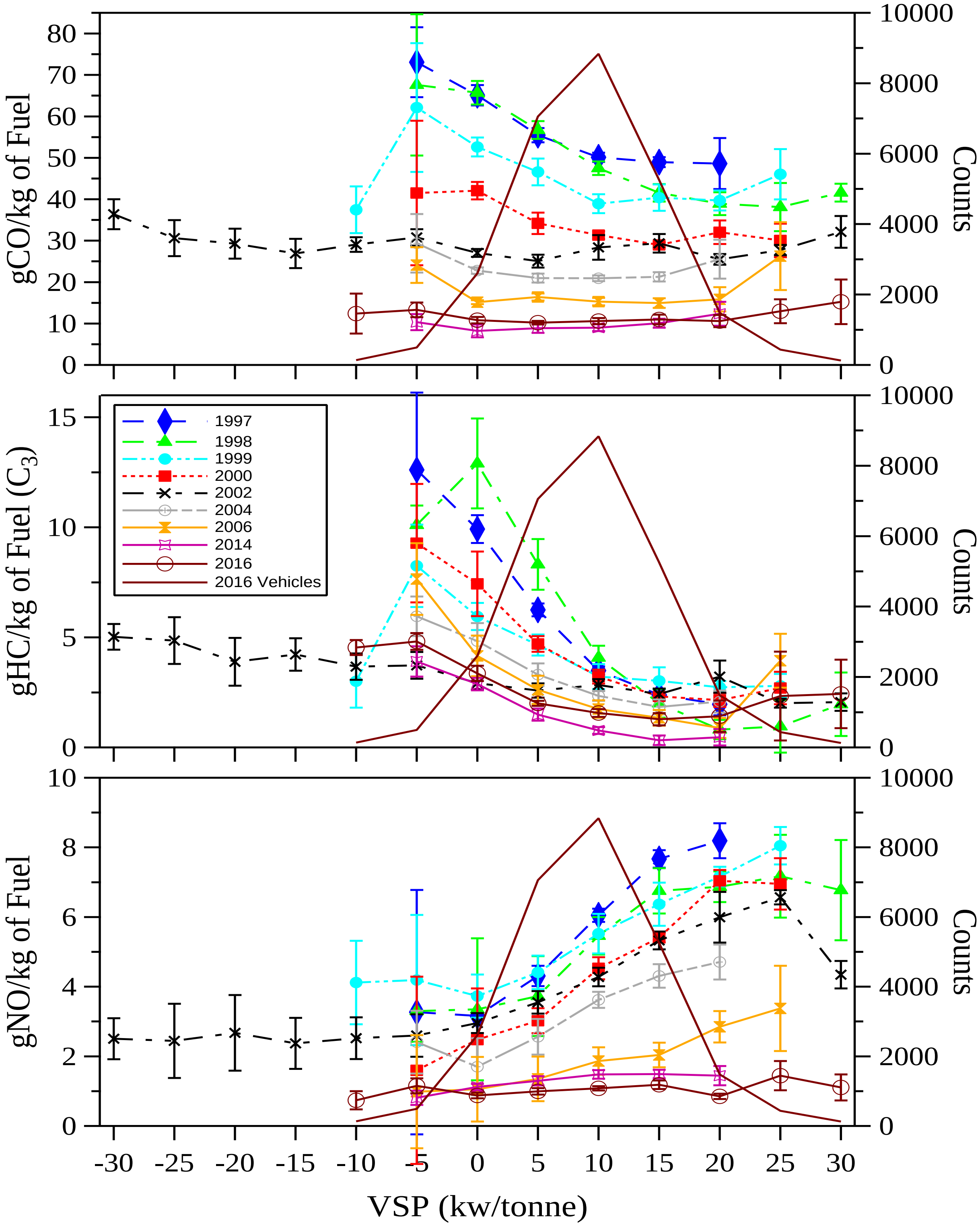


Figure 8. Vehicle emissions as a function of vehicle specific power for all of the Chicago data sets. The uncertainties are plotted as the standard errors of the mean calculated from daily samples. The solid line without markers is the vehicle count profile (right y-axis) for the 2016 data set.

The use of VSP can be used to reduce the influence of any changes in driving behavior from the mean vehicle emissions over the many data sets. Table 4 shows the mean emissions from all vehicles in the 1997, 1998, 1999, 2000, 2002, 2004, 2006, 2014 and 2016 databases with specific powers between –5 and 20 kw/tonne. Note that these emissions do not vary considerably from the mean emissions for the entire set of databases, as shown in Table 3. Table 4 shows the mean emissions for the 1998, 1999, 2000, 2002, 2004, 2006, 2014 and 2016 databases, adjusted for vehicle specific power that match the 1997 VSP distribution.

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

Means	1997 measured (adjusted)	1998 measured (adjusted)	1999 measured (adjusted)	2000 measured (adjusted)	2002 measured (adjusted)	2004 measured (adjusted)	2006 measured (adjusted)	2014 Measured (adjusted)	2016 Measured (adjusted)
gCO/kg	53.4±1.0 (53.4±1.0)	47.2± 1.3 (51.2±1.4)	43.7±2.3 (43.3±2.3)	32.2±0.9 (33.1±0.9)	27.7±1.2 (27.3±1.2)	21.4±0.8 (21.4±0.8)	15.7±0.9 (15.7±0.9)	9.1.±0.8 (9.2±0.8)	10.6±0.3 (10.6±0.3)
gHC/kg[a]	8.2 ±0.2 (4.9±0.2)	9.2±0.6 (5.9±0.4)	6.9±0.5 (4.0±0.3)	3.0±0.2 (4.0±0.3)	3.3±0.3 (2.7±0.2)	3.7±0.3 (2.9±0.3)	2.7±0.5 (2.3±0.5)	1.3±0.2 1.2±0.2)	1.9±0.1 1.9±0.1)
gNO/kg	5.5±0.3 (5.5±0.3)	5.6±0.1 (4.9±0.1)	5.2±0.3 (5.2±0.3)	4.4±0.2 (4.0±0.2)	3.9±0.2 (4.1±0.2)	3.3±0.1 (3.2±0.1)	1.7±0.1 (1.7±0.1)	1.4±0.1 (1.4±0.1)	1.0±0.1 (1.0±0.1)

[a]HC emissions are offset adjusted as described in the text.

The normalization of the data to the 1997 driving mode is accomplished by applying the mean vehicle emissions for each VSP bin (between –5 and 20 kw/tonne) from a certain year's measurements to the vehicle distribution, by vehicle specific power, for each bin from 1997. A sample calculation for vehicle specific power-adjusted mean NO emissions is shown in Appendix D. Because all VSP data are adjusted to the 1997 vehicle frequency distribution by VSP bin, the 1997 adjusted values are the same as the measured values except the HC data, which include the extra calculation to adjust for the yearly HC offset. Each measurement year's adjusted values for HC in Table 4 include this additional adjustment. Over the seventeen year period, the reduction in all three species goes far beyond just driving mode dependence as discussed earlier. VSP normalized CO emissions have declined by almost a factor of 6 and HC and NO emissions have been reduced by a factor of 4.

A similar normalization can be applied to a fleet of specific model year vehicles to track deterioration, provided a baseline of only the model years measured in 1997 is used. A sample calculation, for the model year adjusted mean NO emissions, is shown in Appendix E. Table 5 shows mean emissions for all vehicles from model year 1983 to 1997, as measured in each of the nine years of data. Applying the vehicle frequency distribution by model year observed in 1997 to the mean emissions by model year from the later studies yields the model year adjusted fleet

Table 5. Measured and model year adjusted[a] fleet emissions. Uncertainties are standard errors of the means calculated from the daily means.

Means	1997 measured (adjusted)	1998 measured (adjusted)	1999 measured (adjusted)	2000 measured (adjusted)	2002 measured (adjusted)	2004 measured (adjusted)	2006 measured (adjusted)	2014 measured (adjusted)	2016 measured (adjusted)
gCO/kg	53.0±0.9 (53.0±0.9)	52.0±0.8 (53.3±0.8)	53.8±1.9 (57.1±2.0)	46.4±1.4 (51.2±1.6)	50.6±2.0 (56.8±2.2)	46.3±1.9 (53.3±2.1)	45.9±2.2 (52.8±2.5)	57.1±2.6 (77.3±3.5)	70.5±5.5 (99.1±7.7)
gHC/kg[b]	8.1±0.2 (4.8±0.2)	4.9±1.2 (5.0±0.6)	5.0±0.6 (5.4±0.4)	5.1±0.3 (5.6±0.4)	5.4±0.5 (6.3±0.5)	5.7±0.4 (7.4±0.6)	6.2±0.5 (7.6±0.7)	8.0±1.6 (10.6±0.9)	8.2±0.6 (19.6±1.3)
gNO/kg	5.6±0.3 (5.6±0.3)	6.3±0.1 (6.4±0.1)	6.6±0.3 (6.8±0.3)	6.2±0.2 (6.6±0.2)	6.4±0.3 (7.0±0.3)	7.0±0.3 (7.7±0.3)	4.9±0.4 (5.7±0.5)	10.5±1.2 (11.7±0.6)	10.4±0.8 (9.7±0.8)
Number of Vehicles	18,251	19,319	16,639	13,394	9,372	6,220	4,238	733	513
Age (years)	5.2	6.0	6.8	7.6	9.1	9.9	11.5	20.1	21.7

[a]To match the 1983-1997 model year distribution observed during the 1997 measurements.

[b]HC emissions are offset corrected for all of the years adjusted data.

emissions. Only the CO and NO measured mean emissions have increased significantly since the 1997 measurements (~+25% CO and +48% NO). The model year-adjusted emissions add additional increases to the observed differences for CO and HC (+47% for CO and +120% for HC). NO emissions show similar increases between the measured (+48%) and the adjusted means (+42%) compared to the 1997 means. The number of 1983-1997 models has shrunk by almost a factor of 25 during the 17 years that have elapsed since the first measurements.

Table 5 shows an interesting result: during the nine years from 1997 to 2006 the 1997 fleet saw no statistically significant deterioration with increasing age for the model year adjusted average CO and NO emissions, though both species mean had intermediate gains and losses. In the subsequent ten years large increases have occurred for all species. Since 2006 the fleet age for this select group of model years has almost doubled (11.5 to 21.7 years) and the number of measurements has shrunk dramatically increasing the standard errors of the mean for the adjusted values. It is possible that we have reached the limits of this type of analysis, at least when using the model year adjusted factors, since only two model years (1996 & 1997) include more than 100 measurements and for the 2016 measurements 1983 - 1985 models have zero measurements. Because of the skewed nature of emission distributions, the model year adjusted emissions increases seen in 2016 may now be influenced by sampling bias which is not reflected in the uncertainty estimates. However, even for the measured 2016 mean emissions of the observed 1983 -1997 fleet, where there is no bias caused by the age adjustment, now both the CO and NO emissions have an increase which is statistically significant.

The University of Denver did not have the capability to measure light-duty vehicle NH_3 emissions until 2005, which made Chicago the seventh U.S. site to have NH_3 measurements collected. The mean reported in Table 3 (0.64 ± 0.02) represents a 10% reduction from the mean observed in 2014. Figure 9 shows a graph of gNH_3/kg of fuel emissions by model year for the 2014 and 2016 Chicago data. The uncertainties are standard errors of the means calculated from the daily means. The 2016 and 2017 models measured in 2016 account for 9% of the total fleet and their lower emissions are a major factor in the 10% reduction in mean emissions observed since 2014 despite slight increases in the emissions of the 2014 and 2015 model year vehicles. Other differences between the two measurement years include an unexplained increase in model year 2009 emissions observed in 2014 which was not repeated in the present study.

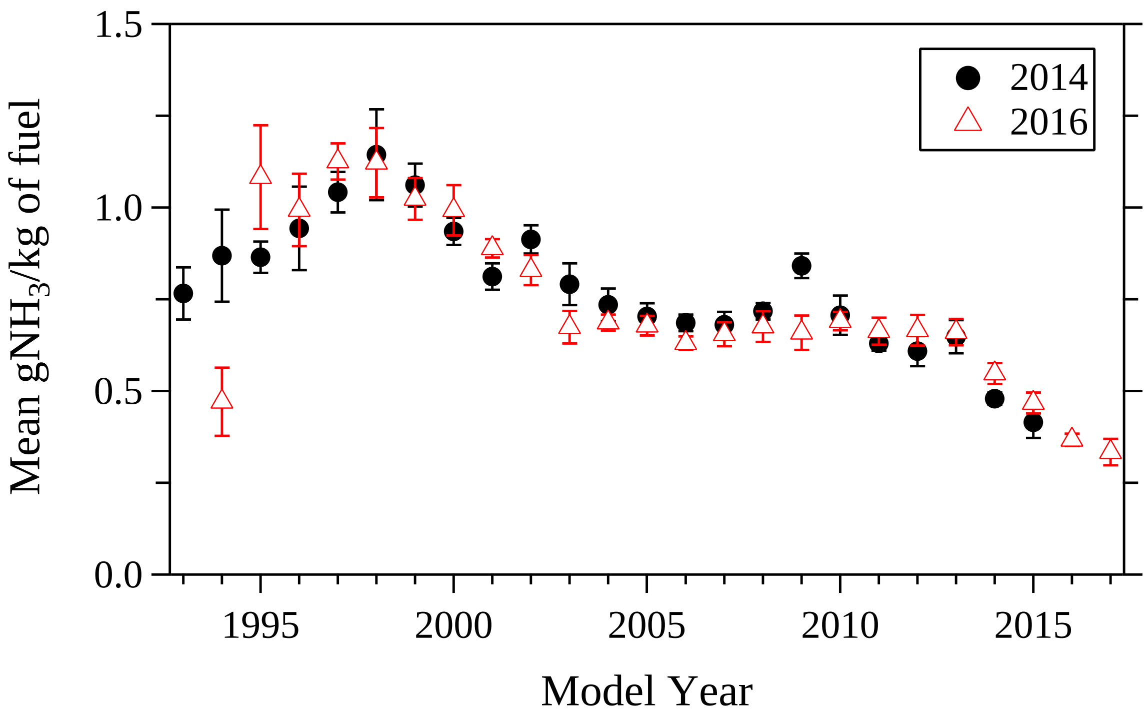


Figure 9. Comparison of gNH_3/kg of fuel emissions by model year for the 2014 and 2016 Chicago data sets. The uncertainties are standard errors of the mean calculated from the daily measurements.

The percent ammonia of total fixed nitrogen was analyzed to see if the percentage of ammonia increased as total fixed nitrogen decreased with decreasing age, as has been shown previously in the analysis of previous fleets. The gNO_x/kg of fuel was calculated by converting gNO/kg of fuel to gNO_2/kg of fuel equivalents and summing with the measured gNO_2/kg of fuel. The percent of ammonia in the total fixed nitrogen (FN_2), in g/kg of fuel, was calculated as shown by Burgard *et al.*[16] All of the N factors were converted to mole/kg of fuel.

$$\text{Molar \% NH}_3 \text{ in Total Fixed Nitrogen} = \frac{100 \text{ x } N_{NH_3}}{N_{NH_3} + N_{NO_x}} \quad (5)$$

Figure 10 shows the results of these calculations for the Chicago 2016 data set. The molar %NO_x and %NH_3 which total 100% are percentages of the gFN_2/kg of fuel values plotted by model year. The noise increases for the molar percentages in the newest model years is due to the shrinking amount of fixed nitrogen emissions. The total fixed nitrogen (filled diamonds, right axis) species have decreased significantly over the last 23 model years. The percent contributed by ammonia (filled circles, left axis) has steadily increased and now dominates the small amount of fixed nitrogen being emitted by the newest model year vehicles. The crossover point in Chicago in 2016 is with ten year-old vehicles, the same as in 2014. This compares with eight year-old vehicles in Tulsa 2015, ten year-old vehicles in west LA in 2015 and three to four year-old vehicles at the Denver site measured in 2015.

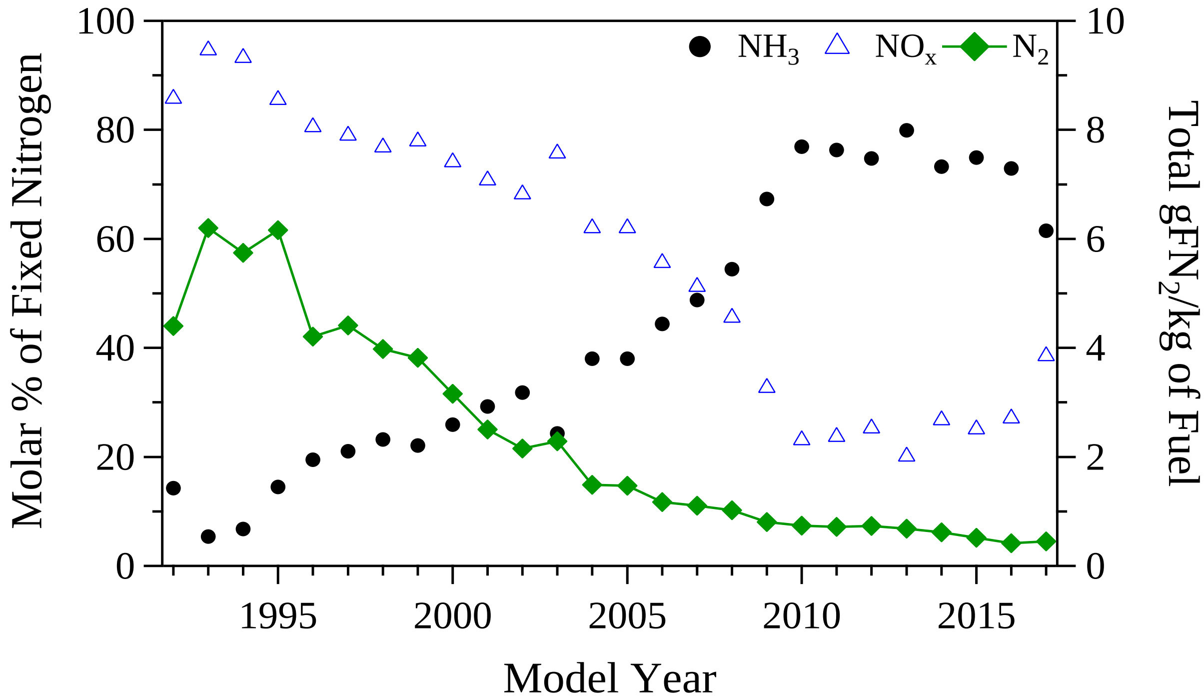


Figure 10. Total fixed nitrogen in g/kg of fuel (diamonds, right axis) with the molar percent composition distributed between the molar %NO_x (triangles, left axis) component and the molar %NH_3 component (circles, left axis).

Figure 11 shows the fuel specific mean emission for CO, HC and NO for all the Chicago measurements to date as well as the mean emissions for the other E-23 and E-106 sites (Omaha is the one exception). The Riverside, CA site was abandoned in favor of the West LA site due to permitting difficulties and lower traffic volumes. The Phoenix site was eliminated due to road construction which eliminated the ramp in favor of a fly over shortly after the 2006 measurements were collected. All of the sites tell a similar story with large reductions in emissions of all three species during the first decade of measurements. Since measurements have resumed in 2013 the reductions have slowed on an absolute basis and only the last measurements at Chicago, Denver

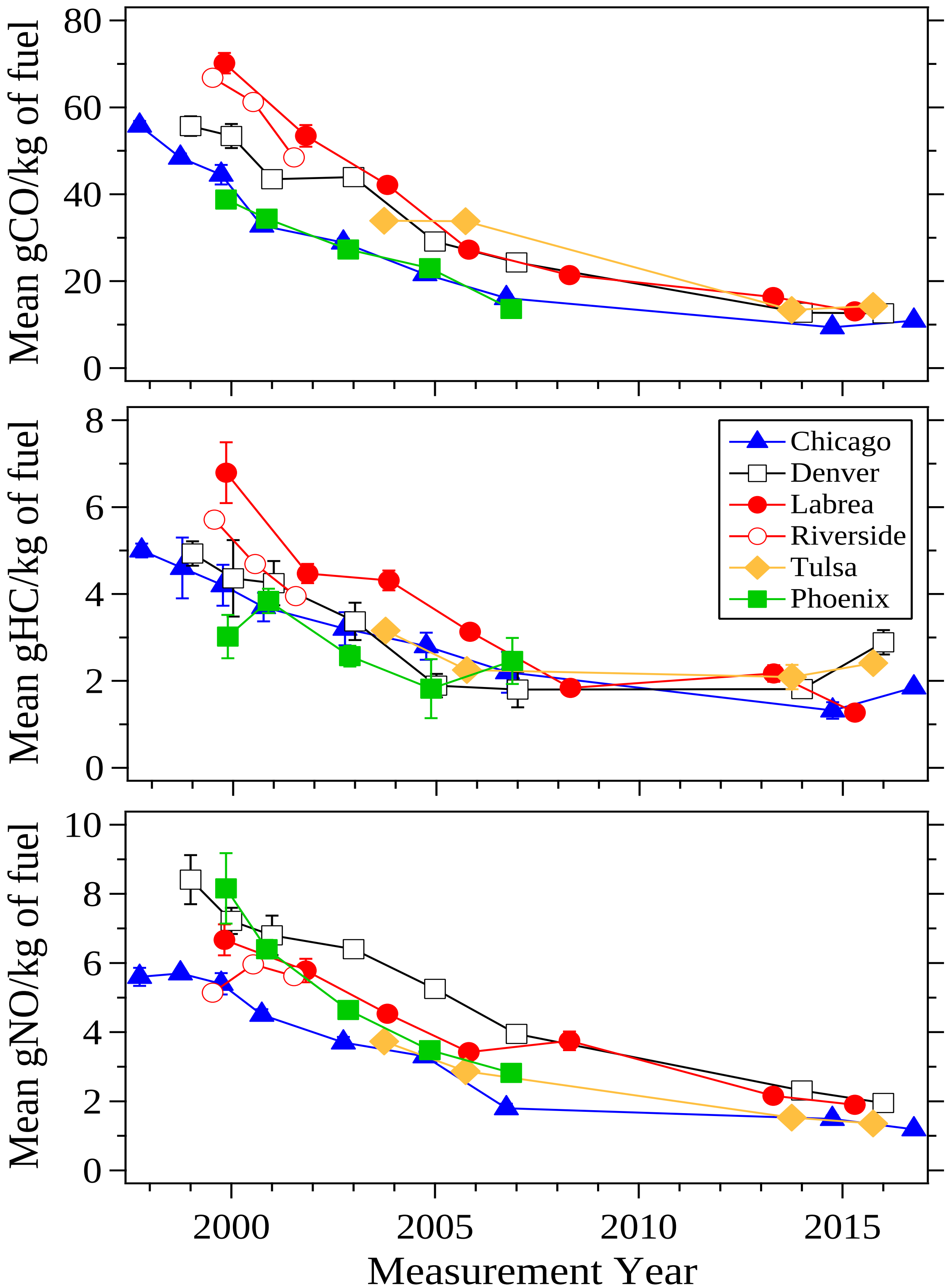


Figure 11. Historical fuel specific mean emission for CO (top), HC (middle) and NO (bottom) for all of the E-23 and E-106 light-duty measurements to date. Uncertainties are standard errors of the mean determined from the daily measurements. HC means have been offset adjusted as described in the text.

and Tulsa have mean emissions increased slightly for CO and HC. Though the Denver ramp was reconstructed in 2014 and the increases in HC emissions observed in 2015 at the Denver site have definitely been influenced by the new driving mode with an increase in the number of negative VSP measurements which HC emissions are still sensitive to (see Figure 8).

There have been nineteen years since the first data set was collected at the Chicago Algonquin Rd. site in the fall of 1997. Figure 12 compares the mean fuel specific CO (top panel), HC (middle panel) and NO emissions (bottom panel) for the 1997 and 2016 data sets plotted against vehicle age for the entire fleet. Zero year vehicles are 1998 and 2017 respectively for the 1997 and 2016 data sets. The uncertainties plotted are standard errors of the mean calculated from the daily measurements. The uncertainties increase for vehicles older than 20 years as less than 0.5% of the fleet in 1997 is older and only 1% of the fleet in the 2016 data set is older. Each data sets HC data have been normalized to the lowest HC emitting vehicles in its data set as previously described in the text (see adjustment values in Table 3).

Consistent with the large reduction in the mean emission are large reductions in similarly aged vehicles. In the 2016 data set 20 year old vehicles have similar mean emissions as 5 and 7 year old vehicles respectively for CO and HC measured in 1997. Both CO and HC emissions show little to no changes in mean emissions for the first 10 to 12 model years, unlike the earlier data set. NO is the only species where 20 year old vehicles in 2016 have similar emissions to 20 year old vehicles measured in 1997. However, NO emissions have only been aggressively targeted for reduction with the introduction of Tier II vehicles, whose phase in began in 2004 and was completed by the 2009 model years (9 year old vehicles in 2016). It is around these 2009 model year vehicles that mean gNO/kg of fuel emissions begins to rise. Going forward we would expect that the NO graph will continue to lengthen the number of vehicle models with little to no NO emission deterioration and begin to look more like the CO and HC graphs. One explanation for the observed slowing in the reduction of fleet mean emissions (see Figure 11) can be explained using Figure 12 when one realizes that a new vehicle purchased today will most likely replace a vehicle with emissions that on average are very close to its own. This limits the reductions that can be achieved in the fleet means from future fleet turnover.

The noticeable increase in emissions for all three species in the zero year vehicles for 1997 is the result of older vehicles being initially measured but by the time plates were transcribed and matched the DMV returned a model year for an upgraded new vehicle. Illinois is a “take your plate with you” state and plate transfers to newer vehicles are the culprit. In 1997 plate images were collected on video tape and plate matches for new vehicles were not corroborated. Images collected today that return a very old or very new model year are crosschecked for make using the digital images and mismatches are discarded which has eliminated this first year increase in emissions observed in the older databases.

Figure 13 compares the emission contribution by model year for the 1997 and 2016 data sets. Plotted is the percent contribution in 1997 emissions by model year. Since the total emissions in 1997 is a function of the size of the database to normalize the 2016 emission percentages we

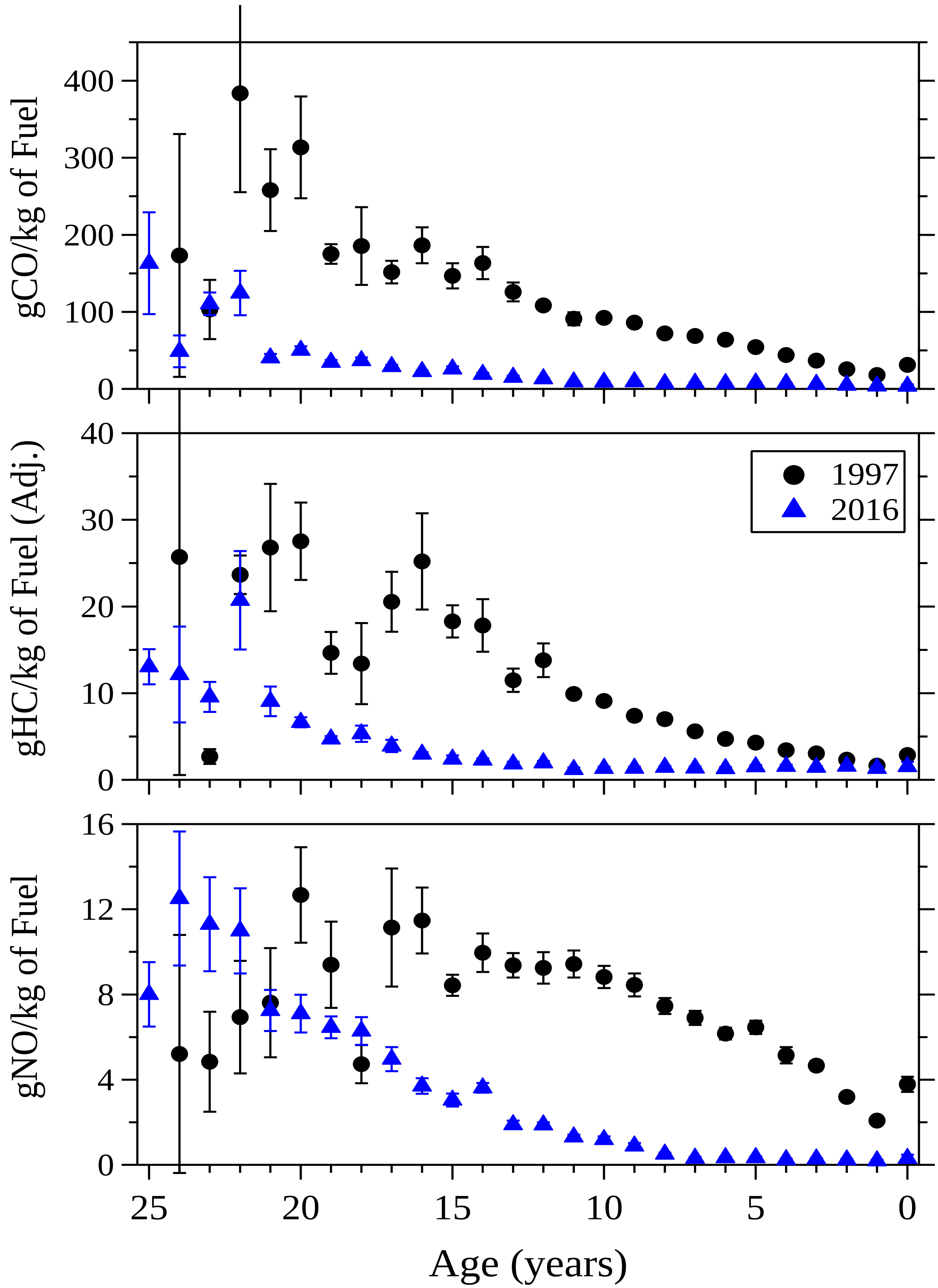


Figure 12. Mean fuel specific emissions by vehicle age for the 1997 (circles) and 2016 (triangles) Chicago data sets for CO (top), HC (middle) and NO (bottom). Uncertainties are standard error of the means calculated from the daily samples.

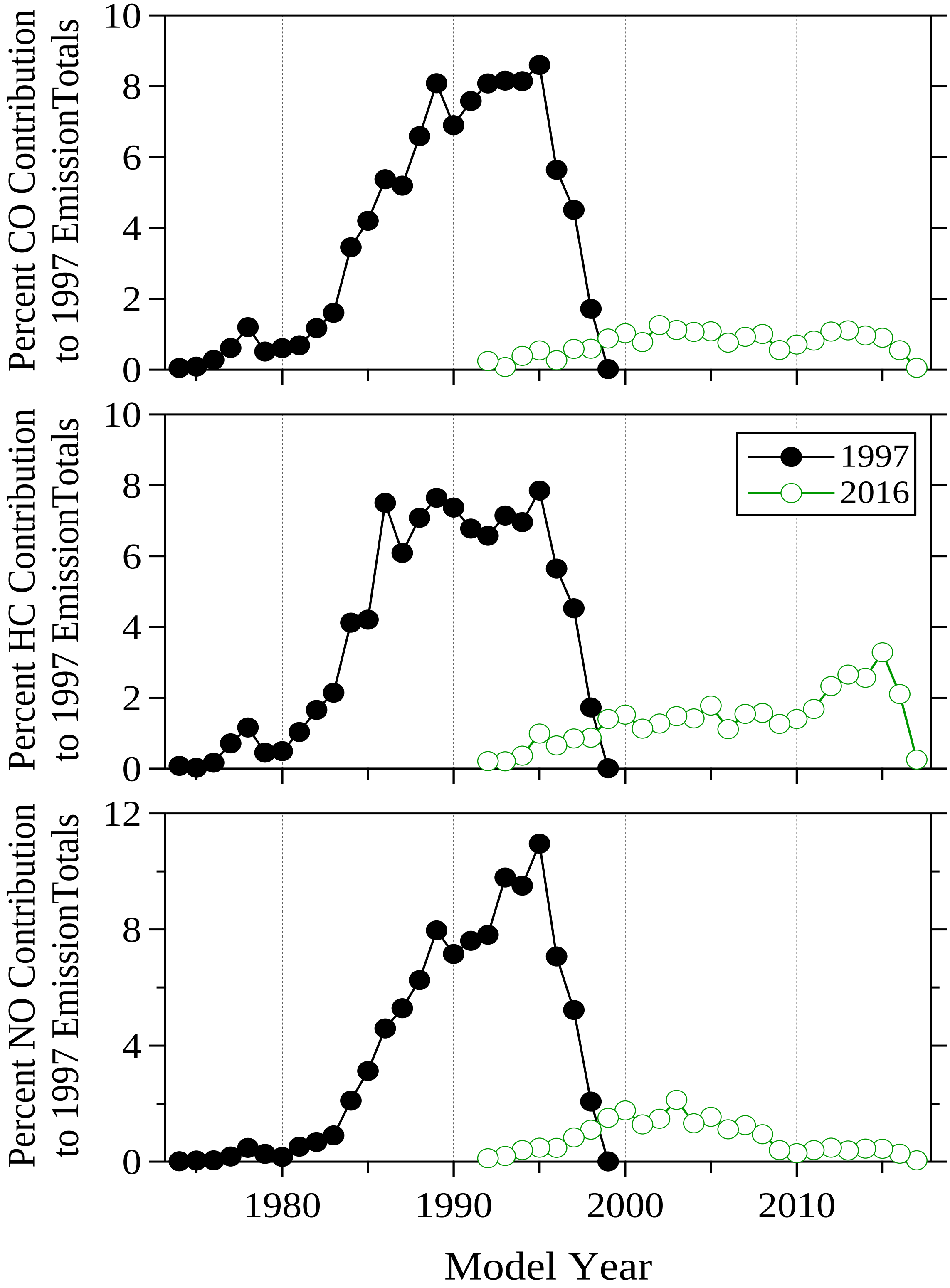


Figure 13. Percent contribution of fuel specific emissions by model year for CO (top), HC (middle) and NO (bottom) for the 1997 (filled circles) and 2016 (open circles) Chicago data sets. The 2016 emissions contribution has been normalized to the 1997 mean emissions.

calculated the total 2016 emissions for each species by multiplying the number of measurements collected in 2016 by the1997 mean emissions for that species. The total contributions add to 100% for the 1997 data but only to 20%, 36% and 21% respectively for CO, HC and NO which reflects the reduction in emission totals between the two data sets. Beyond the flattening of the emissions distribution one of the more important changes during the past nineteen years is the shift from the emissions contribution being a product of the emissions by model year profile and the fleet distribution to one that now mirrors just the fleet distribution. This of course is due to the low mean emissions for a majority of the fleet as shown in Figure 12. The contribution for NO is the lone exception as the increasing NO emissions for the older models still contributes to the emissions distribution but produces a peak emissions contribution which is much later than observed in 1997. This peak will continue to shift to later model years until the diminishing number of vehicles cancels out the emissions contribution and the NO emissions distribution will also begin to mirror the fleet distribution as seen for CO and HC.

Figure 14 is a plot of the fuel specific CO (top panel), HC (middle panel) and NO (bottom panel) 99^{th} percentiles by model year for the 1997, 2006 and 2016 Chicago data sets. The 99^{th} percentile of the emissions distribution represents a level that corresponds to vehicles in disrepair and are only displayed for model years with at least 100 measurements. Much like the mean emissions the emission values of these extreme vehicles has dropped dramatically over the last nineteen years yet emission levels for these vehicles are still large multiples of the mean values. If we compare 10 year old vehicles (2007 model years) in the 2016 database the 99^{th} percentile values for CO are more than a factor of 10 larger (109 vs 8.8 gCO/kg of fuel), a factor of 17 larger for HC (22.2 vs 1.3 gHC/kg of fuel) and more than a factor of 20 for NO (28.4 vs 1.2 gNO/kg of fuel). It is quite remarkable that improvement in dependability, design and efficiencies of modern vehicles has also translated into the ability to cap emissions in vehicles that have obvious problems. However, going forward for mean emissions to see further reductions there will have to be additional reductions in the emissions levels of these extreme emitters.

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.[17] Such plots were constructed for all of the measured species. Linear regression gave best fit lines whose slopes correspond to the inverse of the Laplace factor, which describes the noise present in the measurements. This factor must be viewed in relation to the average measurement for the particular pollutant to obtain a description of noise. The Laplace factors were 4.4, 2.9, 0.33, 0.03 and 0.15 for CO, HC, NO, NH_3 and NO_2 respectively. These values indicate standard deviations of 6.2 gCO/kg (0.05%), 4.1 gHC/kg (93 ppm), 0.5 gNO/kg (64 ppm), 0.04 gNH_3/kg (4 ppm) and 0.2 gNO_2/kg (11 ppm) for individual measurements of CO, HC, NO, NH_3 and NO_2 respectively. CO (50%), HC (14.5%) and NO_2 (80%) saw significant noise reductions over the 2014 values while NO (-66%) and NH_3 (-100%) experienced some degradation. In terms of uncertainty in average values reported here, the numbers are reduced by a factor of the square root of the number of measurements. For example, with an average of 100 measurements, the uncertainty reduces by a factor of 10. Thus, the

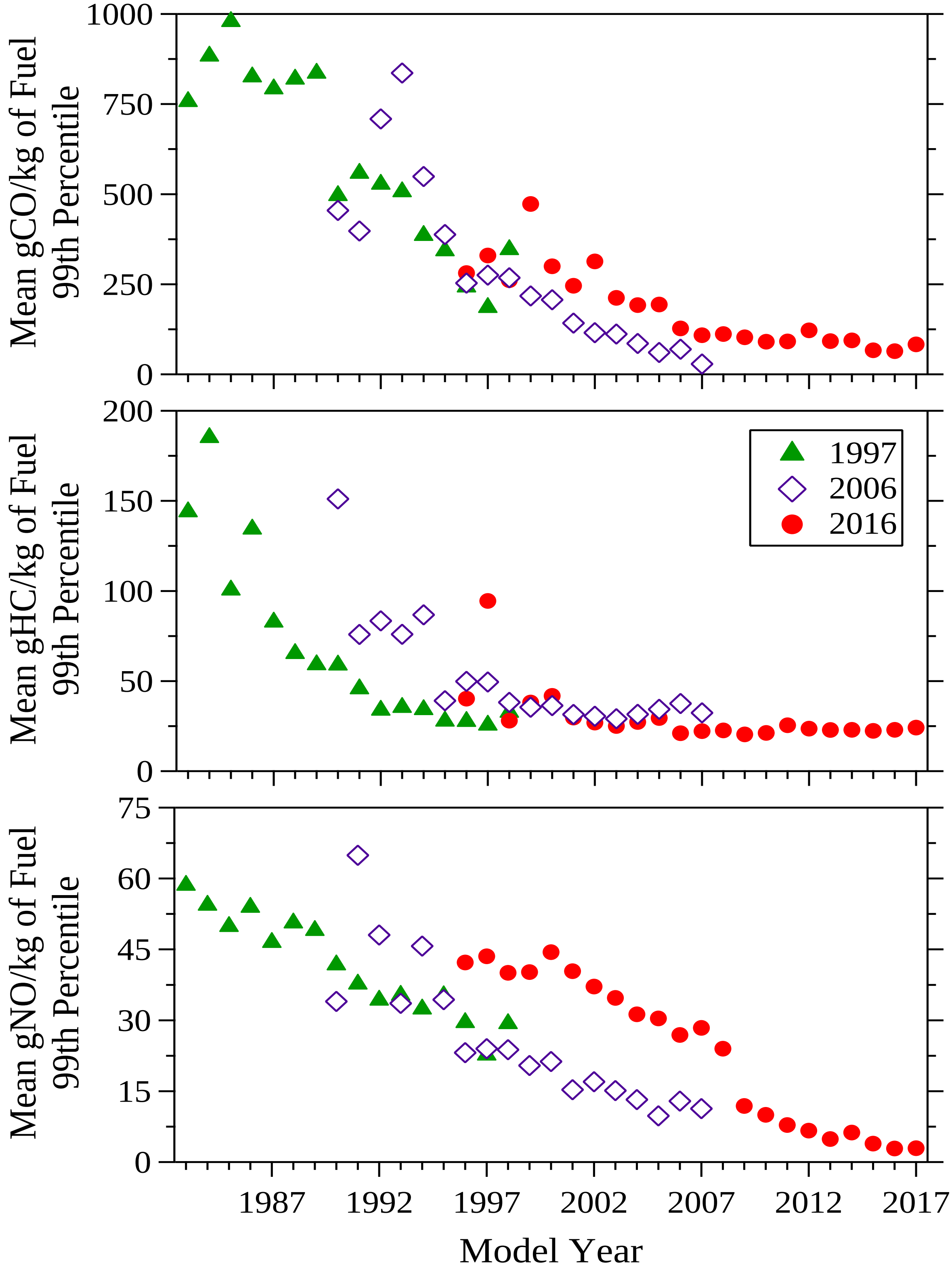


Figure 14. Fuel specific 99th percentiles by model year for CO (top), HC (middle) and NO (bottom) for the 1997 (triangles), 2006 (diamonds) and 2016 (circles) Chicago data sets.

uncertainties in the averages reduce to 0.6 gCO/kg, 0.4 gHC/kg, 0.05 gNO/kg, 0.004 gNH_3/kg and 0.02 gNO_2/kg, respectively.

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

Not measured:

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

2) Vehicle which drives completely through during the 0.1 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 HD diesel trucks, bicycles.

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

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

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

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

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

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

8) Excessive error on NH3/CO2 slope, equivalent to +50ppm.

9) Reported NH3 < -80ppm or > 7000ppm. NH3 “invalid”.

10) Excess error on NO2/CO2 slope, equivalent to +20% for NO2 > 200ppm, 40ppm for NO2 < 200ppm

11) Reported NO2 < -500ppm or > 7000ppm. NO2 “invalid”.

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

APPENDIX B: Explanation of the ill_2016.dbf database.

The ill_2016.dbf is a Microsoft Foxpro database file, and can be opened by any version of MS Foxpro, Excel, Access or Filemaker Pro, regardless of platform. The following is an explanation of the data fields found in this database:

License	Illinois license plate.
Date	Date of measurement, in standard format.
Time	Time of measurement, in standard format.
Percent_co	Carbon monoxide concentration, in percent.
Co_err	Standard error of the carbon monoxide measurement.
Percent_hc	Hydrocarbon concentration (propane equivalents), in percent.
Hc_err	Standard error of the hydrocarbon measurement.
Percent_no	Nitric oxide concentration, in percent.
No_err	Standard error of the nitric oxide measurement.
PercentNH3	Ammonia concentration, in percent.
NH3_err	Standard error of the ammonia measurement.
PercentNO2	Nitrogen dioxide concentration, in percent.
NO2_err	Standard error of the nitrogen dioxide measurement.
Percent_co2	Carbon dioxide concentration, in percent.
Co2_err	Standard error of the carbon dioxide measurement.
Opacity	Opacity measurement, in percent.
Opac_err	Standard error of the opacity measurement.
Restart	Number of times data collection is interrupted and restarted by a close-following vehicle, or the rear wheels of tractor trailer.
HC_flag	Indicates a valid hydrocarbon measurement by a “V”, invalid by an “X”.
NO_flag	Indicates a valid nitric oxide measurement by a “V”, invalid by an “X”.
NH3_flag	Indicates a valid ammonia measurement by a “V”, invalid by an “X”.
NO2_flag	Indicates a valid nitrogen dioxide measurement by a “V”, invalid by an “X”.
Opac_flag	Indicates a valid opacity measurement by a “V”, invalid by an “X”.
Max_co2	Reports the highest absolute concentration of carbon dioxide measured by the remote sensor; indicates the strength of the observed plume.
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.
Exp_month	Indicates the month the current registration expires.
Exp_year	Indicates the year the current registration expires.
Year	Model year of the vehicle.
Make	Manufacturer of the vehicle.
Body_style	Type of vehicle.
Vin	Vehicle identification number.
Zipcode	Zip code of the owners address.
Zip_4	Zip code +4 of the owners address.
Owner_code	Illinois DMV ownership codes (1 – individual, 2 – multiple individuals same last name, 3 – multiple individuals different last names, 4 – corporate owner, 5 – combined corporate and individual, 6 – multiple corporate ownership, 7 – local government, 8 – state government and 9 – Federal government).
Make_abrv	Abbreviated manufacturer.
City_State	City and State of registration
Zipcode	Registration of zipcode
CO_gkg	Grams of CO per kilogram of fuel using 860 gC/kg of fuel.
HC_gkg	Grams of HC per kilogram of fuel using 860 gC/kg of fuel and the molecular weight of propane which is our calibration gas.
NO_gkg	Grams of NO per kilogram of fuel using 860 gC/kg of fuel.
Nh3_gkg	Grams of NH_3 per kilogram of fuel using 860 gC/kg of fuel.
NO2_gkg	Grams of NO_2 per kilogram of fuel using 860 gC/kg of fuel.
NOx_gkg	Grams of NO_x per kilogram of fuel using 860 gC/kg of fuel.
HC_offset	Hydrocarbon concentrations after offset adjustment.
Hcgkg_off	Grams of HC per kilogram of fuel using 860 gC/kg of fuel and using the HC_offset value for this calculation.
VSP	Vehicles specific power calculating using the equation provided in the report.
V_make	VIN decoded make information.
V_model	VIN decoded model information.
V_body	VIN decoded body information.
V_type	VIN decoded vehicle type information.

V_engine	VIN decoded engine size in liters.
V_wtclass	VIN decoded weight class.
V_gvw	VIN decoded gross vehicle weight.
V_fuel	VIN decoded fuel type.
V_trans	VIN decoded transmission type.
V_model	VIN decoded model information.
V_xdrive	VIN decoded all-wheel drive information.

APPENDIX C: Temperature and Humidity Data from Chicago O'Hare Int. Airport.

1997										
Time (CDT)	Sept. 15		Sept. 16		Sept. 17		Sept. 18		Sept. 19	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0700	64	100	68	87	68	81	64	78	71	84
0800	69	78	71	84	69	70	71	68	-	-
0900	73	68	75	73	71	61	75	57	77	76
1000	75	68	78	71	75	46	77	46	78	73
1100	78	61	80	66	77	39	78	44	80	73
1200	80	57	84	60	78	38	82	36	82	69
1300	80	57	82	62	80	32	82	36	80	73
1400	80	57	84	60	80	29	82	36	77	76
1500	80	62	84	58	80	29	82	32	73	87
1600	78	66	82	58	80	27	80	32	71	93
1700	75	73	82	58	78	32	78	38	71	100
1800	73	78	80	68	78	38	77	39	71	93

1998								
Time (CDT)	Sept. 21		Sept. 22		Sept. 23		Sept. 24	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0700	57	66	57	80	51	68	53	89
0800	59	62	62	72	55	54	55	83
0900	60	59	62	72	59	51	57	77
1000	64	51	64	67	60	49	59	72
1100	64	55	66	56	62	42	60	77
1200	64	55	62	67	64	39	64	72
1300	66	48	62	67	64	39	64	72
1400	64	60	64	60	64	36	66	67
1500	64	62	64	51	66	34	64	72
1600	64	62	62	60	66	36	64	72
1700	62	67	62	55	62	51	64	78
1800	62	67	59	53	55	61	62	83

1999								
Time (CDT)	Sept. 20		Sept. 21		Sept. 22		Sept. 23	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0700	54	87	48	89	46	80	54	65
0800	55	80	49	80	54	56	58	56
0900	57	75	53	74	59	43	62	51
1000	60	62	57	67	63	37	70	42
1100	62	56	57	64	66	34	74	36
1200	62	52	59	58	66	33	77	31
1300	60	53	60	58	71	33	78	31
1400	60	50	59	56	72	32	79	31
1500	63	43	60	53	72	33	80	31
1600	62	43	59	58	72	33	78	36
1700	59	51	57	62	71	35	77	37
1800	58	60	55	69	67	40	75	40

2000								
Time (CDT)	Sept. 11		Sept. 12		Sept. 13		Sept. 14	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0800	76	85	63	76	62	60	64	96
0900	79	79	65	70	66	50	63	93
1000	82	71	67	59	69	47	60	96
1100	84	66	68	53	71	44	65	81
1200	87	61	69	45	74	41	68	63
1300	77	73	71	41	76	39	70	53
1400	74	78	71	47	77	36	73	38
1500	66	95	70	46	78	36	72	38
1600	67	95	70	47	79	34	72	44
1700	68	89	68	47	77	36	71	42
1800	69	84	66	49	73	48	67	47
1900	69	87	64	52	64	70	64	52

2002										
Time (CDT)	Sept. 16		Sept. 17		Sept. 18		Sept. 19		Sept. 20	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0700	57	90	60	84	62	100	73	96	71	94
0800	63	70	66	72	64	93	74	94	70	100
0900	67	55	71	63	68	87	75	94	70	100
1000	69	55	74	60	70	76	76	91	70	100
1100	70	53	75	52	72	73	77	90	71	96
1200	72	50	77	50	72	79	76	97	70	90
1300	73	44	76	52	75	79	79	88	69	87
1400	75	40	79	47	78	74	79	82	69	90
1500	75	42	79	42	79	74	78	85	69	87
1600	76	39	77	45	79	74	78	79	69	87
1700	74	41	74	52	78	74	79	77	69	84
1800	67	57	73	57	77	79	77	79	67	87

2004								
Time (CDT)	Sept. 20		Sept. 21		Sept. 22		Sept. 23	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0800	63	54	67	61	69	57	70	61
0900	67	47	72	46	73	50	75	50
1000	71	42	75	37	76	43	79	44
1100	72	41	77	35	78	37	80	39
1200	74	38	80	34	78	37	81	38
1300	76	33	80	34	80	35	83	37
1400	77	28	81	32	80	35	84	35
1500	78	29	82	28	78	40	84	32
1600	77	30	81	30	80	38	84	33
1700	75	39	80	33	76	43	82	34
1800	71	49	70	55	68	63	78	39
1900	67	59	67	59	70	57	76	42

2006								
Time (CDT)	Sept. 12		Sept. 13		Sept. 14		Sept. 15	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0751	67	93	60	93	64	70	65	87
0851	68	93	60	93	66	70	69	76
0951	68	90	61	93	68	68	72	66
1051	68	97	61	90	71	61	72	59
1151	68	97	62	84	71	64	77	52
1251	70	90	62	87	71	64	75	52
1351	70	87	63	84	71	61	77	50
1451	71	84	62	87	72	57	78	47
1551	68	93	63	81	71	61	74	60
1651	66	90	63	81	69	66	73	64
1751	65	90	63	81	67	68	71	68
1851	65	90	62	81	65	75	69	76

2014												
Time (CDT)	Sept. 8		Sept. 9		Sept. 10		Sept. 11		Sept. 12		Sept. 13	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0851	70	51	70	66	71	90	50	66	52	61	47	74
0951	72	46	71	66	73	90	51	69	52	64	49	69
1051	74	43	75	60	73	90	51	69	54	59	51	61
1151	75	40	77	54	74	82	52	64	54	67	53	59
1251	76	43	79	52	78	71	52	64	52	83	54	57
1351	76	42	77	60	79	67	53	62	51	90	57	51
1451	76	43	78	58	78	64	53	64	49	93	56	53
1551	75	46	78	58	77	64	52	66	48	89	56	53
1651	74	48	77	62	76	64	51	66	47	89	57	51
1751	72	50	75	66	68	81	51	69	46	93	54	59
1851	70	51	76	62	63	78	51	69	46	89	52	64

2016										
Time (CDT)	Sept. 12		Sept. 13		Sept. 14		Sept. 15		Sept. 16	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0851	71	55	74	64	71	59	70	68	72	71
0951	73	50	76	62	72	51	72	62	77	67
1051	75	48	78	62	73	52	74	56	80	62
1151	76	47	80	58	73	52	76	50	79	65
1251	77	45	81	53	73	52	77	48	79	69
1351	78	40	82	51	73	50	77	50	82	61
1451	78	40	84	51	73	48	76	54	81	63
1551	78	42	82	47	72	50	75	58	81	63
1651	77	45	80	54	71	53	73	59	80	60
1751	73	52	75	71	69	61	71	66	79	60
1851	70	59	73	76	67	68	70	68	78	62

2016						
Time (CDT)	Sept. 19		Sept. 20		Sept. 21	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0851	76	50	76	50	70	87
0951	80	44	78	40	72	79
1051	82	40	80	35	73	79
1151	85	35	81	30	73	74
1251	86	29	82	27	68	90
1351	87	28	81	28	68	90
1451	87	26	81	27	70	79
1551	86	26	80	28	72	71
1651	84	29	79	28	73	74
1751	82	33	75	33	72	73
1851	79	36	72	40	68	81

APPENDIX D: Calculation of Vehicle Specific Power Adjusted Vehicle Emissions

1997 (Measured)	VSP Bin	Mean NO (ppm)	No. of Measurements	Total Emissions
	-5	236	225	53200
	0	224	1609	360090
	5	307	4985	1531000
	10	431	6146	2648020
	15	548	2624	1438060
	20	590	456	269180
			16045	6299550
			Mean NO (ppm)	**393**

1998 (Measured)	VSP Bin	Mean NO (ppm)	No. of Measurements	Total Emissions
	-5	233	137	31951
	0	239	784	187394
	5	265	3613	956613
	10	385	6685	2576433
	15	475	6012	2856195
	20	483	2392	1156320
			19623	7764906
			Mean NO (ppm)	**396**

1998 (Adjusted)	VSP Bin	'98 Mean NO (ppm)	'97 No. of Meas.	Total Emissions
	-5	233	225	52474
	0	239	1609	384588
	5	265	4985	1319877
	10	385	6146	2368700
	15	475	2624	1246616
	20	483	456	220436
			16045	5592691
			Mean NO (ppm)	**349**

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

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

APPENDIX E: Calculation of Model Year Adjusted Fleet Emissions

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

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

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

APPENDIX F: Field Calibration Record.

1997				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/15	9:35	1.42	1.35	1.07
9/15	14:30	1.26	1.18	0.94
9/16	9:20	1.33	1.25	1.02
9/16	12:40	1.12	1.08	0.86
9/17	8:10	1.39	1.27	1.11
9/17	11:55	1.19	1.12	0.97
9/18	8:15	1.49	1.41	1.20
9/18	12:30	1.15	1.10	0.86
9/19	11:00	1.24	1.16	0.95

1998				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/21	8:15	1.38	1.26	1.21
9/21	13:00	1.31	1.17	1.15
9/22	7:40	1.48	1.36	1.46
9/22	11:40	1.26	1.15	1.27
9/23	8:00	1.64	1.52	1.26
9/23	10:45	1.32	1.25	1.13
9/24	9:00	1.46	1.33	1.41
9/24	12:30	1.30	1.19	1.12

1999				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/20	9:50	1.32	1.05	1.21
9/20	14:30	1.25	0.99	1.15
9/21	8:15	1.45	1.19	1.46
9/21	10:30	1.33	1.07	1.27
9/22	8:30	1.47	1.13	1.32
9/22	11:10	1.22	1.01	1.201
9/23	8:15	1.46	1.16	1.41
9/23	10:30	1.25	0.97	1.12

2000				
Date	**Time**	**CO Cal Factor**	**HC Cal Factor**	**NO Cal Factor**
9/11	8:50	1.22	0.94	1.22
9/11	11:20	1.12	0.87	1.10
9/11	18:05	1.28	0.98	1.35
9/12	8:35	1.29	0.99	1.49
9/13	8:10	1.41	1.11	1.38
9/13	10:35	1.18	0.94	1.13
9/14	8:25	1.36	1.03	1.49
9/14	10:25	1.35	1.07	1.49
9/14	12:35	1.19	0.93	1.25

2002				
Date	**Time**	**CO Cal Factor**	**HC Cal Factor**	**NO Cal Factor**
9/16	11:10	1.35	1.07	1.59
9/17	9:35	1.52	1.19	1.82
9/17	12:00	1.35	1.07	1.46
9/18	9:00	1.51	1.19	1.67
9/18	12:45	1.36	1.07	1.44
9/19	9:20	1.59	1.31	1.60
9/19	12:35	1.39	1.16	1.40
9/20	12:30	1.31	1.17	1.68

2004				
Date	**Time**	**CO Cal Factor**	**HC Cal Factor**	**NO Cal Factor**
9/20	9:00	1.66	1.45	1.47
9/20	11:15	1.37	1.14	1.26
9/21	8:45	1.58	1.32	1.35
9/21	11:10	1.31	1.11	1.19
9/22	8:00	1.77	1.50	1.58
9/22	10:00	1.39	1.19	1.23
9/23	8:00	2.24	1.66	1.87
9/23	10:00	1.43	1.22	1.27

2006				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/12	9:05	1.69	1.41	1.52
9/13	10:00	1.58	1.30	1.51
9/13	11;50	1.75	1.38	1.48
9/13	13:50	1.48	1.20	1.19
9/14	8:00	1.59	1.30	1.41
9/14	11:00	1.43	1.19	1.22
9/15	8:00	2.32	1.91	2.35
9/15	9:30	1.69	1.42	1.56
9/15	11:15	1.46	1.22	1.31

2014						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
9/8	10:00	1.58	1.44	1.44	0.99	0.72
9/8	12:30	1.34	1.23	1.33	0.99	0.6
9/9	9:25	1.62	1.46	1.58	0.96	0.72
9/9	11:30	1.41	1.30	1.37	0.96	0.67
9/10	13:45	1.34	1.24	1.35	0.91	0.69
9/11	9:15	1.83	1.66	1.79	0.98	1.03
9/11	12:20	1.75	1.59	1.73	1.0	0.97
9/11	16:15	1.83	1.63	1.77	0.98	1.04
9/12	9:20	1.85	1.65	1.78	1.02	1.09
9/12	12:15	1.76	1.57	1.68	1.03	0.98
9/13	9:25	1.90	1.70	1.82	0.99	1.13
9/13	12:00	1.75	1.55	1.67	1.03	0.92
9/13	14:35	1.66	1.49	1.62	1.04	0.99

2016						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
9/12	10:00	1.52	1.42	1.36	0.97	1.32
9/12	13:00	1.4	1.3	1.3	1.0	1.0
9/13	09:20	1.53	1.40	1.44	1.0	1.20
9/13	12:00	1.39	1.27	1.35	1.0	0.91
9/14	09:06	1.72	1.61	1.61	0.95	1.30
9/14	11:22	1.52	1.42	1.44	0.98	1.07
9/14	13:53	1.54	1.45	1.46	1.01	1.08
9/15	9:05	1.78	1.63	1.66	0.97	1.4
9/15	13:15	1.56	1.44	1.48	1.01	1.12
9/16	9:00	1.70	1.60	1.61	0.95	1.23
9/16	11:15	1.48	1.41	1.43	0.96	1.06
9/19	9:30	1.68	1.62	1.55	0.94	1.23
9/19	11:10	1.42	1.34	1.24	0.98	1.10
9/20	9:20	1.62	1.54	1.51	0.94	1.10
9/20	12:10	1.45	1.41	1.39	1.03	1.07
9/21	10:10	1.66	1.57	1.54	0.86	1.37
9/21	16:10	1.67	1.53	1.58	0.89	1.34