2019

On-Road Remote Sensing of Automobile Emissions in the Chicago Area: Fall 2018

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CRC Report No. E-123

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June 2019

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On-Road Remote Sensing of Automobile Emissions in the Chicago Area: Fall 2018

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Contract No. E-106

EXECUTIVE SUMMARY

The University of Denver has completed the tenth campaign of a multi-year remote sensing study in the Chicago area, with measurements made in the month of September in 1997, 1998, 1999, 2000, 2002, 2004, 2006, 2014, 2016 and 2018. The remote sensor used in the 2018 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. Non-personal vehicle information was obtained from state registration records from this image. 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 2014 we have not calibrated these measurements and they are not included in the discussion of the results.

The tenth campaign of this study involved six days of fieldwork on September 10 - 15, 2018, conducted at the on-ramp from Algonquin Rd. to eastbound I-290 in northwest Chicago. An extra day (Saturday) was necessary this year to collect a sufficient number of measurements due to an unexplained drop in traffic volume. For the 2018 measurements, a database was compiled containing 21,609 records for which the State of Illinois provided non-personal vehicle registration 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 error of the mean emissions for the fleet measured in this study were 7.3 ± 0.4 gCO/kg of fuel (0.06 ± 0.01 %), 1.7 ± 0.06 gHC/kg of fuel (42 ± 2 ppm), 0.9 ± 0.06 gNO/kg of fuel (62 ± 4 ppm), 0.61 ± 0.02 gNH_3/kg of fuel (76 ± 2 ppm) and 0.08 ± 0.01 gNO_2/kg of fuel (4 ± 0.5 ppm) respectively. When compared with the measurements from 2016 all of the measured species showed reductions of -33%, -6%, -25%, -5% and -20% for CO, HC, NO, NH_3 and NO_2 respectively. The emission measurements in this study exhibit a gamma distribution and the 99th percentile for the 2018 measured fleet is responsible for 36%, 27%, 34% and 10% of the CO, HC, NO and NH_3 total fleet-wide emissions, respectively. The average age of the vehicles in the 2018 fleet remained constant at the 2014 and 2016 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 five other sites. 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 in the absolute reduction of measurements with time has slowed, since

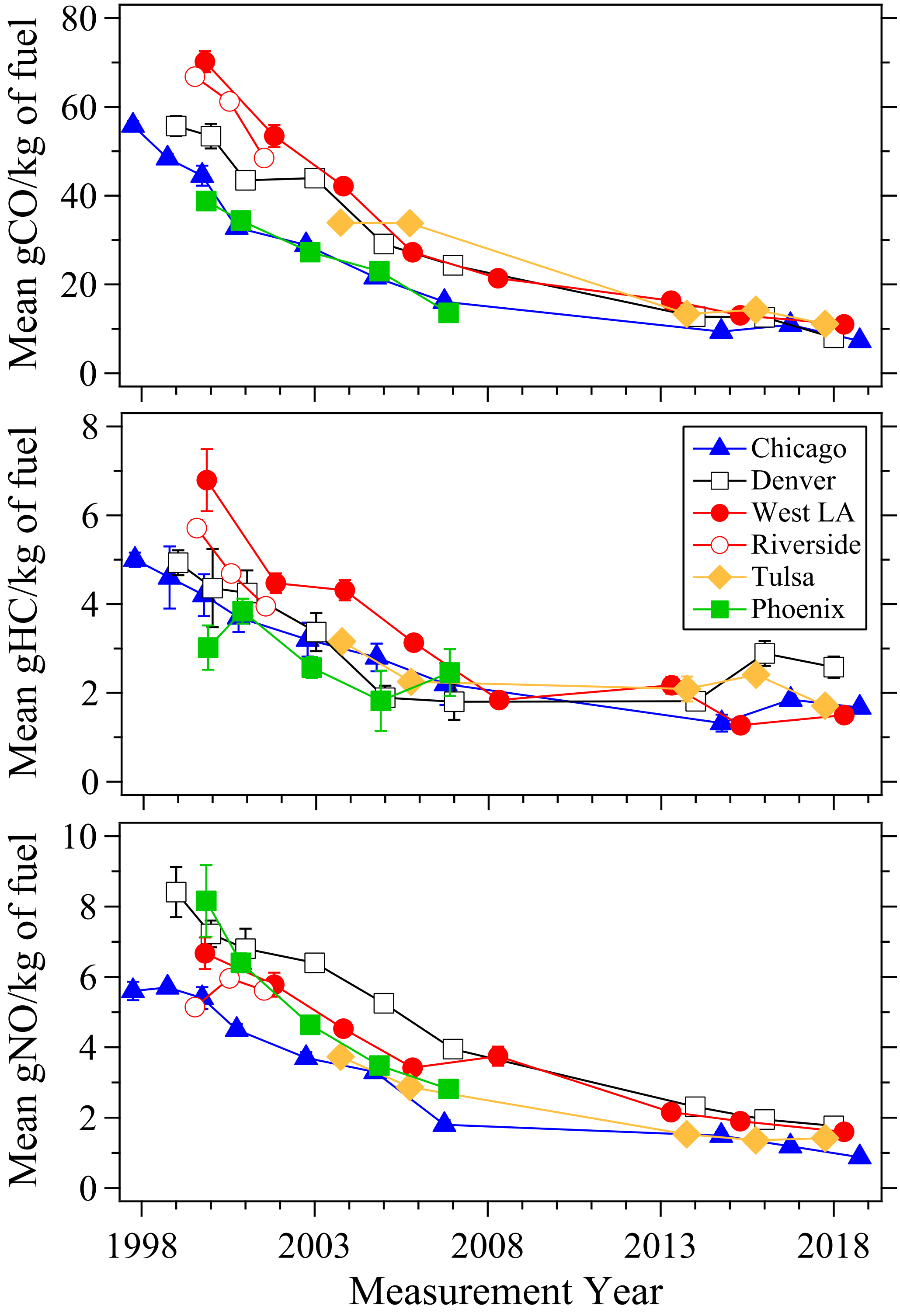

Figure E1. Historical fuel specific mean emission for CO (top), HC (middle) and NO (bottom) for all of the E-23 and E-106 light-duty measurements to date. Uncertainties are standard error of the mean determined from the daily measurements. HC means have been offset adjusted as described in the text.

2013. In 2016, the measurements in Chicago showed an increase in the mean emissions for CO and HC, but all of the measured species show resumed decreases in the 2018 campaign. However, it is apparent that for the HC measurements the mean values are simply moving around a lower limit since the 2007 measurements indicating that they have likely reached a lower limit.

Several factors have likely contributed to the slowdown in the reduction in the Chicago mean emissions. Due to the recession of 2008 and 2009, the average age of the Chicago fleet increased 1.5 model years from around 6 years old in 2006 to 7.5 years old in 2014. The fleet age observed in 2018 at the Chicago site has not changed since 2014. An additional factor can be seen in Figure E2 that 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 2018. The mean CO and HC emissions for the 20 to 23 year old vehicles measured in 2018 are similar to those of the average 5 and 6-year-old vehicle measured in 1997. In 2018, both CO and HC emissions show little change in mean emissions for the first 16 to 18 model years, unlike in the 1997 data set. NO is the only species where 20 year old vehicles in 2018 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 (2009 – 2016 models) and now Tier III vehicles, whose phase in began with 2017 models. In 2018, the NO emissions of the newest nine model years of vehicles are very low and indistinguishable from each other. The lack of any significant emission deterioration works against fleet turnover contributing to meaningful reductions in the fleet emission means since a new vehicle purchased today will most likely replace a vehicle with emissions that are, on average very similar.

Mean fuel specific NH_3 (0.61 ± 0.02 gNH_3/kg of fuel) in 2018 continued to decrease and is 5% lower than that observed in 2016 (0.64 ± 0.02 gNH_3/kg of fuel). Emissions reductions observed from the two newest models measured in 2018 are offset by increases in emissions for vehicles 2 to 7 years old. The total fixed nitrogen species have continued to decrease and the percent contributed by ammonia appears to have leveled out and started to decrease. However, ammonia remains the dominate reactive nitrogen emission from vehicles up to 13 years of age in Chicago in the 2018 measurements.

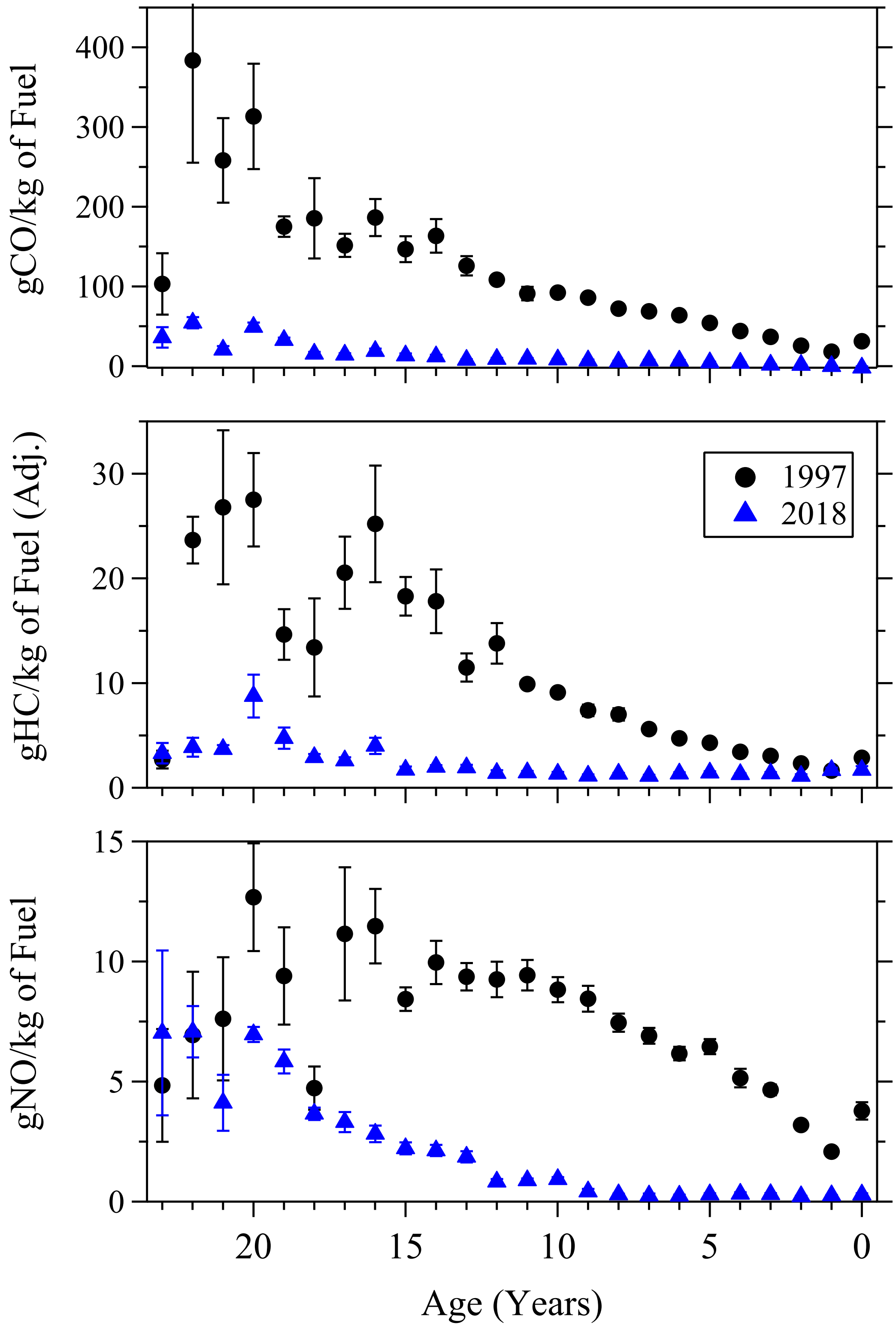

Figure E2. Mean fuel specific emissions by vehicle age for the 1997 (circles) and 2016 (triangles) Chicago data sets for CO (top), HC (middle) and NO (bottom). Uncertainties are standard error of the mean calculated from the daily samples.

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 2017, on-road vehicles continued to be estimated as one of the larger sources for major atmospheric pollutants, contributing approximately 38% of the CO, 13% of the VOC's, 3% of the NH_3 and 35% 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, beyond Federal and California certification standards, include inspection and maintenance 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 (80ppb), lowered in 2008 (75ppb) and again in 2015 (70ppb)) means that many new locations are likely to continue 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 other researchers to study fleet emission trends and construct emission inventories.[6-8]

Reflecting a desire to continue evaluation of historical and recent emissions trends, several of the E-23 sites were chosen for additional data collection campaigns. This report describes the on-road emission measurements taken in the Chicago IL area in the fall of 2018, under CRC Contract No. E-123. Measurements were made on parts of six weekdays, from Monday, September 10, to Saturday, September 15 between the hours of 9:00 and 18:30 on the on-ramp (1°) from Algonquin Rd. to southbound I-290/SH53 (see Figures 1 & 2). Measurements have previously been collected nine times at this same location in 1997, 1998, 1999, 2000, 2002, 2004, 2006, 2014 and 2016.

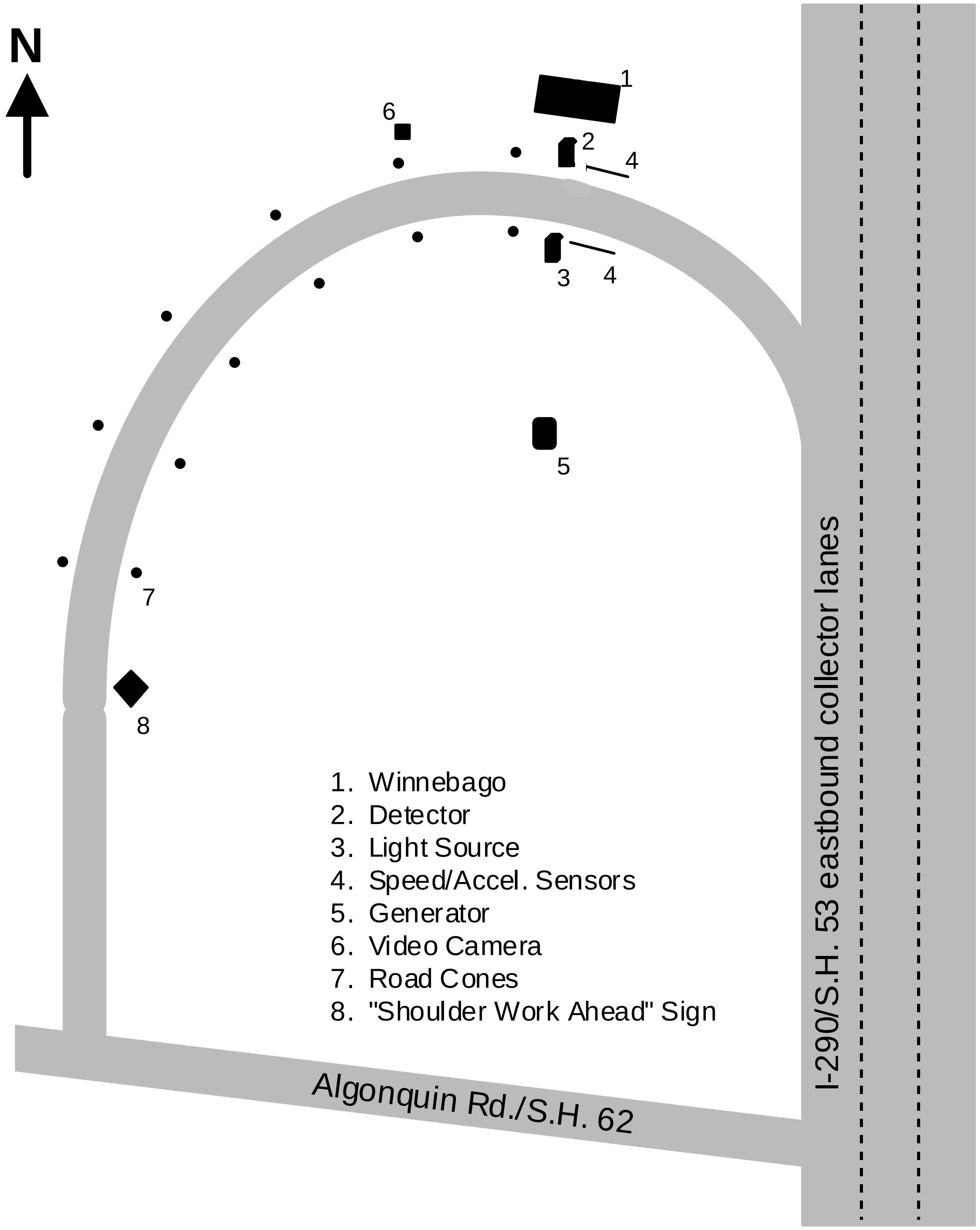

Figure 1. Area map of the on-ramp from Algonquin Road to eastbound I-290 in northwest Chicago, showing remote sensor configuration and safety equipment.

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

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.[9-11] 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.[12] 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.[13] 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:

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

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.[13]

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

Quality assurance calibrations are performed at least twice daily in the field unless observed voltage readings or meteorological changes are judged to warrant additional calibrations. 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.[14, 15] The NO channel used in this study has been extensively tested by the University of Denver, but has not been independently validated in an extensive double-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.[10] 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 six days of data collection in September of 2018, 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 21,609 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 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 21,609 records used in this analysis, 11,731 (54.3%) were contributed by vehicles measured once, and the remaining 9,878 (45.7%) records were from vehicles measured at least twice.

Table 3 provides the data summary for 2018 and 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, 2014

Table 1. Validity Summary.

	CO	HC	NO	NH_3	NO_2
Attempted Measurements	28,677				
Valid Measurements	24,846	24,828	24,845	24,822	23,659
Percent of Attempts	86.6%	86.6%	86.6%	86.6%	82.5%
Submitted Plates	21,767	21,755	21,767	21,746	20,776
Percent of Attempts	75.9%	75.8%	75.9%	75.8%	72.4%
Percent of Valid Measurements	87.6%	87.6%	87.6%	87.6%	87.8%
Matched Plates	21,609	21,597	21,609	21,588	20,622
Percent of Attempts	75.4%	75.3%	75.4%	75.3%	71.9%
Percent of Valid Measurements	87.0%	87.0%	87.0%	87.0%	87.0%
Percent of Submitted Plates	99.3%	99.3%	99.3%	99.3%	99.3%

Table 2. Number of measurements of repeat vehicles.

Number of Times Measured	Number of Vehicles
1	11,731
2	1,855
3	898
4	489
5	258
6	23
7	8
>7	4

Table 3. Historical data summary.

Study Year	1997	1998	1999	2000	2002	2004	2006	2014	2016	2018
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)	0.057 (7.3)
Median CO (%)	0.14	0.15	0.09	0.05	0.07	0.04	0.02	0.011	0.023	0.006
%Total CO from the 99th Percentile	13.9%	14.6%	16.5%	19.6%	20.4%	22.3%	26.3%	34.4%	27.1%	36.2%
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	42 (1.7) 31
Median HC (ppm)[a]	50	50	50	40	40	30	30	9	22	22
%Total HC from the 99th Percentile	21.0%	26.7%	22.8%	22.2%	21.9%	24.8%	33.9%	42.5%	24.5%	26.8%
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)	62 (0.88)
Median NO (ppm)	160	140	121	79	52	39	14	5	3	0.5
%Total NO from the 99th Percentile	8.7%	8.1%	9.7%	11.2%	13.2%	13.5%	18.8%	24.9%	30.8%	34.4%
Mean NH_3 (ppm) (g/kg of fuel)								89 (0.71)	79 (0.64)	76 (0.61)
Median NH_3 (ppm)								43	38	37
%Total NH_3 from the 99th Percentile								10.3%	10.4%	10.4%
Mean NO_2 (ppm) (g/kg of fuel)								-1.5 (-0.04)	5 (0.1)	4 (0.08)
Median NO_2 (ppm)								-3.6	2	2
%Total NO_2 from the 99th Percentile								N.A.	36.6%	43.9%
Mean Model Year	1992.7	1993.6	1994.3	1995.5	1997.4	1999.2	2001.0	2007.5	2009.6	2011.6
Mean Fleet Age[c]	5.3	5.4	5.7	5.5	5.6	5.8	6	7.5	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	23.7
Mean Acceleration (mph/s)	0.1	0.8	0.2	0.5	-0.4	0.4	0.4	0.2	0.5	0.1
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°	4.6 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.

and 2016. Unlike the increase observed from 2014 to 2016 CO emissions in 2018 have again shown a decreasing trend along with NO and to a lesser extent HC and NH_3. Fleet average HC emissions have essentially bottomed out over the past several campaigns and the slight fluctuations in mean emissions are likely attributable to instrument noise and not to significant changes in tailpipe emissions. The decreases in fleet NO emissions are astonishing with the fleet median approaching zero for the first time. These decreases have now skewed the NO fleet emissions distribution such that the contribution of the 99th percentile to the total emissions is similar to CO and HC (see Table 3). Certainly, these reductions reflect the fact that the fleet is now dominated by Tier II vehicles that exhibit very low emission deterioration levels. The fleet age in 2018 remained unchanged at 7.5 years – still above that observed before the 2008 - 2009 recession. Traffic volumes in 2018 were uncharacteristically low compared to previous measurement years that necessitated the extra day of measurements. This lowered the amount of afternoon stop-and-go driving lowering average acceleration rates. As will be discussed in more detail later this does not affect the emission measurement comparisons because driving mode no longer significantly effects fuel specific emissions.

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. Since it is assumed that the cleanest vehicles emit few hydrocarbons, this approximation will only err slightly towards clean as 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 use 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 ten campaigns. The HC data have been offset adjusted as previously described. Since the fleet fractions in Chicago are dominated by the newest ten model years (~70% of the fleet), the effects of emission changes in this group will be strongly reflected in the mean emissions. With the phase-in of Tier III vehicles beginning with the 2017 model year, the lower CO and NO emissions for these models have helped to reduce the fleet means. Mean NO emissions for the newest model year vehicles continue to be defined by very low and stable fuel specific NO emissions with no statistical differences in mean gNO/kg of fuel emissions now for the 10 newest model years (2010 and newer) and only small increases for the next three model years (2007 – 2009). The mean CO and HC emissions by model year also continue to show very low levels for the newest 15+ model years in the fleet.

The 2018 fleet vehicle emissions by model year, were divided into quintiles and plotted using the format originally presented by Ashbaugh et al.[16] 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

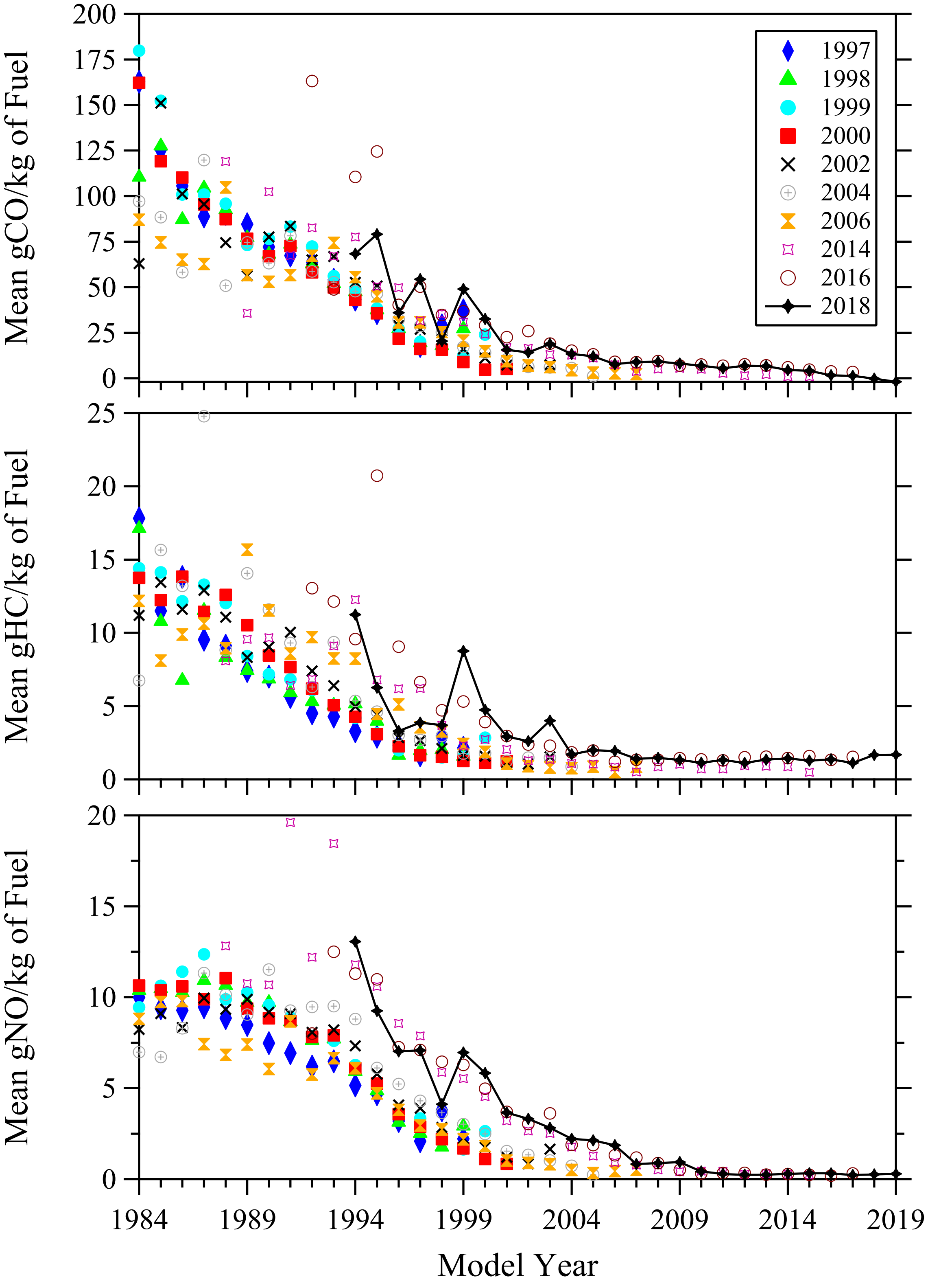

Figure 3. Chicago historical fuel specific mean vehicle emissions plotted as a function of model year. HC data have been offset adjusted as described in the text.

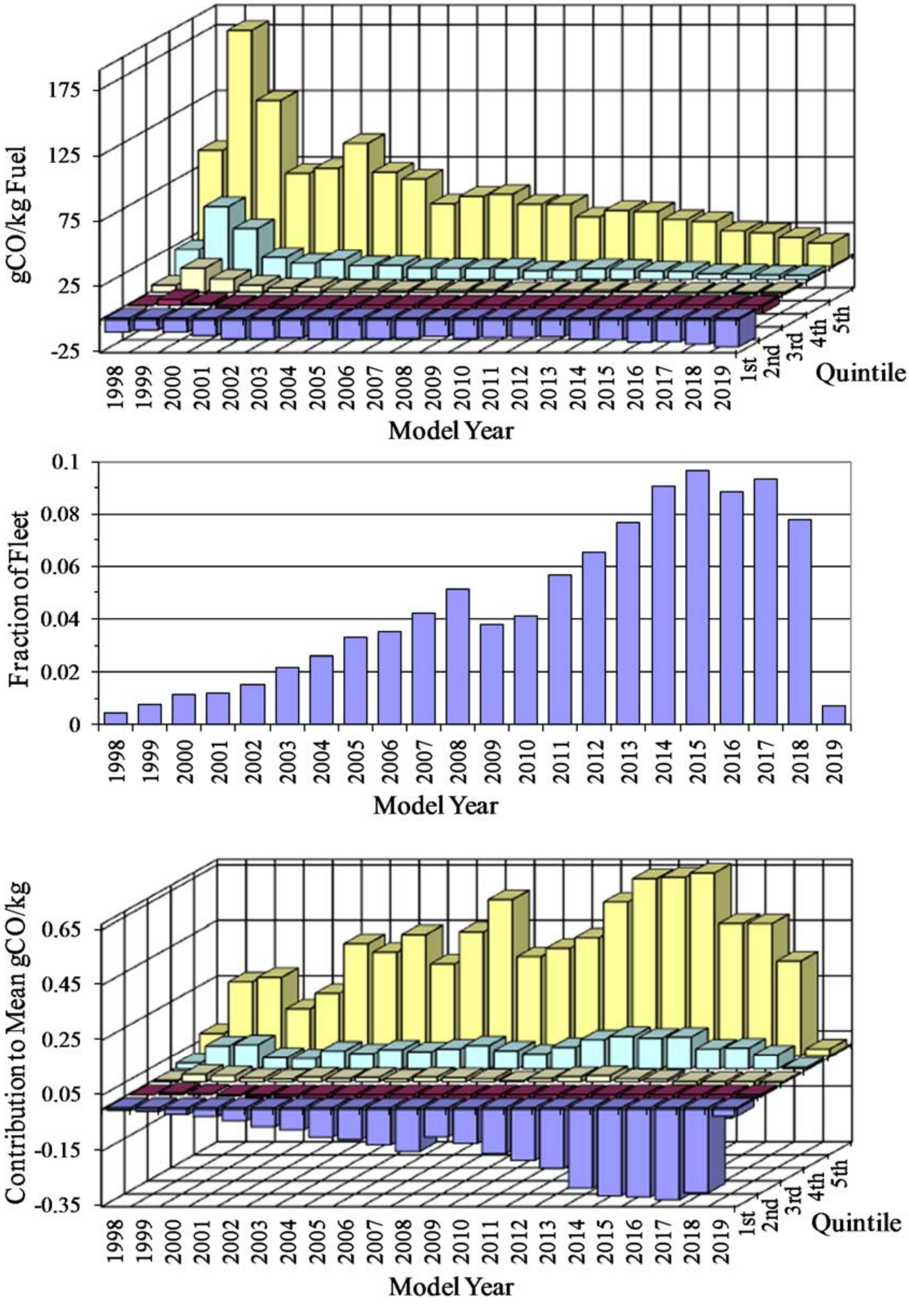

Figure 4. 2018 CO emissions by model year and quintile (top), fleet distribution (middle) and their product showing the total fractional CO emissions by model year and quintile (bottom).

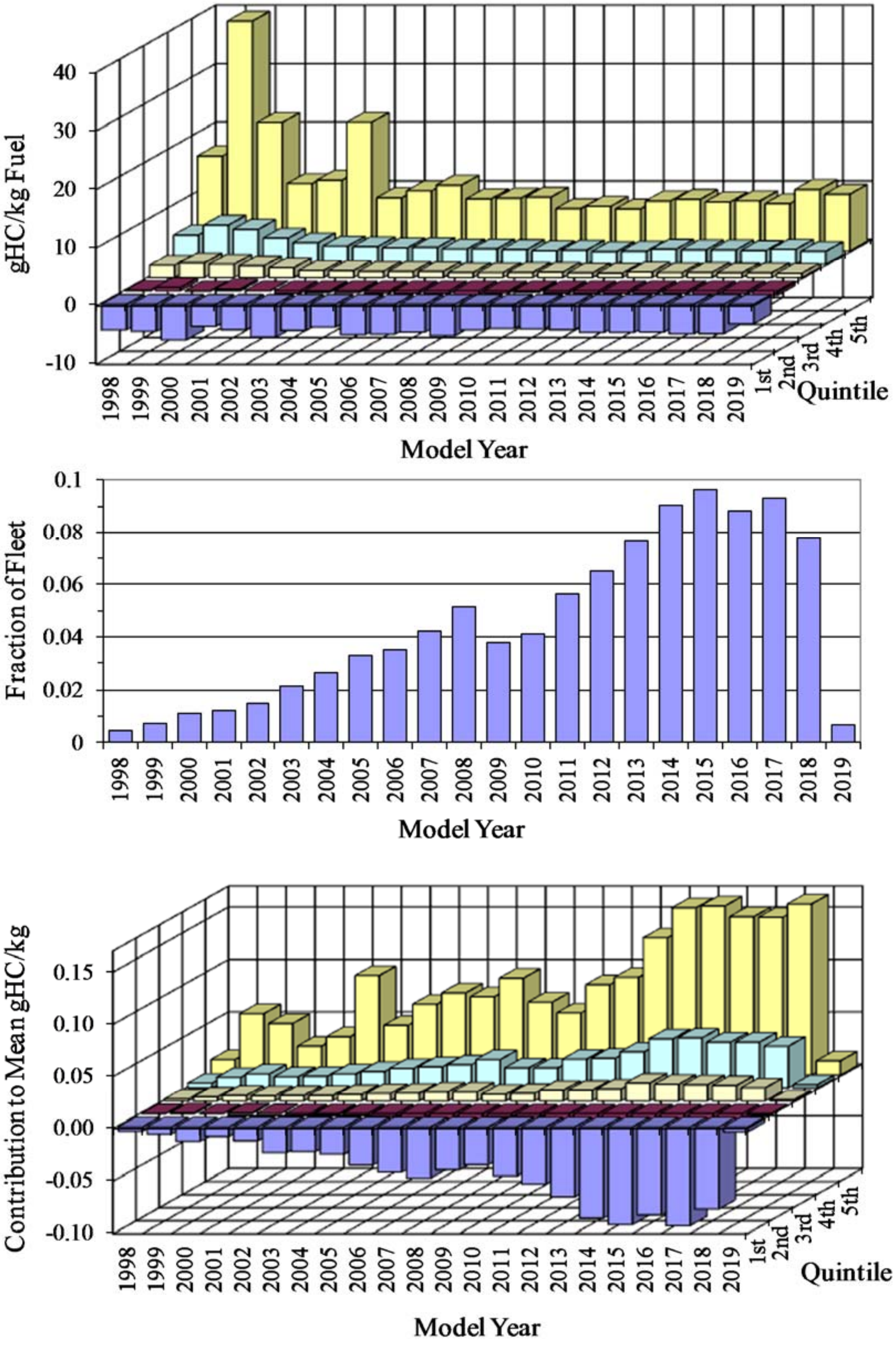

Figure 5. 2018 HC emissions by model year and quintile (top), fleet distribution (middle) and their product showing the total fractional HC emissions by model year and quintile (bottom).

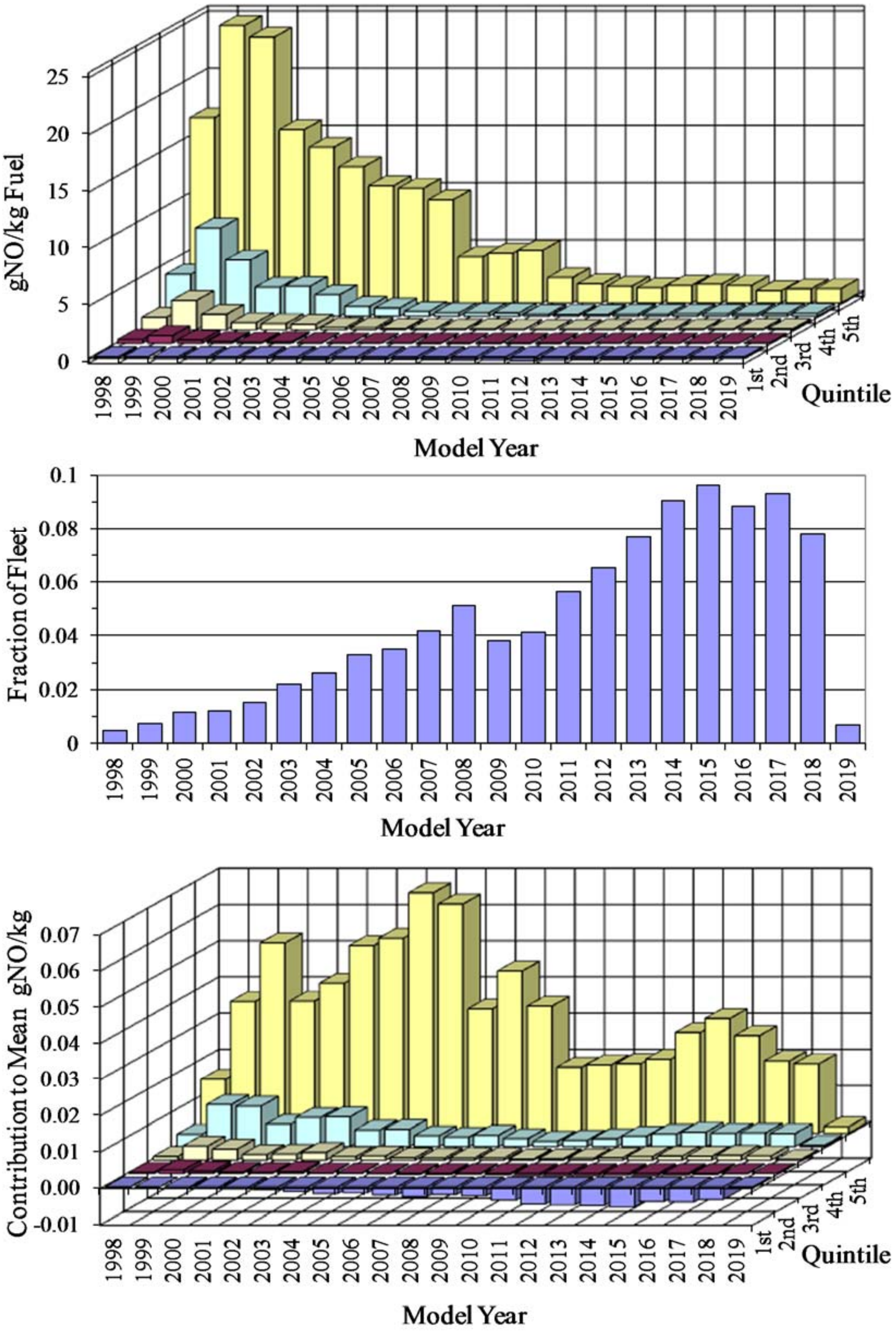

Figure 6. 2018 NO emissions by model year and quintile (top), fleet distribution (middle) and their product showing the total fractional NO emissions by model year and quintile (bottom).

the 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 evident in the model year fractions beginning in 2009 and continuing through 2012. The bottom graphs, which are a product of the first two graphs, display the contribution each model year and quintile makes to the mean emissions. Model years older than 1998 that are not graphed account for only ~1% of the measurements and the contribution ranges between 5.5% (HC) to 11.6% (CO) of the emissions. The bottom graphs for each species illustrate that the first three quintiles of the measurements (60%) make an essentially negligible contribution to the mean emissions, regardless of model year. For CO and HC only the last quintile now contributes significant amounts. 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 approach 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.

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 reduced fractions of 2009 – 2011 models in the fleet are still visible and still exert an important influence on the mean age of the Chicago fleet. Fleet age has remained stable since the 2014 measurements (see Table 3) at ~7.5 years old. Since vehicles 10 years old and newer now represent ~70% of the Chicago fleet, there is the possibility that the Chicago fleet age will begin to get younger in the next two years as the 2009 and 2010 models turn over and move out of this group. For the first time since measurements have been collected at this Chicago site, vehicles identified as trucks from the VIN information exceeded passenger vehicles. In 2018 ~51% of the measurements are from vehicles identified as trucks.

An equation for determining the instantaneous power demand of an on-road vehicle published by Jimenez[17], takes the form

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

where VSP is the vehicle specific power in kW/metric tonne, *slope* is the slope of the roadway (in degrees, see Table 3), 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 7. All of the specific power bins for 2018 contain at least 100 measurements and the HC data have been offset adjusted.

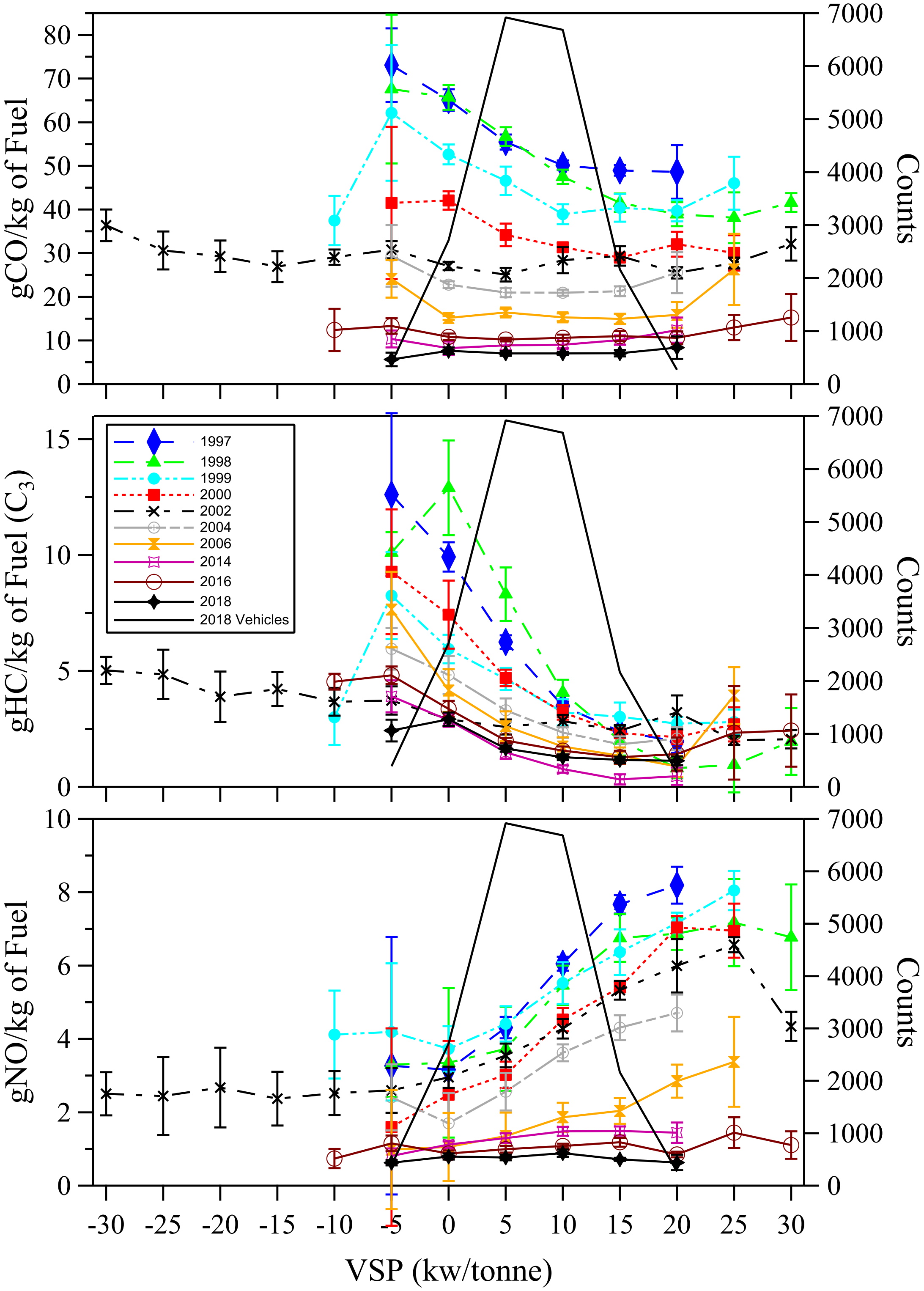

Figure 7. Vehicle emissions as a function of vehicle specific power for all of the Chicago data sets. The uncertainties are plotted as the standard errors of the mean calculated from daily samples. The solid line without markers is the vehicle count profile (right y-axis) for the 2018 data set.

All of the species generally show reduced emissions when compared with previous data sets. HC is the one exception as not all of the VSP bins for the 2018 measurements have the lowest emissions. As seen in the previous measurements all three emissions species show little dependence on vehicle specific power. CO and NO emissions are especially flat across the VSP range while only the influence of decelerations, which increases HC emissions, remains as a significant driving mode factor for mean emissions. The uncertainty 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.[18] Each day's average emission for a given VSP bin was assumed an independent measurement of the average emissions at that VSP. Normal statistics were then applied to these daily averages.

The use of VSP can be used to reduce the influence of 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, 2016 and 2018 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, 2016 and 2018 databases, adjusted for vehicle specific power that match the 1997 VSP distribution.

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 the 1997 measurements. 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 twenty-one year period, the reduction in all three species goes far beyond just driving mode dependence as discussed earlier. VSP normalized CO and NO emissions have declined by a factor of 7 and HC have been reduced by a factor of 3.

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 ten 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 emissions. Only the CO and NO measured mean emissions for this model year grouping have increased significantly since the 1997 measurements (~+51% CO and +33% NO). However, all three species have seen the age adjusted mean emissions about double over the 21-year period. The number of 1983-1997 models has shrunk by almost a factor of 25 during the 21 years that

Table 4. Vehicle specific power emissions (-5 to 20 kw/tonne only) with standard errors of the means calculated using daily averages and means adjusted to the 1997 VSP distribution.

Year	Mean gCO/kg Measured (Adjusted)	Mean gHC/kg[a] Measured (Adjusted)	Mean gNO/kg Measured (Adjusted)
1997	53.4 ± 1.0 (53.4 ± 1.0)	8.2 ± 0.2 (4.9 ± 0.2)	5.5 ± 0.3 (5.5 ± 0.3)
1998	47.2 ± 1.3 (51.2 ± 1.4)	9.2 ± 0.6 (5.9 ± 0.4)	5.6 ± 0.1 (4.9 ± 0.1)
1999	43.7 ± 2.3 (43.3 ± 2.3)	6.9 ± 0.5 (4.0 ± 0.3)	5.2 ± 0.3 (5.2 ± 0.3)
2000	32.2 ± 0.9 (33.1 ± 0.9)	3.0 ± 0.2 (4.0 ± 0.3)	4.4 ± 0.2 (4.0 ± 0.2)
2002	27.7 ± 1.2 (27.3 ± 1.2)	3.3 ± 0.3 (2.7 ± 0.2)	3.9 ± 0.2 (4.1 ± 0.2)
2004	21.4 ± 0.8 (21.4 ± 0.8)	3.7 ± 0.3 (2.9 ± 0.3)	3.3 ± 0.1 (3.2 ± 0.1)
2006	15.7 ± 0.9 (15.7 ± 0.9)	2.7 ± 0.5 (2.3 ± 0.5)	1.7 ± 0.1 (1.7 ± 0.1)
2014	9.1 ± 0.8 (9.2 ± 0.8)	1.3 ± 0.2 1.2 ± 0.2)	1.4 ± 0.1 (1.4 ± 0.1)
2016	10.6 ± 0.3 (10.6 ± 0.3)	1.9 ± 0.1 1.9 ± 0.1)	1.0 ± 0.1 (1.0 ± 0.1)
2018	7.1 ± 0.4 (7.1 ± 0.4)	1.66 ± 0.07 (1.55 ± 0.07)	0.80 ± 0.06 (0.80 ± 0.06)

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

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 twelve years, increases have occurred for all species. Since 2006, the fleet age for this select group of model years has more than doubled (11.5 to 24 years) and the number of measurements has shrunk dramatically increasing the uncertainties 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 model year 1997 has more than 50 measurements and for the 2018 measurements 1983 - 1989 models have only 5 measurements. Because of the skewed nature of emission distributions, the model year adjusted emissions increases seen in 2018 may now be influenced by sampling bias

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

Year	Mean gCO/kg Measured (Age Adjusted)	Mean gHC/kg[a] Measured (Age Adjusted)	Mean gNO/kg Measured (Age Adjusted)	Vehicles
1997	53.0 ± 0.9 (53.0 ± 0.9)	8.1 ± 0.2 (4.8 ± 0.2)	5.6 ± 0.3 (5.6 ± 0.3)	18,251
1998	52.0 ± 0.8 (53.3 ± 0.8)	5.0 ± 0.6 (5.4 ± 0.4)	6.3 ± 0.1 (6.4 ± 0.1)	19,319
1999	53.8 ± 1.9 (57.1 ± 2.0)	5.0 ± 0.6 (5.4 ± 0.4)	6.6 ± 0.3 (6.8 ± 0.3)	16,639
2000	46.4 ± 1.4 (51.2 ± 1.6)	5.1 ± 0.3 (5.6 ± 0.4)	6.2 ± 0.2 (6.6 ± 0.2)	13,394
2002	50.6 ± 2.0 (56.8 ± 2.2)	5.4 ± 0.5 (6.3 ± 0.5)	6.4 ± 0.3 (7.0 ± 0.3)	9,372
2004	46.3 ± 1.9 (53.3 ± 2.1)	5.7 ± 0.4 (7.4 ± 0.6)	7.0 ± 0.3 (7.7 ± 0.3)	6,220
2006	45.9 ± 2.2 (52.8 ± 2.5)	6.2 ± 0.5 (7.6 ± 0.7)	4.9 ± 0.4 (5.7 ± 0.5)	4,238
2014	57.1 ± 2.6 (77.3 ± 3.5)	8.0 ± 1.6 (10.6 ± 0.9)	10.5 ± 1.2 (11.7 ± 0.6)	733
2016	70.5 ± 5.5 (99.1 ± 7.7)	8.2 ± 0.6 (19.6 ± 1.3)	10.4 ± 0.8 (9.7 ± 0.8)	513
2018	80.2 ± 6.4 (106.8 ± 8.5)	7.4 ± 1.3 (11.4 ± 2.0)	8.4 ± 1.0 (9.7 ± 1.1)	204

[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.

that is not reflected in the uncertainty estimates.

In 2014 Chicago became the seventh U.S. site to have the University of Denver collect fleet NH_3 measurements. The 2018 mean reported in Table 3 (0.61 ± 0.02) represents a 5% reduction from the mean observed in 2016. Figure 8 is a graph of gNH_3/kg of fuel emissions by model year for the three Chicago data sets with NH_3 measurements. The uncertainties are standard error of the mean calculated using the daily means. We continue to see lower ammonia emissions from the newest model year vehicles that work to lower the emission means. There is a 22% decrease between the zero-year 2017 and 2019 model year vehicles from the two most recent data sets. However, emissions deterioration in 2 to 7-year-old vehicles limits the overall reductions.

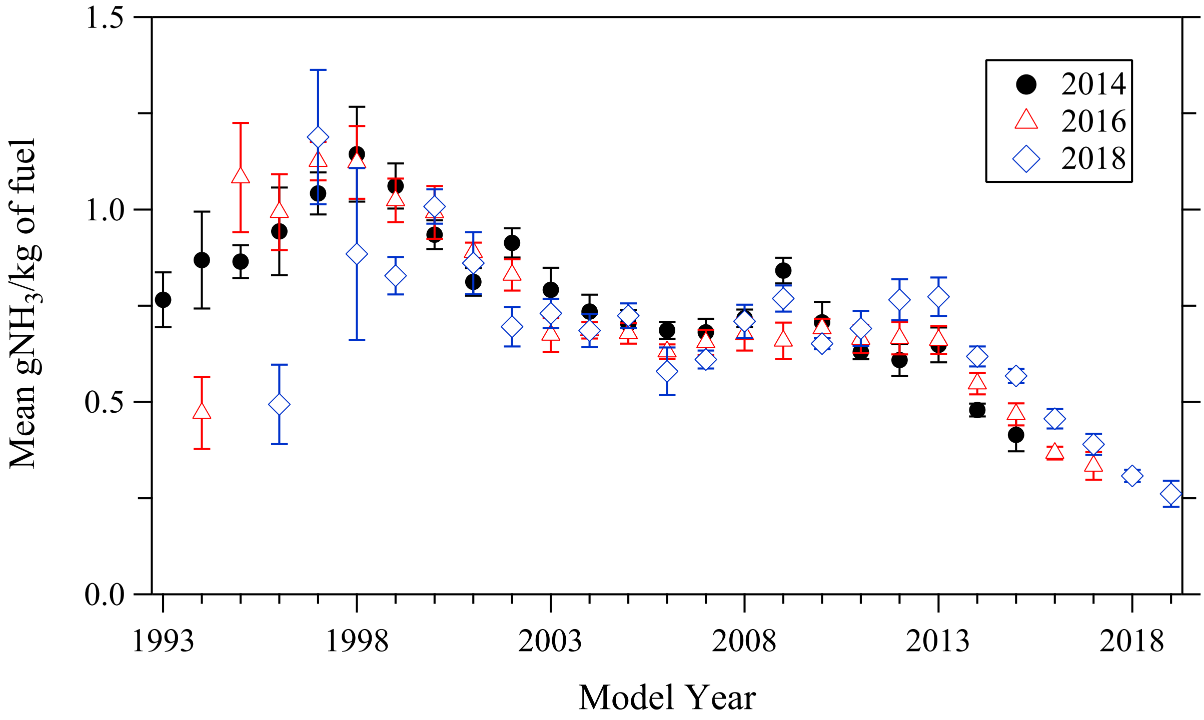

Figure 8. Comparison of gNH_3/kg of fuel emissions by model year for the 2014, 2016 and 2018 Chicago data sets. The uncertainties are standard error of the mean calculated using the daily measurements.

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 in the analysis of previous fleets. Total fixed nitrogen for this calculation neglects the minor contributions of nitrous oxide (N_2O) and nitrous acid (HONO) and is the sum of the moles of nitrogen contributed by NO, NO_2 and NH_3. The gNO_x/kg of fuel was calculated by converting the measured 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.*[19] All of the N factors were converted to mole/kg of fuel.

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

Figure 9 shows the results of these calculations for the Chicago 2018 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 continues to decrease with subsequent model year vehicles. The percent contributed by ammonia (●, left axis) had steadily increased in the Chicago fleet but has now peaked and while still the dominate species of fixed nitrogen being emitted its percentage is on the decline. This pattern has

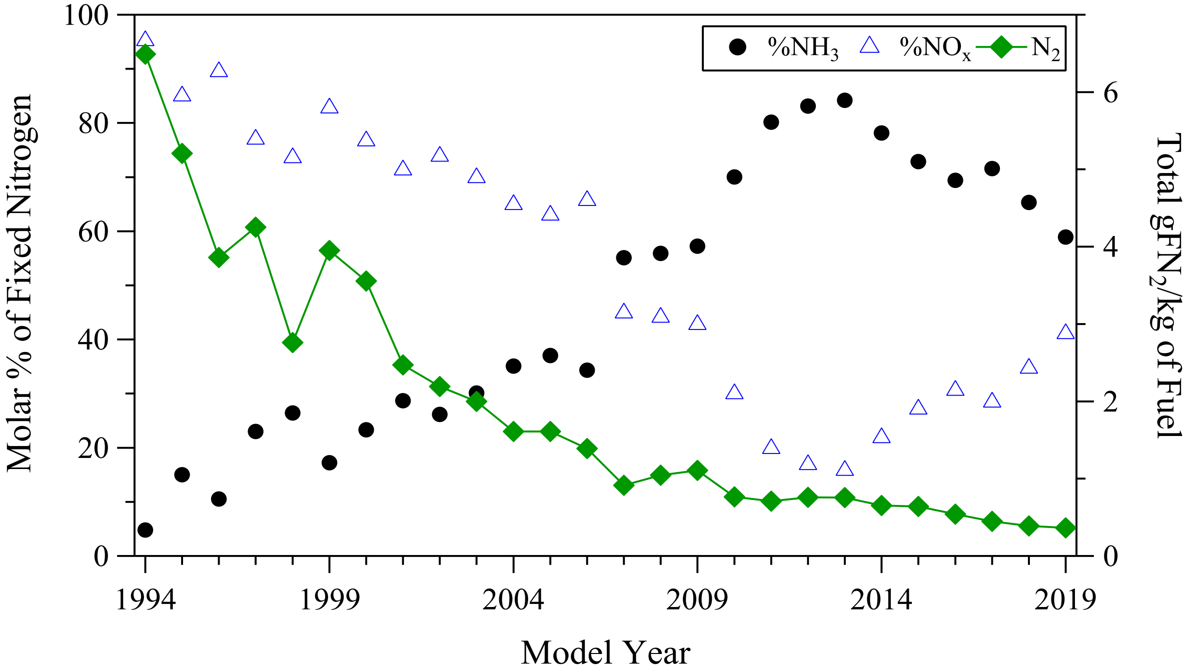

Figure 9. Total fixed nitrogen in g/kg of fuel (diamonds, right axis) with the molar percent composition distributed between the molar $\%NH_3$ (circles, left axis) component and the molar $\%NO_x$ component (triangles, left axis) by model year for the 2018 measurements.

not been consistently observed across all of our study sites. In Denver, 2017 measurements showed decreases in the ammonia percentage with the newest model year vehicles as in Chicago. However, 2018 data from the West Los Angeles site shows no NH_3 decline.

Figure 10 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 when the ramp was replaced with 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 rate of reductions have slowed on an absolute basis and HC emissions in particular appeared to have plateaued. Ramp reconstruction in Denver in 2014 increased the percentage of deceleration events that were observed raising the measured fuel specific HC emissions, confounding the HC time trend at that site.

There have been twenty-one years since the first data set was collected at the Chicago Algonquin Rd. site in the fall of 1997. Figure 11 compares the mean fuel specific CO (top panel), HC (middle panel) and NO emissions (bottom panel) for the 1997 and 2018 data sets plotted against vehicle age for the entire fleet. Zero-year vehicles are 1998 and 2019 respectively for the 1997 and 2018

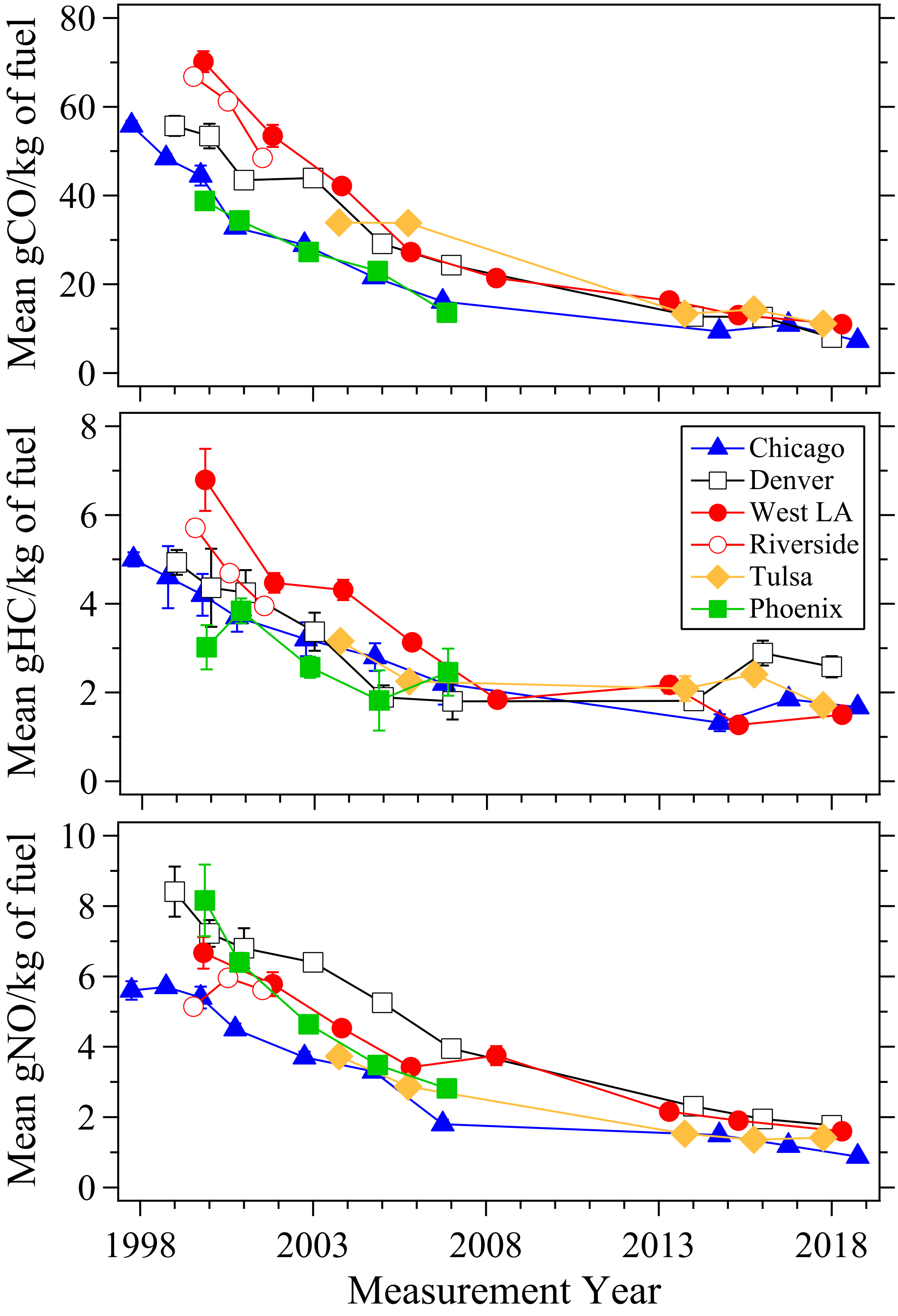

Figure 10. Historical fuel specific mean emission for CO (top), HC (middle) and NO (bottom) for all of the E-23 and E-106 light-duty measurements to date. Uncertainties are standard error of the mean determined from the daily measurements. HC means have been offset adjusted as described in the text.

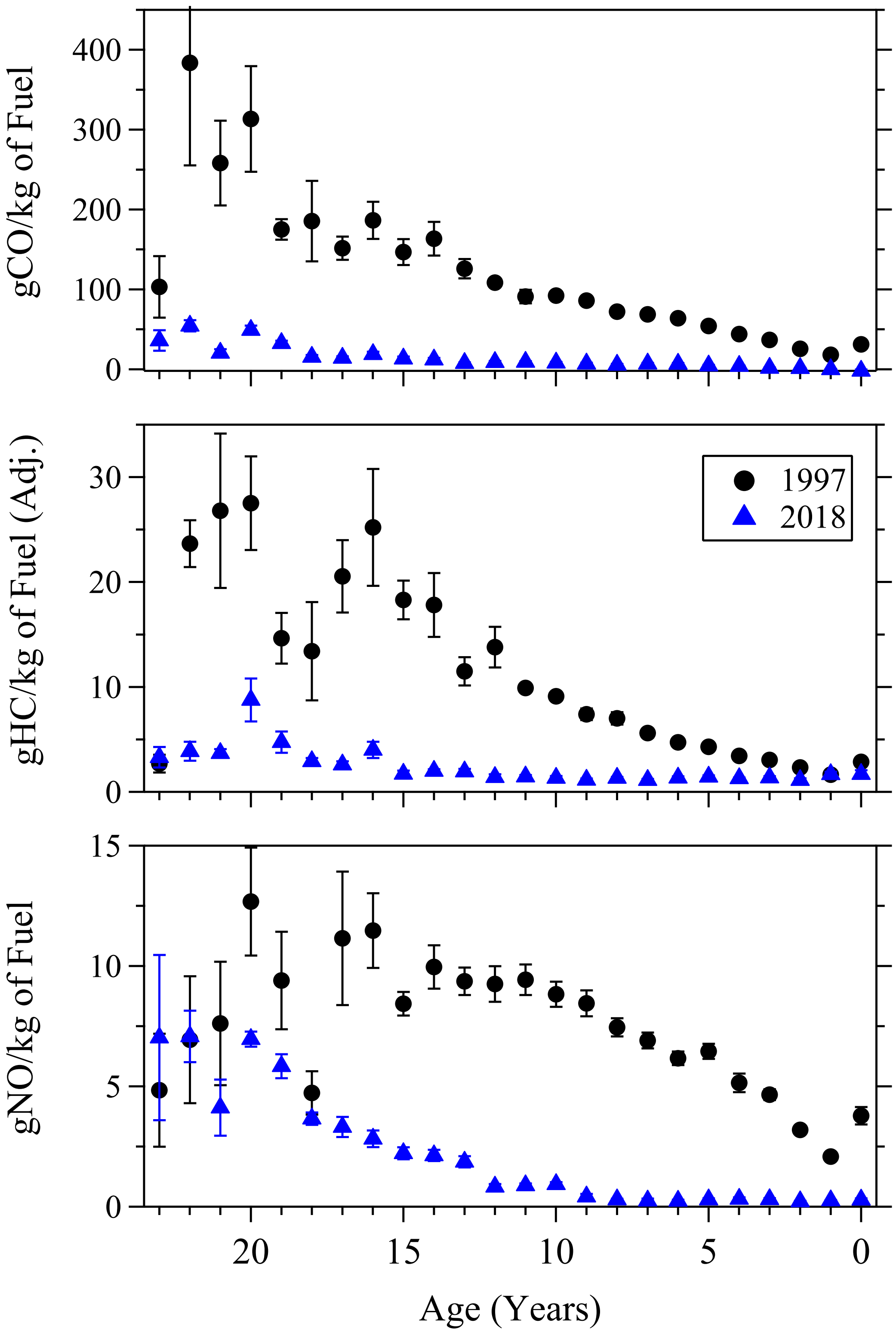

Figure 11. Mean fuel specific emissions by vehicle age for the 1997 (circles) and 2018 (triangles) Chicago data sets for CO (top), HC (middle) and NO (bottom). Uncertainties are standard error of the mean calculated from the daily samples.

data sets. The uncertainties plotted are standard error of the mean calculated from the daily measurements. The uncertainties increase significantly for vehicles older than 20 years as less than 0.6% of the fleet in both measurement years is older. The HC data have been normalized to the lowest HC emitting vehicles in each of the respective data sets as previously described in the text (see adjustment values in Table 3).

Consistent with the large reduction in the mean emissions are large reductions in similarly aged vehicles. In the 2018 data the 20- to 23-year-old vehicles have similar mean emissions as 5- to 6-year-old vehicles respectively for CO and HC measured in 1997. In the 2018 measurements, CO and HC emissions show little to no changes in mean emissions for the newest 16 to 18 model years, unlike the earlier data set. NO is the only species where 20-year-old and older vehicles in 2018 have similar emissions to the same aged vehicles measured in 1997. However, NO emissions have only been aggressively targeted for reduction with the introduction of Tier II (2009 – 2016 models) and now Tier III vehicles, whose phase in began with 2017 models. Both certification standards significantly lowered the gNO_x/mile emission limits and also increased the useful life mileage that they are required to meet them.[20] In 2018, the first nine model years have NO emissions that are low and indistinguishable from each other. It is not until the 2009 model year vehicles that the first noticeable increase is NO emissions are found. However, it is not until after the 2007 model year vehicles that consistent year over year increases in the model year averages return. One factor driving the slowing in the reduction of fleet mean emissions (see Figure 10) can be explained using Figure 11 when one realizes that a new vehicle purchased today will most likely replace a vehicle with emissions that on average are similar in magnitude. This limits the reductions that can now be achieved in the fleet means from future fleet turnover.

Figure 12 compares the contribution by model year to the fleet mean emissions for the 1997 and 2018 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 2018 emission percentages we calculated the total 2018 emissions for each species by multiplying the number of measurements collected in 2018 by the 1997 mean emissions for that species. The total contributions add to 100% for the 1997 data but only to 13%, 33% and 16% respectively for CO, HC and NO that reflects the reduction in emission totals between the two data sets. The flattening of the emissions distribution for all of the species is one of the more important changes during the past twenty-one years and is the result of the flattening of the emissions by model year profile (see Figure 11).

Figure 13 is a plot of the fuel specific CO (top panel), HC (middle panel) and NO (bottom panel) 99th percentiles by model year for the 1997, 2006 and 2018 Chicago data sets. The 99th percentile of the emissions distribution can be used to represent an emissions level that generally corresponds to vehicles in disrepair and are only displayed for model years with at least 100 measurements. Much like the mean values the emissions of these vehicles has dropped dramatically over the last twenty-one years yet emission levels for these vehicles are still large multiples of the mean values.

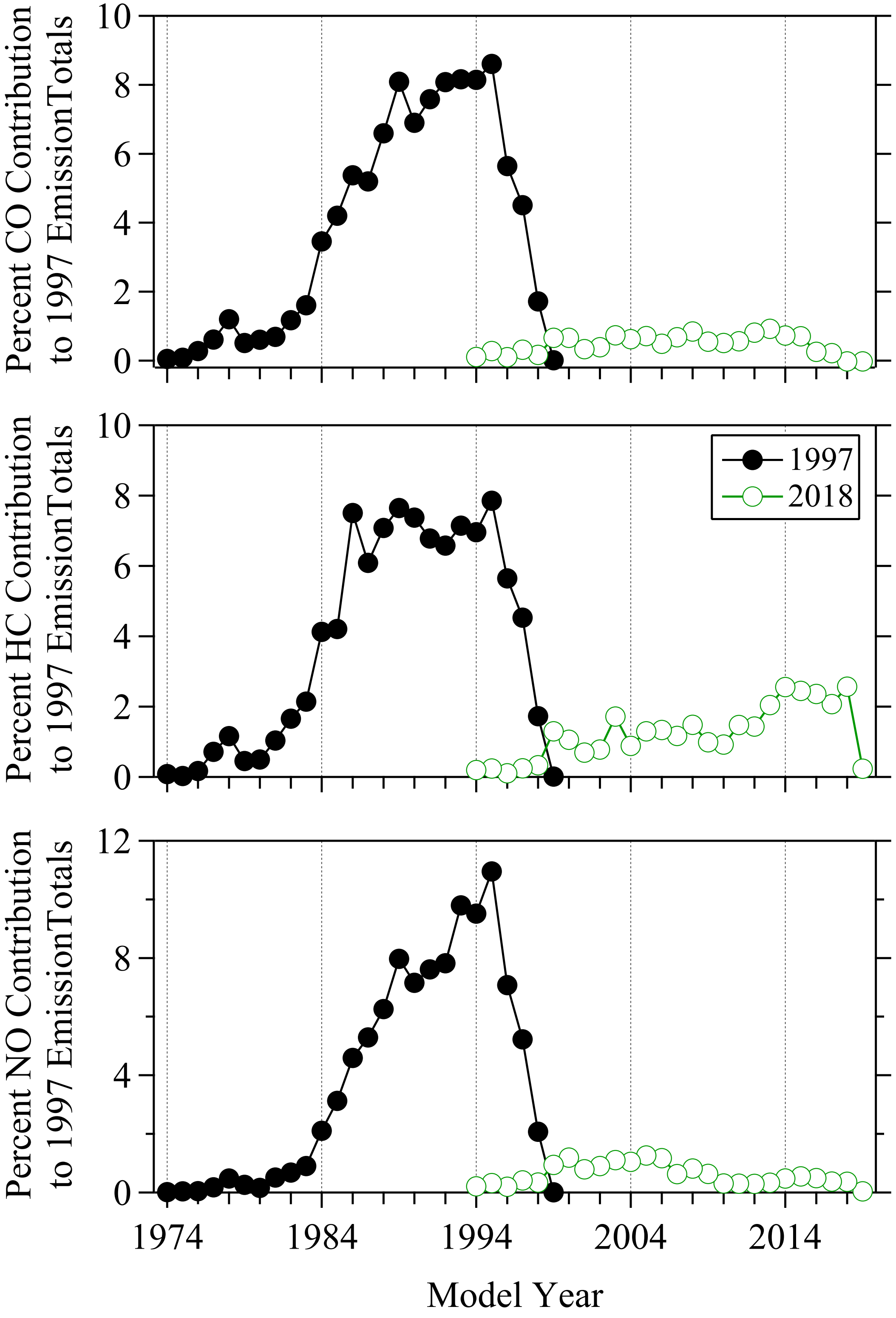

Figure 12. Percent contribution of fuel specific emissions by model year for CO (top), HC (middle) and NO (bottom) for the 1997 (filled circles) and 2018 (open circles) Chicago data sets. The 2018 emissions contribution has been normalized to the 1997 mean emissions.

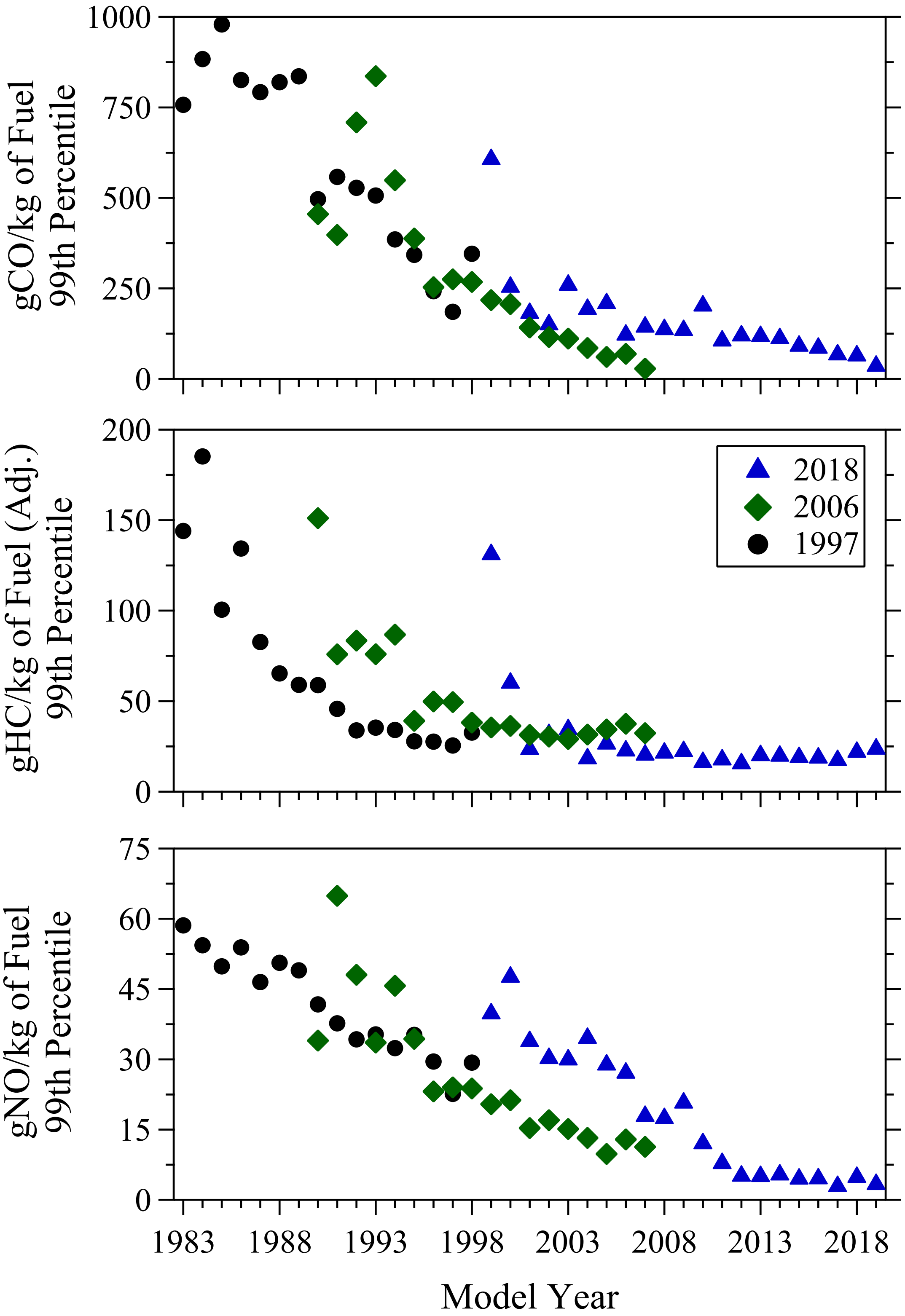

Figure 13. Fuel specific 99th percentiles by model year for CO (top), HC (middle) and NO (bottom) for the 2018 (triangles), 2006 (diamonds) and 1997 (circles) Chicago data sets.

The 99th percentile values for 10 year old vehicles (2009 model years) in the 2018 database for CO are more than a factor of 16 larger than their mean emissions (134 vs 8.1 gCO/kg of fuel). For HC the 99th percentile is a factor of 17 larger (22.3 vs 1.3 gHC/kg of fuel) and for NO it is more than a factor of 20 larger (20.7 vs 0.9 gNO/kg of fuel). However, it is quite remarkable that an 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, for there to be future reductions in mean emissions, 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.[21] 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 7.2, 2.0, 0.11, 0.03 and 0.23 for CO, HC, NO, NH_3 and NO_2 respectively. These values indicate standard deviations of 10.2 gCO/kg (0.08%), 2.9 gHC/kg (74 ppm), 0.16 gNO/kg (11 ppm), 0.05 gNH_3/kg (6 ppm) and 0.3 gNO_2/kg (15 ppm) for individual measurements of CO, HC, NO, NH_3 and NO_2 respectively. In terms of uncertainty in average values reported here, the numbers are reduced by a factor of the square root of the number of measurements. For example, with an average of 100 measurements, the uncertainty reduces by a factor of 10. Thus, the uncertainties in the averages reduce to 1 gCO/kg, 0.3 gHC/kg, 0.02 gNO/kg, 0.005 gNH_3/kg and 0.03 gNO_2/kg, respectively.

ACKNOWLEDGEMENTS

The authors would like to thank the Illinois Secretary of State's Office for help with the plate match and Mrs. Annette Bishop whose plate reading skills are crucial to the successful outcome of the sampling. Comments from the various reviewers of this report were also invaluable.

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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 ±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 ±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 ±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_2018.dbf database.

The ill_2018.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.
V_class	VIN decoded body type information.
V_cylinder	VIN decoded number of engine cylinders.
V_engine	VIN decoded engine size in liters.
V_model	VIN decoded model information.
V_year	VIN decoded model year.
V_series	VIN decoded model series information.
V_fuel	VIN decoded fuel type.
V_type	VIN decoded vehicle type information (passenger or truck).
V_wtclass	VIN decoded weight class.
V_trans	VIN decoded transmission type.
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.

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

2018												
Time (CDT)	Sept. 10		Sept. 11		Sept. 12		Sept. 13		Sept. 14		Sept. 15	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0851	68	68	69	70	73	62	70	61	78	60	76	69
0951	70	64	72	61	76	58	73	57	81	53	79	56
1051	70	66	74	54	78	52	75	52	84	44	80	54
1151	71	66	77	47	79	52	77	50	84	44	81	51
1251	73	62	77	45	81	45	78	50	85	45	82	51
1351	72	64	79	45	81	45	78	52	85	43	81	53
1451	72	61	79	45	80	42	77	52	83	46	81	53
1551	72	64	79	44	79	38	77	54	81	49	80	49
1651	70	66	78	47	77	35	75	55	80	47	78	52
1751	67	71	76	48	74	43	73	59	77	52	75	62
1851	66	73	72	64	71	53	70	68	75	55	73	66

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

2018						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
9/10	10:10	1.54	1.52	1.30	0.79	0.86
9/10	13:00	1.46	1.42	1.27	0.82	0.92
9/11	9:15	1.73	1.67	1.54	0.82	1.16
9/11	10:45	1.53	1.48	1.38	0.86	1.06
9/11	13:00	1.46	1.43	1.32	0.92	0.97
9/12	9:10	1.68	1.65	1.42	0.89	1.21
9/12	10:40	1.51	1.45	1.28	0.92	1.00
9/12	13:00	1.40	1.38	1.23	0.93	0.98
9/13	9:15	1.78	1.73	1.52	0.91	1.27
9/13	10:40	1.63	1.57	1.43	0.94	1.12
9/13	13:00	1.51	1.49	1.33	0.94	1.03
9/14	9:15	1.84	1.83	1.57	0.85	1.16
9/14	10:45	1.56	1.58	1.35	0.89	1.12
9/14	13:00	1.47	1.48	1.30	0.91	1.05
9/15	9:25	1.61	1.60	1.39	0.88	1.11
9/15	11:00	1.48	1.48	1.30	0.91	1.00
9/15	12:25	1.42	1.41	1.23	0.94	0.98