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ON-ROAD REMOTE SENSING OF AUTOMOBILE EMISSIONS IN THE TULSA AREA: FALL 2017

March 2018

COORDINATING RESEARCH COUNCIL, INC.
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On-Road Remote Sensing of Automobile Emissions in the Tulsa Area: Fall 2017

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EXECUTIVE SUMMARY

The University of Denver conducted a five-day remote sensing study in the Tulsa, Oklahoma area in September of 2017. The remote sensor used in this study measures the ratios of CO, HC, NO, SO_2, NH_3 and NO_2 to CO_2 in motor vehicle exhaust. From these ratios, we calculate the percent concentrations of CO, CO_2, HC, NO, SO_2, NH_3 and NO_2 in the exhaust that would be observed by a tailpipe probe, corrected for water and any excess oxygen not involved in combustion. Mass emissions per mass or volume of fuel can also be determined and are generally the preferred units for analysis. The 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 have followed suit and while we collected vehicle SO_2 measurements we did not calibrate those readings and they are not included in the discussion of the results.

Five days of fieldwork, September 11 – 15, 2017, were conducted on the uphill interchange ramp from westbound US64 (Broken Arrow Expressway) to southbound US169. This is the same location previously used for measurements in the fall of 2003, 2005, 2013 and 2015. A database was compiled containing 22,583 records for which the State of Oklahoma and the Cherokee Nation provided registration information. All of these records contained valid measurements for at least CO and CO_2, and most records contained valid measurements for the other species as well. The database, as well as others compiled by the University of Denver, can be found at www.feat.biochem.du.edu.

The 2017 mean CO, HC, NO, NH_3 and NO_2 emissions for the fleet measured in this study were 11.1 g/kg of fuel (0.09%), 1.7 g/kg of fuel (44 ppm), 1.4 g/kg of fuel (100 ppm), 0.37 g/kg of fuel (47 ppm) and 0.03 g/kg of fuel (1 ppm) respectively. When compared with previous measurements from 2015 we find that mean CO (-22%) and HC (-29%) emissions decreased while NO (+4%) and NH_3 (0%) emissions changed little. Figure ES1 graphs the mean fuel specific emissions for CO (○, left axis), HC (▲, right axis) and NO (□, right axis) versus measurement year for all the data sets collected at the Tulsa site. Uncertainties are standard errors of the mean calculated using the daily means. Since 2003 the fuel specific CO emissions have decreased by 67%, HC by 46% and NO by 62%. As seen in the plot these decreases have not been consistent with the largest reductions occurring between the 2005 and 2013 measurements.

The average Tulsa fleet age again increased by 0.1 years (2010.1) which is approximately 8 years old. Unlike recent data from Los Angles showing a rebound from the 2008 recession with a slightly younger fleet, the Tulsa fleet shows signs of a slowdown in new car purchases with the percentage of one year old vehicles dropping again in the 2017 measurements (6.5% of the fleet in 2015 to 5.8% of the fleet in 2017). Fleet mean emissions are still dominated by a few high emitting vehicles and for the 2017 data set the highest emitting 1% of the measurements (99^{th} percentile) are responsible for 31%, 40%, 29%, 16 % and 100% of the CO, HC, NO, NH_3 and NO_2 emissions, respectively.

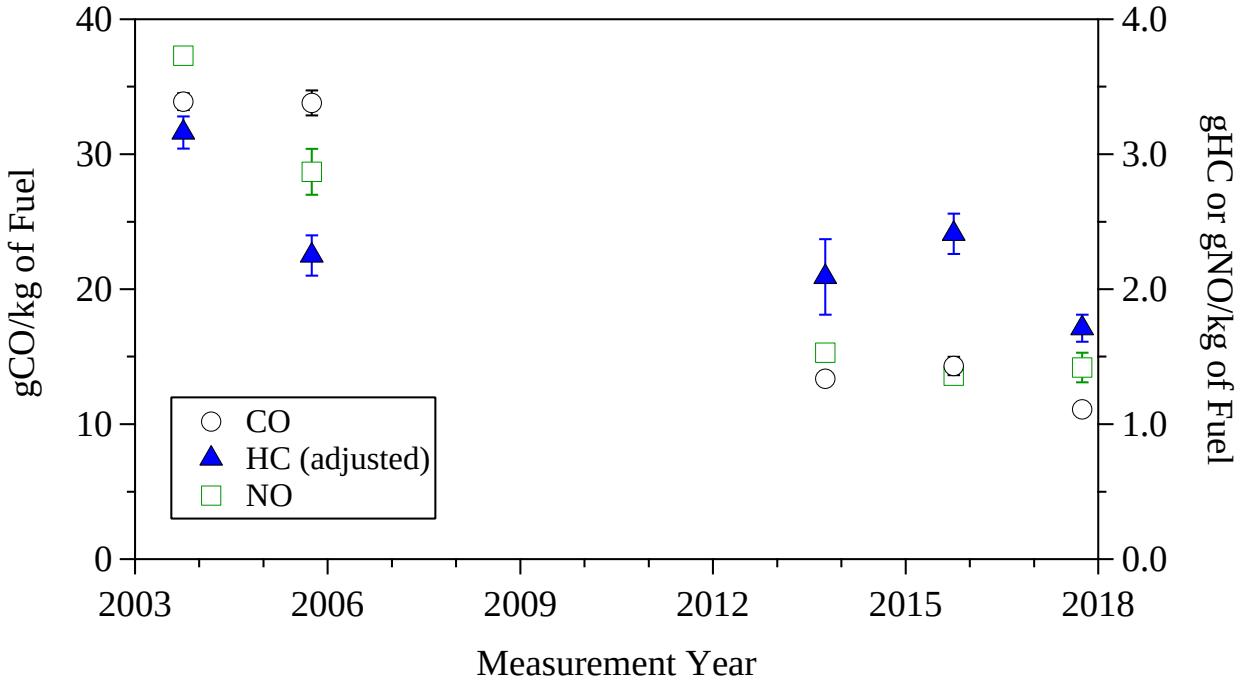

Figure ES1. Tulsa area historical fuel specific fleet mean emissions for CO (○, left axis), HC (▲, right axis) and NO (□, right axis) by measurement year. Uncertainties are standard errors of the mean calculated using the daily measurements. The fuel specific HC means have been adjusted as described in the report.

The Tulsa site was one of the first in which the University of Denver collected NH_3 emissions from light-duty vehicles in 2005 and now has one of the longest running NH_3 measurement trends. The NH_3 mean emissions observed in 2005, 2013, 2015 and 2017 were 0.5 ± 0.01, 0.43 ± 0.01, 0.37 ± 0.001 and 0.37 ± 0.005 g/kg of fuel respectively, which is an overall 26% reduction in emissions over twelve years but as previously mentioned no change since 2015. Figure ES2 shows the fuel specific NH_3 emissions versus model year for the four data sets collected. The peak NH_3 emissions remain around the 19 year old vehicles as observed in 2015 but the increase in noise due to fewer measurements in the older model year vehicles makes an exact assignment difficult. The NH_3 reduction rates are much smaller than observed for the tailpipe NO emissions which have decreased by 51% (2.9 gNO/kg of fuel in 2005 to 1.4 gNO/kg of fuel in 2017) over the same time period.

We also investigated what, if any, differences there were between vehicles registered with the Cherokee Nation and those registered in the State of Oklahoma. The Cherokee Nation fleet is smaller than the Oklahoma fleet making up only 5.8% of the matched plates and newer (mean model year of 2011.3 versus 2010). Because of the younger age the Cherokee Nation fleet has lower mean emission for all of the species except for HC, however, they are accompanied with larger uncertainties due to their fewer number. When the Oklahoma plated vehicles are age adjusted to match the age distribution of the Cherokee Nation fleet the Oklahoma fleet is actually lower emitting for every species but NH_3.

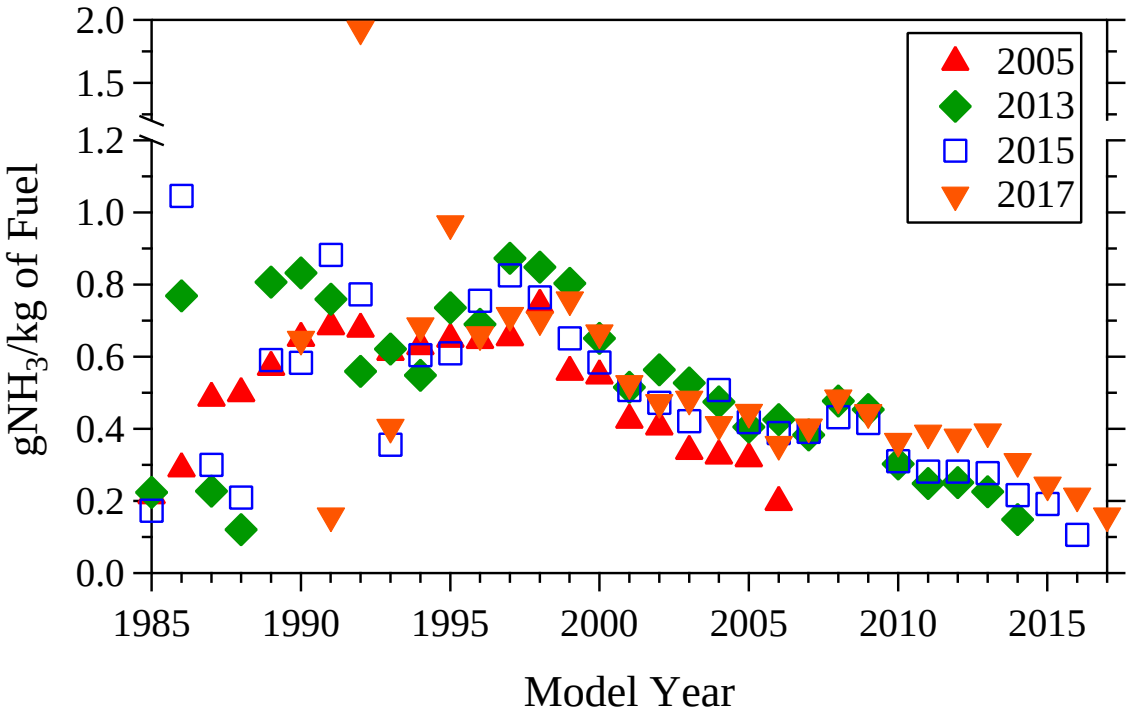

Figure ES2. Mean gNH_3/kg of fuel emissions plotted against vehicle model year for the four measurement data sets collected at the Tulsa site with a split y-axis.

INTRODUCTION

Since the early 1970's many heavily populated cities in the United States have violated the National Air Quality Standards (NAAQS) that have been established by the Environmental Protection Agency (EPA) pursuant to the requirements of the Federal Clean Air Act.[1, 2] Carbon monoxide (CO) levels become elevated primarily due to direct emission of the gas. Ground-level ozone, a major component of urban smog, is produced by the photochemical reaction of nitrogen oxides (NO_x) and hydrocarbons (HC). Ambient levels of particulate emissions can result either from direct emissions of particles or semi-volatile species or from secondary reactions between gaseous species, such as ammonia and nitrogen dioxide (NO_2). As of 2015, on-road vehicles continued to be estimated as one of the larger sources for major atmospheric pollutants, contributing approximately 39% of the CO, 14% of the volatile organic carbons, 3% of the ammonia (NH_3) and 36% of the NO_x to the national emission inventory.[3]

The use of the internal combustion engine and the combustion of carbon based fuels as one of our primary means of transportation accounts for it being 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, hydrocarbons (HC) and nitric oxide (NO) emissions to carbon dioxide (CO_2), water and nitrogen. Control measures to decrease mobile source emissions in non-attainment areas include inspection and maintenance (I/M) programs, reformulated and oxygenated fuel mandates, and transportation control measures, but the effectiveness of these measures are difficult to quantify. Many areas remain in non-attainment for ozone. The further 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.[5]

Beginning in 1997 the University of Denver began conducting on-road tailpipe emission surveys at selected sites to follow long term vehicle emission trends. A site northwest of Chicago IL, in Arlington Heights, was the first to be established but over the years we have also collected measurements in Los Angeles CA, Denver CO, Omaha, NE, Phoenix AZ, Riverside CA, and Tulsa OK.[6] 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 and the data have been used by many researchers to establish fleet emission trends and inventories.[7-13]

Reflecting a desire to continue evaluating the historical and recent emissions trends several of the previous E-23 sites were chosen for additional data collection. As part of the E-106 program two additional measurement campaigns were conducted in Tulsa, OK in 2013 and 2015. CRC E-123 continues these measurements and this report describes the on-road emission measurements collected in Tulsa, OK area in the fall of 2017. Measurements were made on five consecutive weekdays, from Monday, September 11, to Friday, September 15, between the hours of 7:00 and 19:00 on the uphill interchange ramp from westbound US64 (Broken Arrow Expressway) to southbound US169.

The Tulsa area was originally selected as a location to study vehicle emissions because it is one of the larger metropolitan areas in the US that has never been required to have a vehicle Inspection & Maintenance program (I/M). Tulsa is also geographically isolated from cities that do have I/M programs which helps to limit importation of I/M failing vehicles. For this reason a program to conduct remote sensing emission measurements in Tulsa can provide a useful baseline for comparison with similar data collected from other cities.

MATERIALS AND METHODS

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

The UV light is reflected from the surface of the dichroic mirror and is focused onto the end of a quartz fiber bundle that is mounted to a coaxial connector on the side of the detector unit. The quartz fiber bundle is divided in half to carry the UV signal to two separate spectrometers. The first spectrometer was adapted to expand its UV range down to 200nm in order to measure the peaks from SO_2 and NH_3 and continue to measure the 227nm peak from NO. The absorbance from each respective UV spectrum of SO_2, NH_3, and NO is compared to a calibration spectrum using a classical least squares fitting routine in the same region in order to obtain the vehicle emissions. The second spectrometer measures only NO_2 by measuring an absorbance band at 438nm in the UV spectrum and comparing it to a calibration spectrum in the same region.[17] Since the removal of sulfur from gasoline and diesel fuel in the US SO_2 emissions have become negligibly small and as such, while SO_2 measurements were collected as a part of this study, they will not be reported or discussed because the sensor was not calibrated for SO_2 emissions.

The exhaust plume path length and density of the observed plume are highly variable from vehicle to vehicle, and are dependent upon, among other things, the height of the vehicle's exhaust pipe, engine size, wind, and turbulence behind the vehicle. For these reasons, the remote sensor only directly measures ratios of CO, HC, NO, NH_3 or NO_2 to CO_2. The molar ratios of CO, HC, NO, NH_3 or NO_2 to CO_2, termed Q^{CO}, Q^{HC}, Q^{NO}, Q^{NH3} and Q^{NO2} respectively, are constant for a given exhaust plume, and on their own are useful parameters for describing a hydrocarbon combustion system. This study reports measured emissions as molar %CO, %HC, %NO, %NH_3 and %NO_2 in the exhaust gas, corrected for water and excess air not used in combustion. The HC measurement is calibrated with propane, a C_3 hydrocarbon. But based on measurements using flame ionization detection (FID) of gasoline vehicle exhaust, the remote sensor is only half as sensitive to exhaust hydrocarbons on a per carbon atom basis as it is to

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

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

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 close to 100% NO in the case of gasoline fueled vehicles.

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

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

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 fuel (this translates to 860 gC/kg of fuel), assuming gasoline is stoichiometrically CH_2. Again, the HC/CO_2 ratio must use two times the reported HC (see above) because the equation depends upon carbon mass balance and the NDIR HC reading is about half a total carbon FID reading.[18]

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

Quality assurance calibrations are performed twice daily in the field unless observed voltage readings or meteorological changes are judged to warrant additional calibrations. For the multi-species instrument three calibration cylinders are needed. The first contains CO, CO_2, propane

and NO, the second contains NH_3 and propane and the final cylinder contains NO_2 and CO_2. A puff of gas is released into the instrument's path, and the measured ratios from the instrument are then compared to those certified by the cylinder manufacturer (Air Liquide and PraxAir). 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.

Double blind studies sponsored by the California Air Resources Board and General Motors Research Laboratories have shown that the remote sensor is capable of CO measurements that are correct to within ±5% of the values reported by an on-board gas analyzer, and within ±15% for HC.[19, 20] The NO channel used in this study has been extensively tested by the University of Denver, but has not been subjected to an extensive double blind study and instrument intercomparison to have it independently validated. Tests involving a late-model low-emitting vehicle indicate a detection limit (3σ) of 25 ppm for NO, with an error measurement of ±5% of the reading at higher concentrations.[15] Comparison of fleet average emission by model year versus IM240 fleet average emissions by model year show correlations between 0.75 and 0.98 for data from Denver, Phoenix and Chicago.[21] Appendix A gives a list of criteria for determining data validity.

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

RESULTS AND DISCUSSION

Measurements were made on five consecutive weekdays in 2017, from Monday, September 11, to Friday, September 15, between the hours of 7:00 and 19:00 on the uphill interchange ramp from westbound US64 (Broken Arrow Expressway) to southbound US169. A schematic of the measurement location is shown in Figure 1 and a photograph of the setup from a previous measurement campaign is shown in Figure 2. Appendix C gives temperature and humidity data for the study dates obtained from Tulsa International Airport, approximately ten miles north of the measurement site.

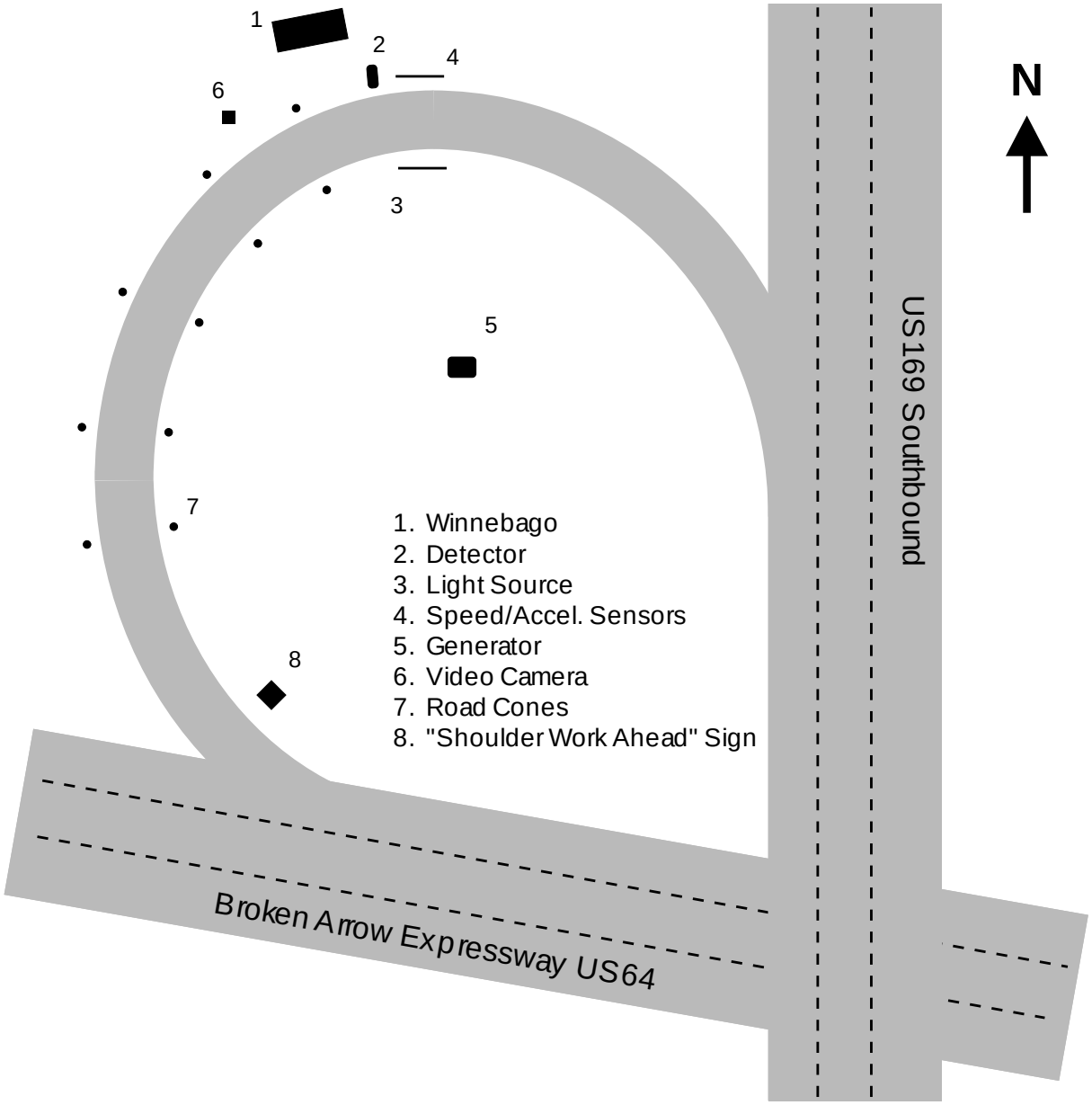

Figure 1. A schematic drawing of the ramp from Westbound US64 (Broken Arrow Expressway) to Southbound US169. The location and safety equipment configuration was for all five days of measurements.

Figure 2. Tulsa monitoring site looking west toward downtown Tulsa.

The digital video images of the license plates were subsequently transcribed for license plate identification. Oklahoma license plates are issued by the state and at least 20 tribal nations. Plates were transcribed for Oklahoma and the Cherokee Nation, which is the largest tribal plate visiting this site. One complication experienced this year was the fact that Oklahoma was replacing all of its vehicle plates with a new series. This did increase the fraction of vehicles not matched with a state registration record, though it was significantly limited by the extra effort of the Oklahoma Tax Commission employees who kindly processed the plates a second time against an older database. The resulting 2017 database contains 22,583 records (21,282 from Oklahoma and 1,301 from the Cherokee Nation) with make and model year information and valid measurements for at least CO and CO_2. Most of these records also contain valid measurements for HC, NO, NH_3 and NO_2. This database and all previous databases compiled for CRC E-23 and E-106 campaigns can be found at www.feat.biochem.du.edu.

The validity of the attempted measurements is summarized in Table 1. The table describes the data reduction process beginning with the number of attempted measurements and ending with the number of records containing both valid emissions measurements and vehicle registration information. An attempted measurement is defined as a beam block followed by a half second of

Table 1. Validity Summary.

	CO	HC	NO	NH_3	NO_2
Attempted Measurements	30,711				
Valid Measurements	28,705	28,658	28,704	28,693	28,062
Percent of Attempts	93.5%	92.3%	93.5%	93.4%	91.4%
Submitted Plates	23,003	22,976	23,002	22,995	22,525
Percent of Attempts	74.9%	74.8%	74.9%	74.9%	73.3%
Percent of Valid Measurements	80.1%	80.2%	80.1%	80.1%	80.3%
Matched Plates	22,583	22,558	22,582	22,575	22,118
Percent of Attempts	73.5%	73.5%	73.5%	73.5%	72.0%
Percent of Valid Measurements	78.7%	78.7%	78.7%	78.7%	78.8%
Percent of Submitted Plates	98.2%	98.2%	98.2%	98.2%	98.2%

data collection. If the data collection period is interrupted by another beam block from a closely following vehicle, that measurement attempt is aborted and an attempt is made at measuring the second vehicle. In this case, the beam block from the first vehicle is not recorded as an attempted measurement. Invalid measurement attempts arise when the vehicle plume is highly diluted or absent (elevated or electric/hybrid engine off operation), or the reported error in the ratio of the pollutant to CO_2 exceeds a preset limit (see Appendix A). The greatest loss of data in this process occurs during the plate reading process, when out-of-state vehicles, vehicles with unreadable plates (obscured, missing, dealer, out of camera field of view) and non-Cherokee tribal plates are omitted from the database. Oklahoma has expanded the use of Q's in its plates and combined with D's and O's makes it difficult to successfully transcribe some plates. To combat mistaken matches we have visually rechecked the matched makes of all of the plates with Q's, D's and O's in them and removed records where the matched makes are incorrect.

Table 2 provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured. Of the 22,583 records used in this fleet analysis, 11,939 (52.9%) were contributed by vehicles measured only once, and the remaining 10,644 (47.1%) records were from vehicles measured at least twice.

Table 2. Number of measurements of repeat vehicles.

Number of Times Measured	Number of Vehicles
1	11,943
2	2,202
3	947
4	485
5	162
6	47
7	28
>7	20

Table 3 summarizes the data for the current and all of the previous measurements collected at this site in 2015, 2013, 2003 and 2005. The average HC values have been adjusted for this comparison to remove an artificial offset in the measurements. This offset, restricted to the HC channel, has been reported in earlier CRC E-23-4 reports. Calculation of the offset is accomplished by computing the mode and means of the newest model year and vehicles, and assuming that these vehicles emit negligible levels of hydrocarbons and that the median of these groups emissions distribution should be very close to zero, using the lowest of either of these values as the offset. The offset adjustment subtracts or adds this value to the hydrocarbon data. This normalizes each data set to a similar emissions zero point since we assume the cleanest vehicles emit few hydrocarbons. Such an approximation will err only slightly towards clean because the true offset will be a value somewhat less than the average of the cleanest model year and make. This adjustment facilitates comparisons with the other E-23 sites and/or different collection years for the same site. The offset adjustments have been performed where indicated in the analyses in this report and an example of how it is calculated is included in Appendix D.

The 2017 Tulsa measurements have again given indications that fleet average emissions are reaching a leveling out point. In 2015 mean emission levels for CO and HC showed slight increases for the first time. In the 2017 measurements those species showed modest declines of 22% for CO and 29% for HC. NO and NH_3 emissions changed little between the two measurement years with NO increasing by only 4% and NH_3 emissions being unchanged from 2015. The percent of emissions contributed by the highest emitting 1% of the fleet (the 99th percentile) increased for CO, HC and slightly for NO while NH_3 slightly decreased.

An inverse relationship between vehicle emissions and model year is shown in Figure 3 for the five periods sampled in calendar years 2003, 2005, 2013, 2015 and 2017. The HC data have been offset adjusted here for comparison and the y-axis has been split for all species. In general for model years 2005 and older, fleet model year emissions averages have crept up slowly as the age of those repeat model years has increased. Note that there is considerable uncertainty in the mean emission levels for model years 1995 and older because of the small sample sizes (less than 58 measurements per model year). All three species graphed in Figure 3 show an ever increasing number of model years with emission levels that are not significantly different from zero and that vary little for subsequent model years. NO emissions are the quickest to rise but the Tier II certified vehicles (2009 & newer) have now locked down fleet average NO emissions deterioration.

Following the data analysis and presentation format originally shown by Ashbaugh et al.,[22] the vehicle emissions data by model year from the 2017 study were divided into quintiles and plotted. The results are shown in Figures 4 - 6. The bars in the top plot represent the mean emissions for each model year's quintile, but do not account for the number of vehicles in each model year. The middle graph shows the fleet fraction by model year for the newest 22 model years showing the impacts the last recession had on car sales between 2009 and 2010 and perhaps the effects of the oil and gas downturn on 2016 models. Model years older than 1997 and not graphed only account for 1.3% of the measurements and contribute between 9.4% (HC)

Table 3. Data Summary.

Study Year Location	Tulsa 2003	Tulsa 2005	Tulsa 2013	Tulsa 2015	Tulsa 2017
Mean CO (%) (g/kg of fuel)	0.27 (34.0)	0.27 (33.6)	0.11 (13.4)	0.11 (14.3)	0.09 (11.1)
Median CO (%)	0.06	0.11	0.028	0.046	0.020
Percent of Total CO from the 99th Percentile	21.9%	20.8%	31.2%	26.2%	30.7%
Mean HC (ppm)[a] (g/kg of fuel)[a] Offset (ppm)	85 (3.2) 30	61 (2.2) 10 / -40[b]	57 (2.1) 0	64 (2.4) 60	44 (1.7) 19
Median HC (ppm)[a]	40	40	35	17	19
Percent of Total HC from the 99th Percentile	18.5%	34.1%	41.7%	33.8%	39.9%
Mean NO (ppm) (g/kg of fuel)	265 (3.7)	202 (2.9)	109 (1.5)	96 (1.4)	100 (1.4)
Median NO (ppm)	53	33	5	2	8
Percent of Total NO from the 99th Percentile	12.3%	13.9%	25.1%	27.8%	29%
Mean NH_3 (ppm) (g/kg of fuel)	NA	62 (0.5)	54 (0.43)	46 (0.37)	47 (0.37)
Median NH_3 (ppm)	NA	25	19	15	16
Percent of Total NH_3 from the 99th Percentile	NA	12.2%	14.5%	16.3%	15.7%
Mean NO_2 (ppm) (g/kg of fuel)	NA	NA	6 (0.14)	6 (0.13)	1 (0.03)
Median NO_2 (ppm)	NA	NA	3	3	0
Percent of Total NO_2 from the 99th Percentile	NA	NA	49.7%	29.6%	100%
Mean Model Year	1997.6	1999.3	2006.3	2008.2	2010.1
Mean Fleet Age[c]	6.4	6.7	7.8	7.9	8.0
Mean Speed (mph)	24.1	24.4	24.3	24.2	24.2
Mean Acceleration (mph/s)	0.06	-0.4	-0.01	-0.07	0.02
Mean VSP (kw/tonne) Slope (degrees)	7.8 2.6°	5.3 2.6°	7.7 2.7°	7.2 2.7°	7.8 2.7°

[a]Indicates values that have been HC offset adjusted as described in text.
[b]The offset changed on 9/23 and a separate -40ppm offset was applied for that day.
[c]Assumes new vehicle model year starts September 1.

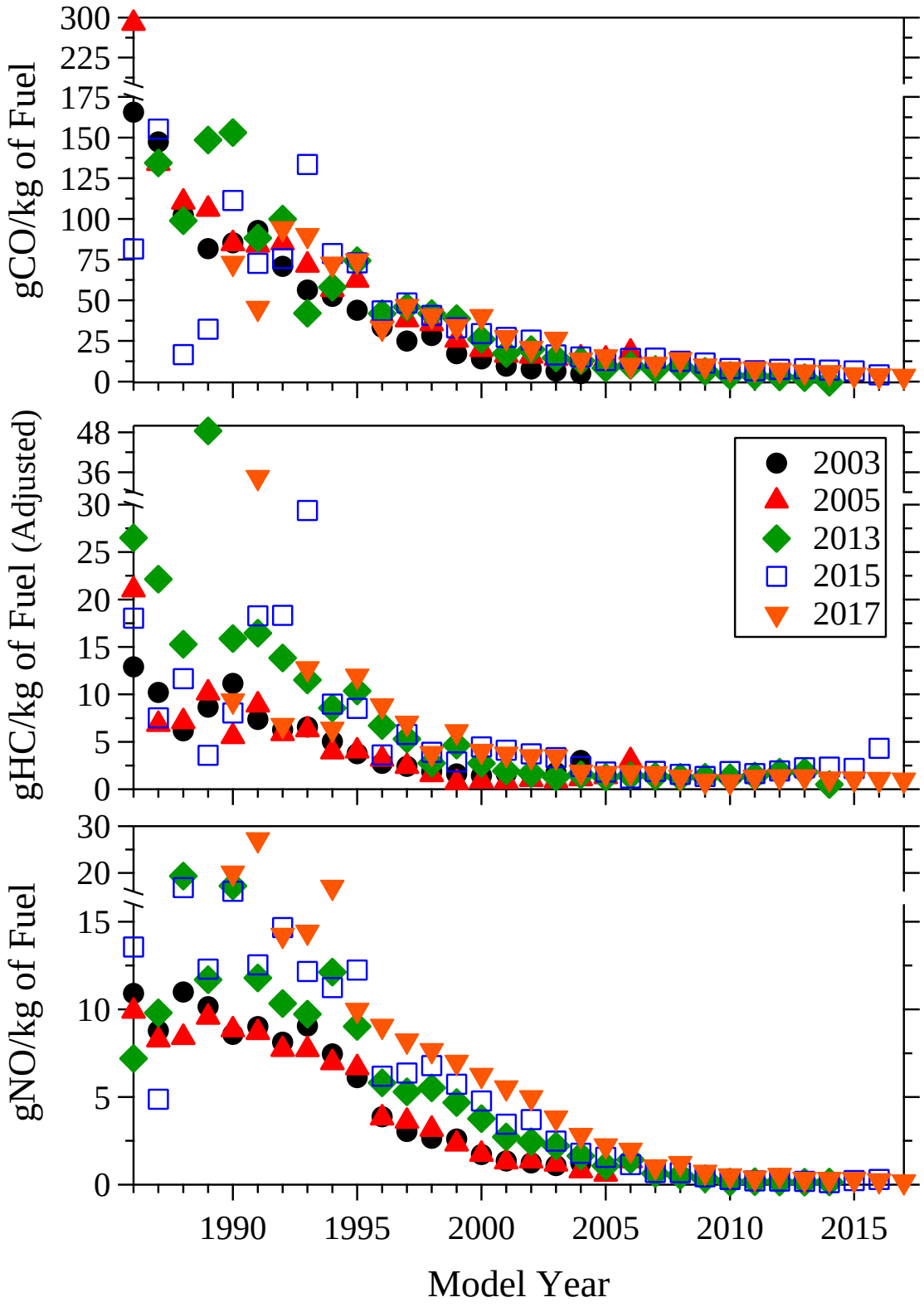

Figure 3. Mean fuel specific vehicle emissions plotted as a function of model year for the five Tulsa data sets, 2003 (circles), 2005 (triangles), 2013 (diamonds), 2015 (squares) and 2017 (inverted triangle). HC data have been offset adjusted as described in the text and the y-axis have been split.

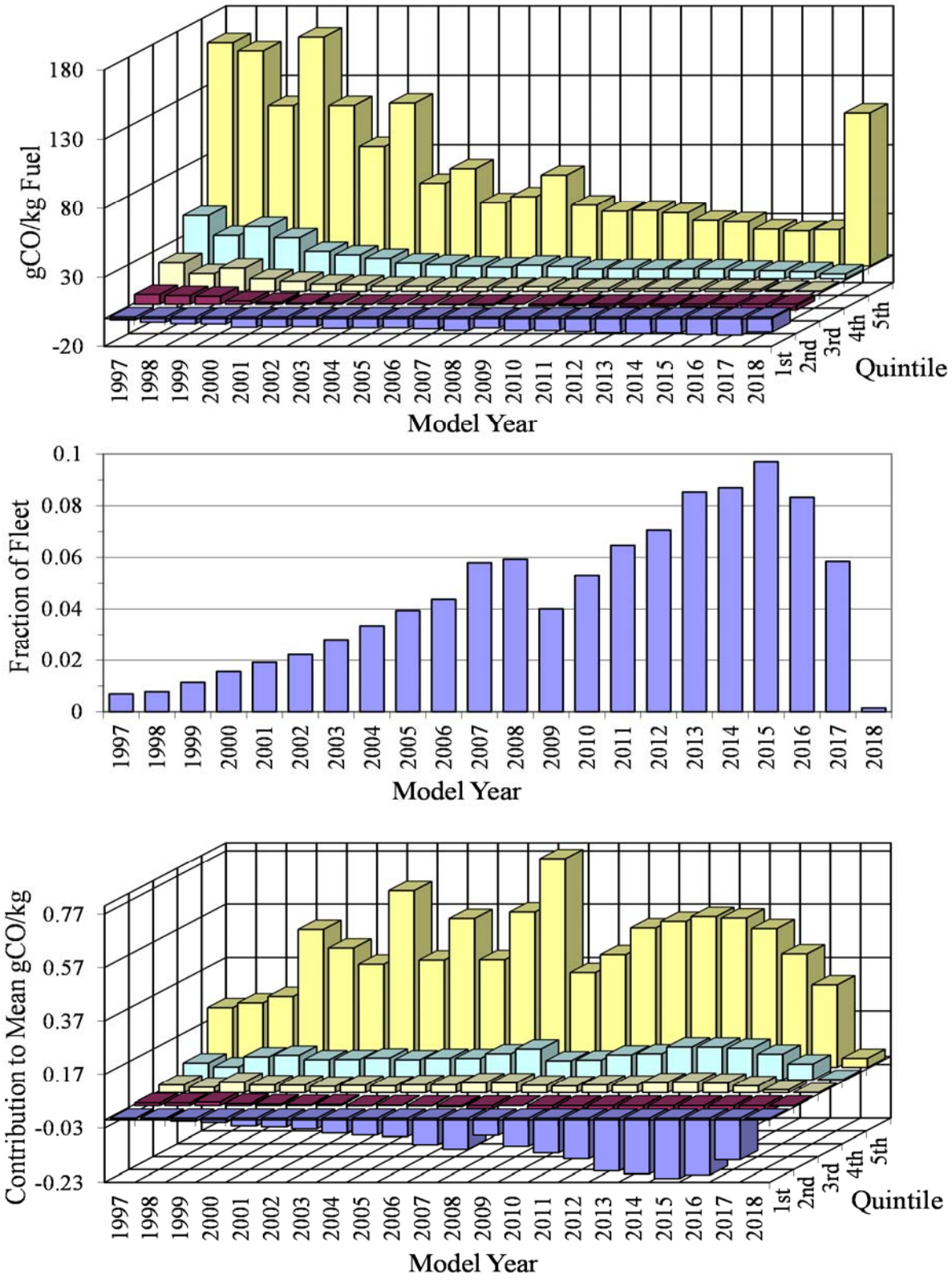

Figure 4. Mean gCO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gCO/kg of fuel emissions by model year and quintile (bottom).

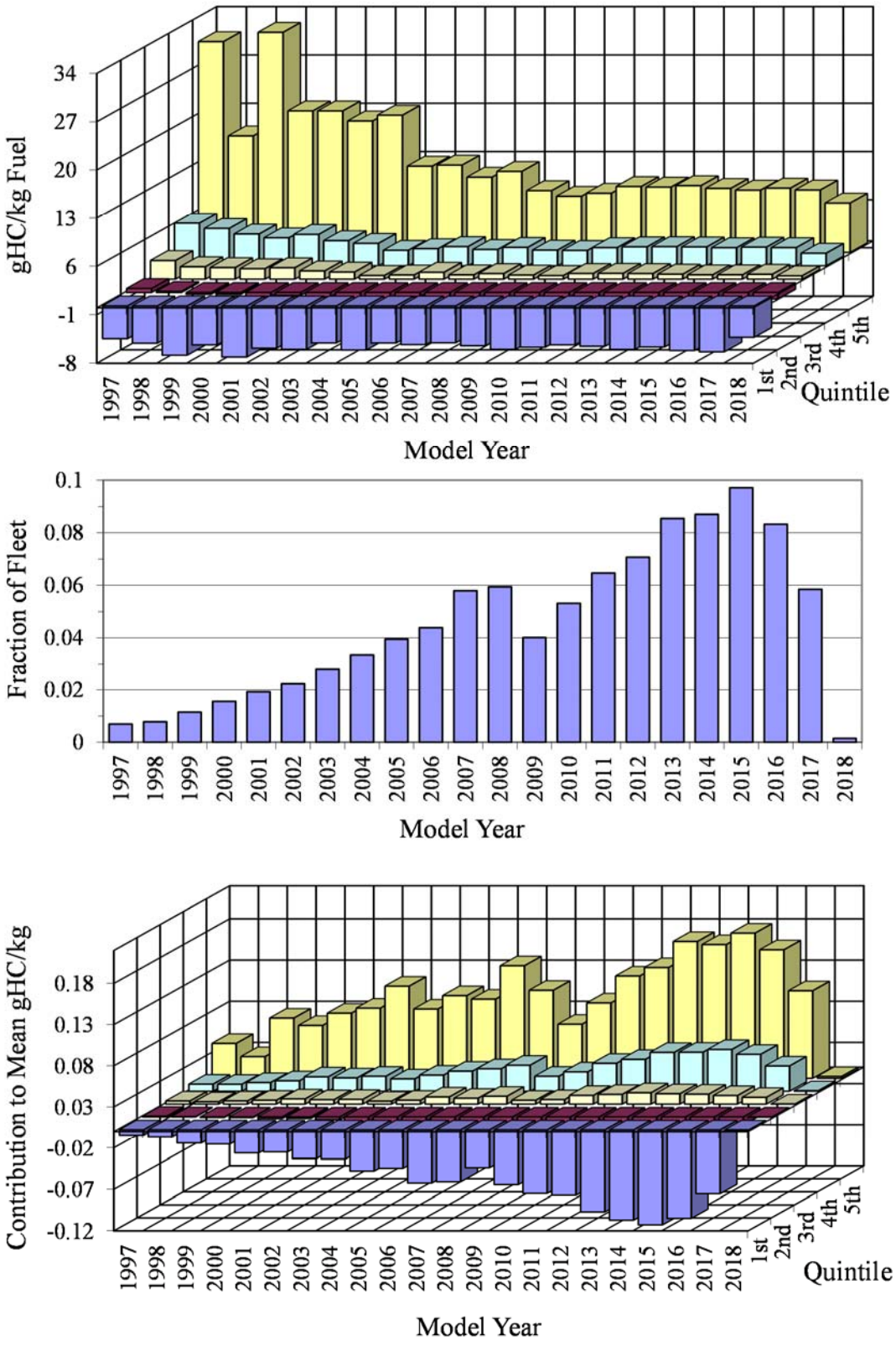

Figure 5. Mean gHC/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gHC/kg of fuel emissions by model year and quintile (bottom).

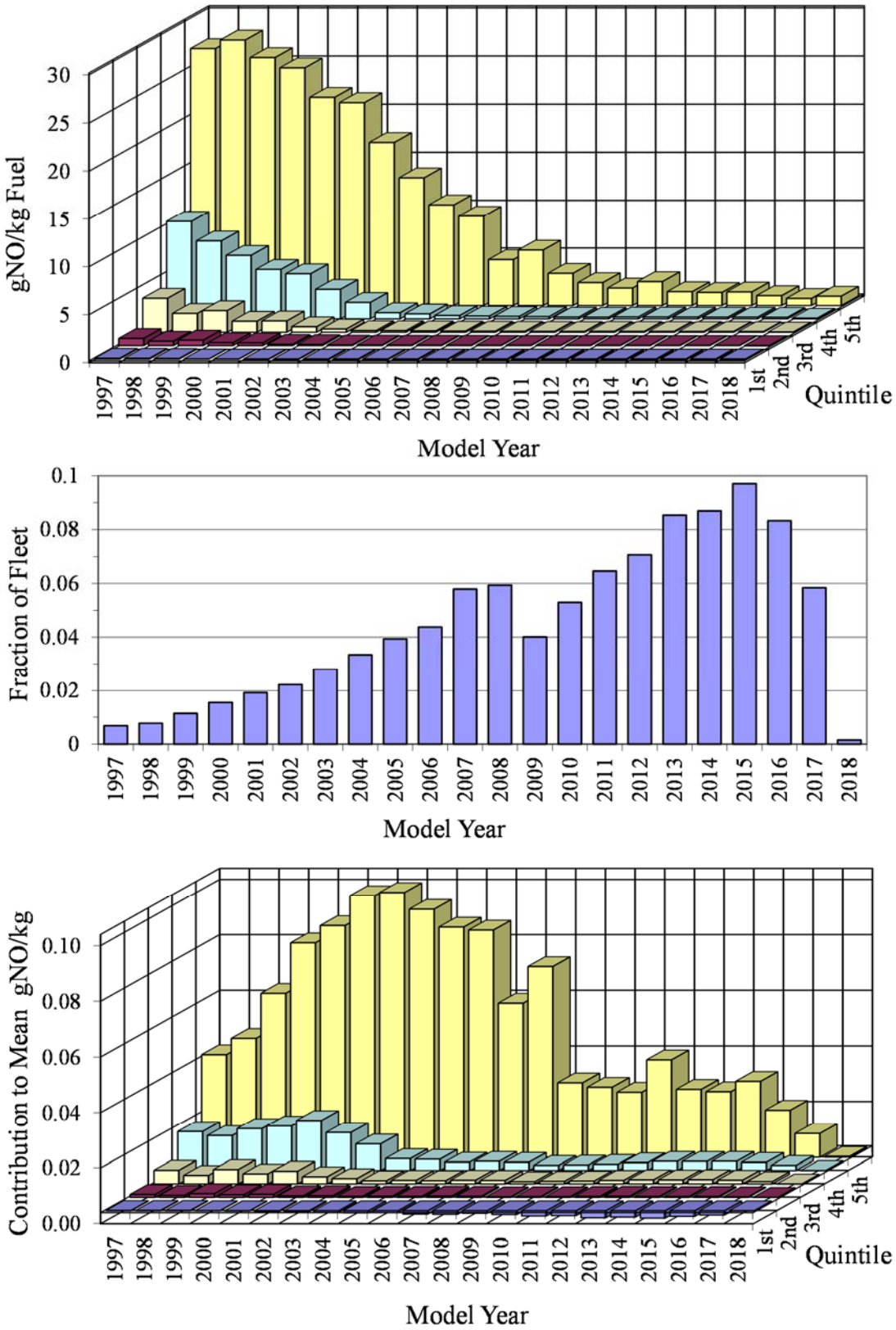

Figure 6. Mean gNO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gNO/kg of fuel emissions by model year and quintile (bottom).

and 11.9% (NO) of the total emissions. The bottom graph for each species is the combination of the top and middle figures. These figures illustrate that the cleanest 60% of the vehicles, regardless of model year, make an essentially negligible contribution to the overall fleet mean emissions. The accumulations of negative emissions in the first two quintiles are the result of ever decreasing emission levels. Our instrument is designed such that when measuring true zero emission plumes (a ratio of zero), approximately half of the readings will be negative and half will be positive. As the lowest emitting segments of the fleets continue to trend toward zero emissions, the negative emission readings will continue to grow toward half of the measurements.

The middle graph in Figures 4 – 6 shows the fleet fractions by model year for the 2017 Tulsa database. The impact of the 2008 recession and the resultant reduction in light-duty vehicle sales is still visible in the 2017 data (for a review of this impact, please see the 2013 Tulsa report and other recent publications).[23, 24] Of the three cities discussed, Tulsa was the most resilient at the time in resisting the large increases in vehicle fleet age. In both Denver and Los Angeles the 2008 recession increased average fleet ages by 2 full model years. Table 3 shows that for Tulsa between 2005 and 2013 fleet age only increased a little more than one full model year or about half of what the other two cities experienced. However, since the recession the Tulsa fleet at this site has very slowly crept up in age with the 2017 fleet's age increasing again slightly (0.1 years) to 8 years old.

Figure 7 is a plot of fleet percentage by vehicle age for the 2013, 2015 and 2017 Tulsa data sets. The cavity created by the 2008 recession continues to work its way through the fleet age distribution and is now located at 9 years old. As previously mentioned the fleet share of one year old vehicles has decreased two data sets in a row which contributes to the slight increase in fleet age. Figure 8 is a plot of cumulative fleet age in years verses vehicle age in years to help show where the age differences lie between the three data sets. Continuing in 2017, 3 to 7 year old vehicles are responsible for slight increases in the fleet age when compared with the previous two data sets. The 2008 recession has pushed the first 2017 inflection point to 9 year old vehicles and it's not until 17 year old vehicles you reach the second crossing leading to a slightly older fleet.

While NH_3 is not a regulated pollutant it is a necessary precursor for the production of ammonium nitrate and sulfates which are often a significant component of secondary aerosols found in urban areas.[25] Ammonia is most often associated with farming and livestock operations but it can also be produced by 3-way catalyst equipped vehicles.[26] The production of exhaust NH_3 emissions is contingent upon the vehicle's ability to produce NO in the presence of a catalytic convertor that has enough hydrogen available to reduce that NO to NH_3. The absence of either of these species precludes the formation of exhaust NH_3. Dynamometer studies have shown that these conditions can be met when acceleration events are preceded by a deceleration event though not necessarily back to back.[27] Previous on-road ammonia emissions have been reported by Baum *et al.* for a Los Angeles site in 1999, by Burgard *et al.* in 2005 from gasoline-powered vehicles for sites in Denver and this site in Tulsa and by Kean et al in 1999 and 2006 from the Caldecott tunnel near Oakland.[28-31] In 2008 the University of Denver collected NH_3 measurements at three sites in California, San Jose, Fresno and the West LA site and from a Van

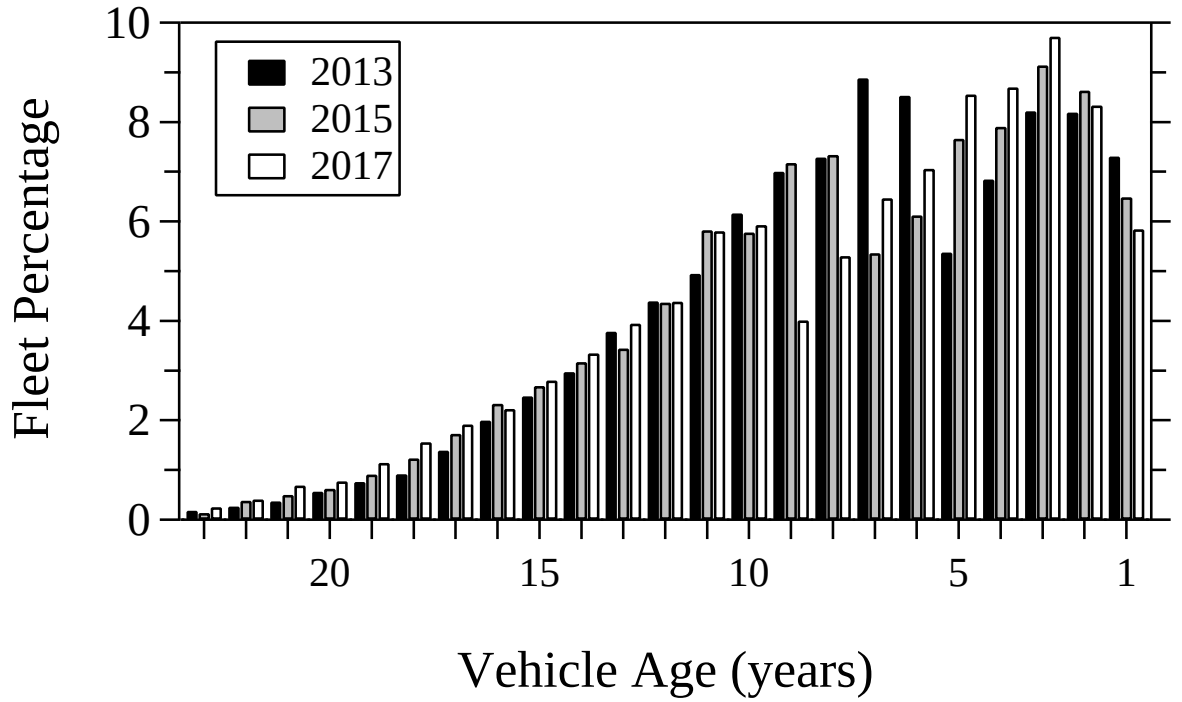

Figure 7. Fleet percentages plotted by vehicle age for the 2013 (black bars), 2015 (grey bars) and 2017 (open bars) Tulsa data sets. One year old vehicles represent the 2013, 2015 and 2017 model years in the 2013, 2015 and 2017 data sets, respectively.

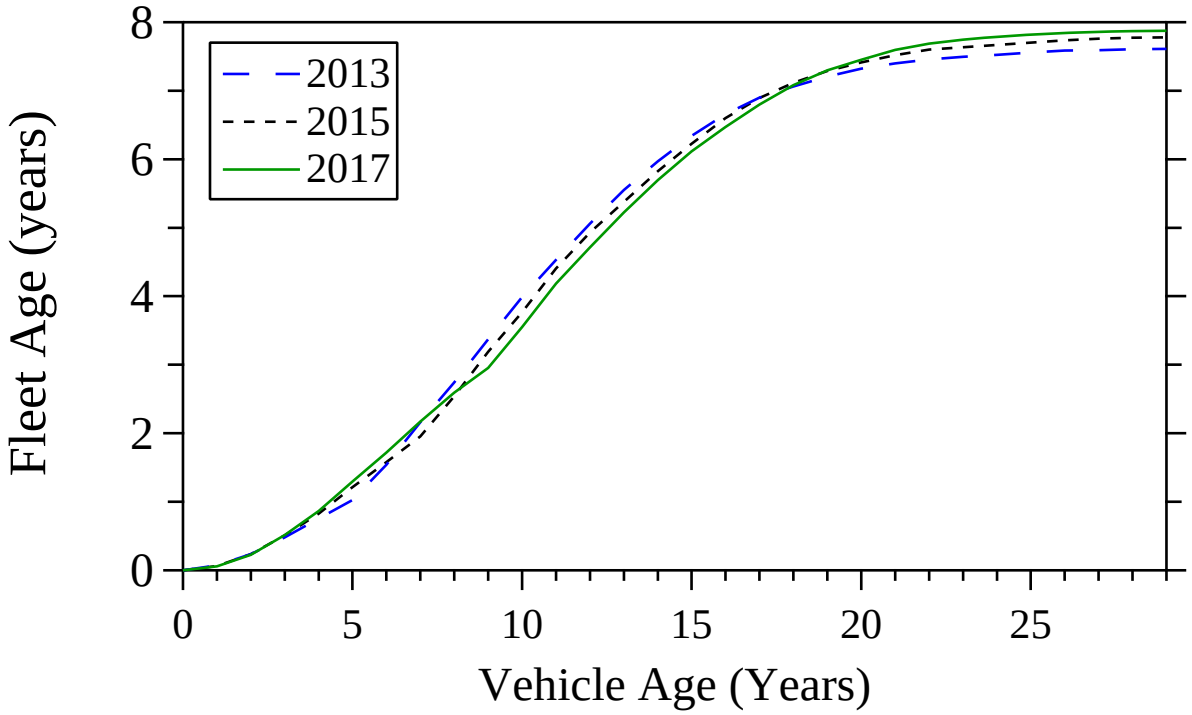

Figure 8. Cumulative fleet Age (years) versus vehicle age in years for the 2013 (long dashed line), 2015 (short dashed line) and 2017 (solid line) Tulsa data sets.

Nuys site in 2010.[32, 33] In addition air borne measurements of ammonia were collected in 2010 over the South Coast Air Basin as part of the CalNex campaign.[11] Most recently we have reported on ammonia emissions that we collected in 2013 from the West LA site, Denver and this Tulsa site.[34]

With the collection of the 2017 data set we now have 4 Tulsa data sets that can be used to look at the changes in NH_3 emissions. Figure 9 compares gNH_3/kg of fuel emissions collected at the Tulsa site for all four measurement campaigns by model year. The data show the characteristic shape with NH_3 emissions increasing with model year until the vehicles reach between 15 to 20 years old when the emissions start decreasing to levels that are approaching zero. One peculiar feature is the increased NH_3 emissions that are associated with the 2008 and 2009 model year vehicles. We have now observed this in the past three data sets for which those model years are present which suggests it is a real difference but we currently have no explanation for this observation.

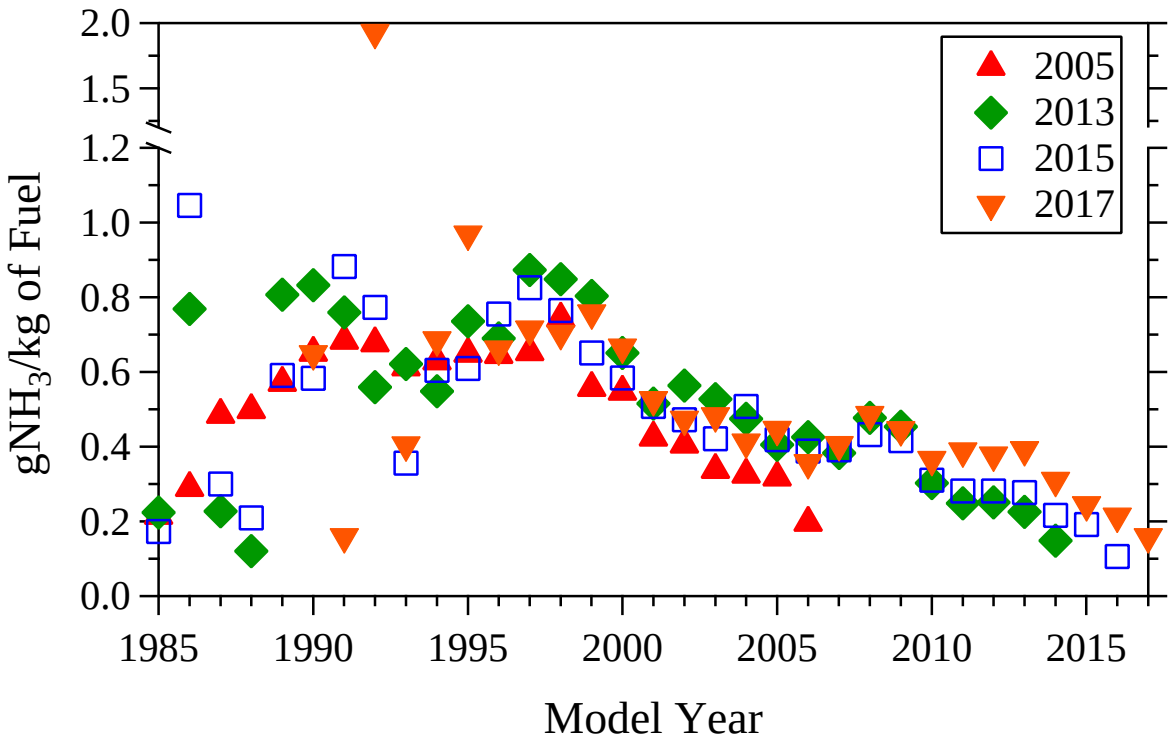

Figure 9. Mean gNH_3/kg of fuel emissions plotted against vehicle model year for the four measurement data sets collected at the Tulsa site with a split y-axis.

Because NH_3 emissions are sensitive to vehicle age it often helps to plot the data against vehicle age as opposed to model year. Figure 10 compares the four Tulsa data sets in this way where year 0 vehicles are 2018, 2016, 2014 and 2006 models for the 2017, 2015, 2013 and 2005 data sets. The uncertainties plotted are standard errors of the mean calculated from distributing the daily means for each year's data.

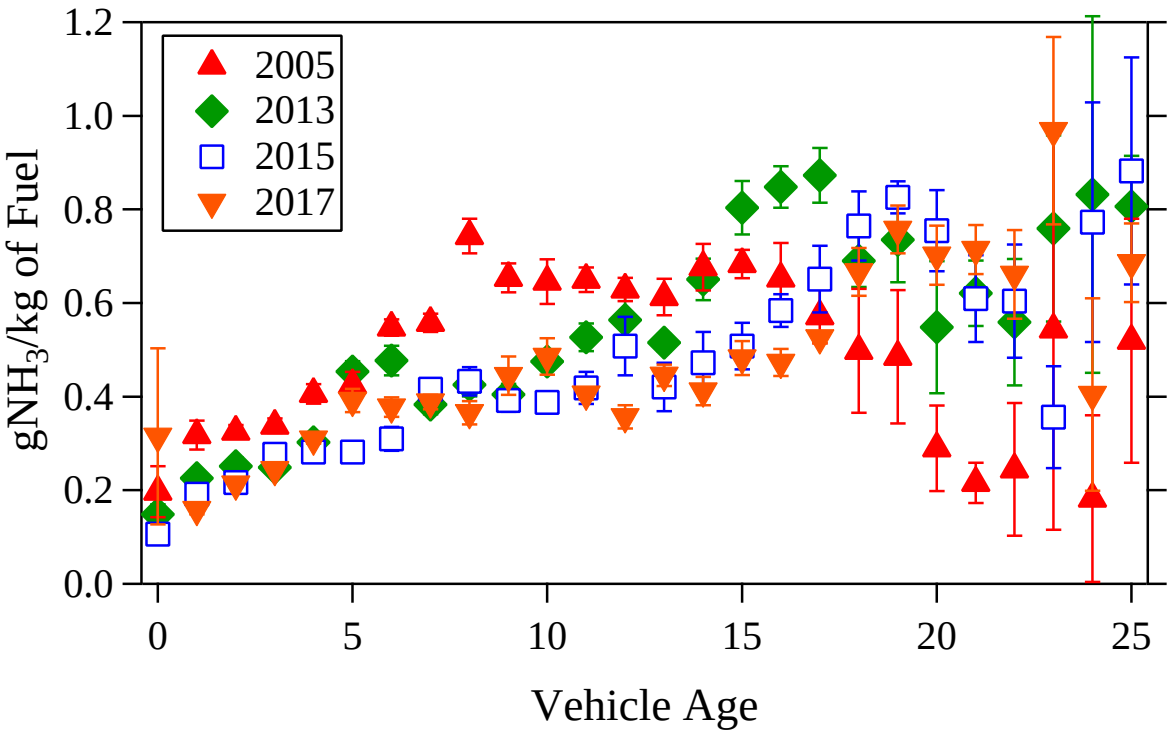

Figure 10. Mean gNH_3/kg emissions plotted against vehicle age for the 2017, 2015, 2013 and 2005 measurements at the Tulsa site. The uncertainty bars plotted are the standard error of the mean determined from the daily samples.

The differences between the data sets in Figure 10 are more obvious. The lower rate of increase in NH_3 emissions as a function of vehicle age seen initially with the 2013 data set is still a feature of the 2017 data. While the rate of increase has slowed it appears that the average vehicle age at which NH_3 emissions peak and then begin to decrease keeps getting pushed older. The unique shape of the NH_3 emissions trend, rising for a number of years and then retreating, has been linked with the path that the reducing capability of the three-way catalytic converter follows. The period of increasing NH_3 emissions has grown since 2005, though it is debatable as to the exact point in the 2005 data that the emissions peak. The 2005 data set rises for ~10 years (1996 models) and starts to decline at ~15 years (1991 models). The 2013 data set rises for ~17 years (1997 models) and then declines which is more consistent with several other data sets collected since 2008.[33] The 2015 data set appears to not peak until ~19 year old vehicles though there is increased uncertainty about assigning the exact point because the small sample sizes at these model years complicates that determination. The 2017 data set extends as least as long as the 2015 data set and again the exact model year that emissions peak is difficult to pin point. Certainly declining fuel sulfur levels have improved the longevity of catalytic converters and that undoubtedly is a factor in these NH_3 emission trends.

The NH_3 mean emissions observed in 2005, 2013, 2015 and 2017 were 0.5 ± 0.01, 0.43 ± 0.01, 0.37 ± 0.001 and 0.37 ± 0.005 g/kg of fuel respectively, which is a 26% reduction in emissions over ten years with no significant change since the 2015 measurements. In addition NO emissions at this Tulsa site have decreased by 51% (2.9 gNO/kg in 2005 to 1.4 gNO/kg in 2017)

over the same time period. This raises the question as to why NO emissions have decreased more during the ten year period than NH_3 since they have a common origination point in engine out NO emissions. Fuel changes might be a contributing factor, as fuel sulfur levels have decreased significantly during this period, but laboratory research on the fuel effects of NH_3 emissions is contradictory, owing in part to the small number of vehicles tested.[26, 35] Driving mode and catalyst age are two additional factors discussed in the literature that impact NH_3 emissions and might be involved in the answer to this question.[27, 35] Also as previously mentioned NH_3 emissions are not regulated while NO emissions are and we can only speculate that engine operating conditions that minimize tailpipe NO emissions will be emphasized.

An equation for determining the instantaneous power of an on-road vehicle has been proposed by Jimenez,[36] which takes the form

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

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. Derived from dynamometer studies, and necessarily an approximation, the first term represents the work required to climb the gradient, the second term is the $f = ma$ work to accelerate the vehicle, the third is an estimated friction term, and the fourth term represents aerodynamic resistance. Using equation 4, VSP was calculated for all measurements in each of the five years' databases. This equation, in common with all dynamometer studies, does not include any load effects arising from road curvature. The emissions data were binned according to vehicle specific power, and graphed in Figure 13. Each of the specific power bins contains at least 125 measurements, except for the 25 VSP bin in 2005 which only contains 57 measurements, and the HC data have been offset adjusted for this comparison. The uncertainty bars included in the plot are standard errors of the mean calculated from the daily means. 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 emissions at that VSP. Normal statistics were then applied to the daily means. Within each vehicle specific power bin there have been significant year over year reductions in mean emissions of CO and NO between the 2003 and 2017 datasets. There have been smaller reductions observed between the various HC data sets. All of the datasets show a similar NO emissions trends with increasing NO emissions with increasing VSP, however, that trend has flattened out with each successive campaign and the 2017 data set continues that trend. The solid line in the bottom graph is the frequency count distribution of vehicles in the 2017 dataset sorted by specific power bin.

The Cherokee Nation has kindly provided us with vehicle information in 2017 and we have repeated the emission comparison with Oklahoma plates that was included in previous reports. Table 4 provides a summary of the number of measurements, fleet statistics and mean emissions with standard errors of the mean determined from the daily means. The Cherokee Nation fleet is smaller than the Oklahoma fleet making up only 5.8% of the matched plates and is newer. Mean fuel specific emissions are similar between the two fleets with all of the means being within the combined uncertainties despite the Cherokee Nation fleet being younger. This comparison changes when the Oklahoma plated vehicles are age adjusted so that they match the age of the Cherokee fleet. After the age adjustment the Oklahoma plated fleet is significantly lower emitting for all species except ammonia.

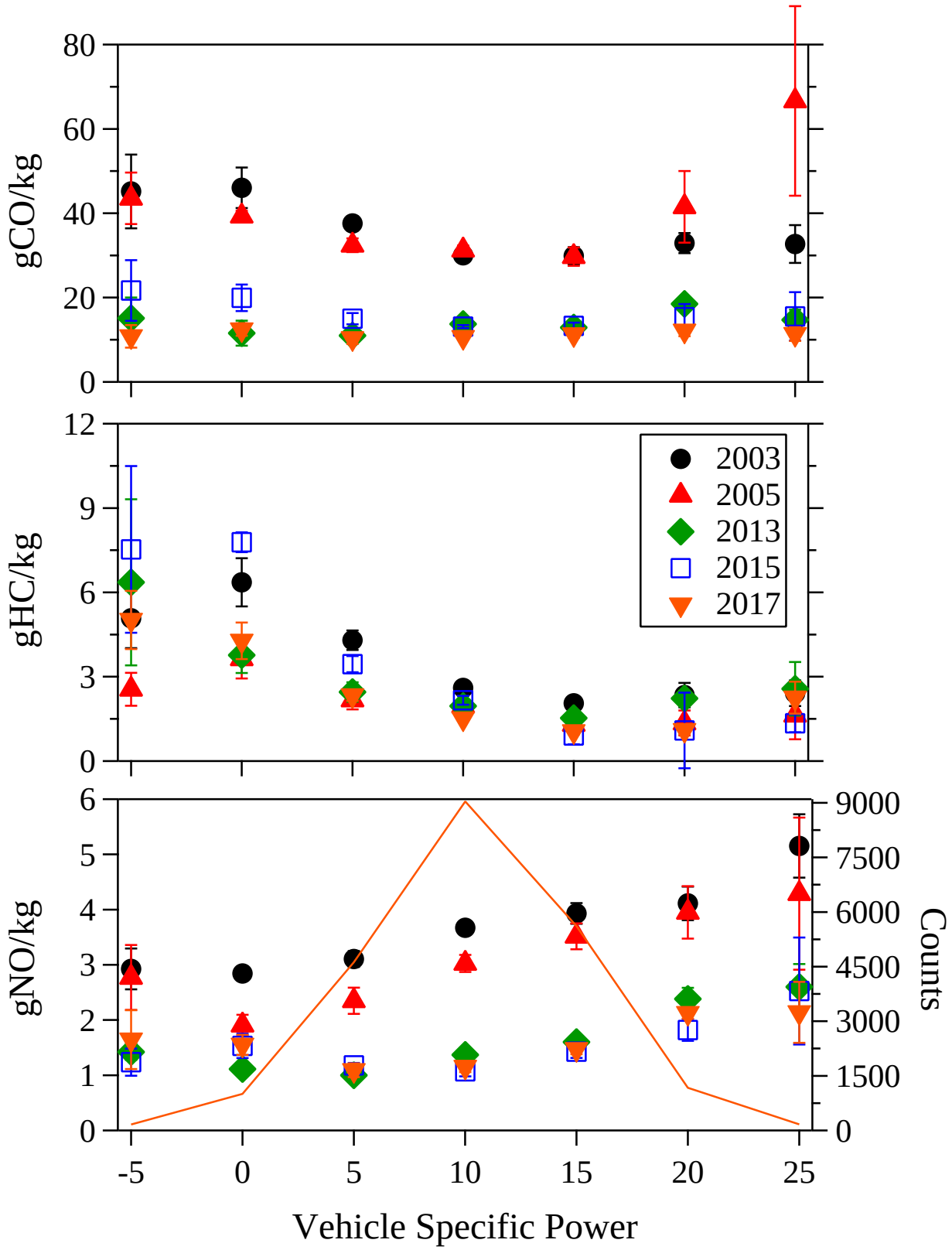

Figure 13. Vehicle emissions as a function of vehicle specific power for all of the Tulsa data sets. Uncertainties plotted are standard errors of the mean calculated from the daily samples. The solid line without markers in the bottom graph is the vehicle count profile for the 2017 data.

Table 4. Comparison of Vehicle Measurements by Nation of Registration

Nation	Measurements	Mean Model Year	Unique Vehicles	Mean gCO/kg	Mean gHC/kg	Mean gNO/kg	Mean gNH_3/kg	Mean gNO_x/kg
US	21,282	2010	14,851	11.1±0.2	1.7±0.1	1.4±0.1	0.37±0.005	2.2±0.2
Cherokee	1,301	2011.3	983	11.1±1.9	1.9±0.2	1.2±0.2	0.34±0.03	1.8±0.3
US Age Adjusted to Cherokee Fleet				9.1	1.5	1.1	0.35	1.7

In the manner described in the E-23 Phoenix, Year 2 report, instrument noise was evaluated using the slope of the negative portion of a plot of the natural log of the binned emission measurement frequency versus the emission level.[37] Such plots were constructed for the five pollutants. 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 5.2, 3.1, 0.1, 0.013 and 0.27 for CO, HC, NO, NH_3 and NO_2, respectively. These values indicate standard deviations of 7.4 g/kg (0.06%), 4.4 g/kg (99ppm), 0.14 g/kg (11ppm), 0.019 g/kg (3ppm) and 0.38 g/kg (18ppm) for individual measurements of CO, HC, NO, NH_3 and NO_2, respectively. For CO and HC these levels are lower than the low noise level as discussed in the Phoenix report and are a significant reduction from noise levels experienced during the 2015 Tulsa measurements.[37] In terms of uncertainty in average values reported here, the numbers are reduced by a factor of the square root of the number of measurements. For example, with averages of 100 measurements the uncertainty reduces by a factor of 10. Thus, the uncertainties in the averages of 100 measurements reduce to 0.7 g/kg, 0.4 g/kg, 0.01 g/kg, 0.002 g/kg and 0.04 g/kg, respectively.

CONCLUSIONS

The University of Denver successfully completed the fifth year of a multi-year remote sensing study in Tulsa. Five days of fieldwork, September 11 – 15, 2017, were conducted on the uphill interchange ramp from westbound US64 (Broken Arrow Expressway) to southbound US169. A database was compiled containing 22,583 records for which the State of Oklahoma and the Cherokee Nation provided registration information. All of these records contained valid measurements for at least CO and CO_2, and most records contained valid measurements for the other species as well. Of these measurements, 11,939 (52.9%) were contributed by vehicles measured only once, and the remaining 10,644 (47.1%) records were from vehicles measured at least twice.

The mean CO, HC, NO, NH_3 and NO_2 emissions for the fleet measured in this study was 11.1 g/kg of fuel (0.09%), 1.7 g/kg of fuel (44 ppm), 1.4 g/kg of fuel (100 ppm), 0.37 g/kg of fuel (47 ppm) and 0.03 g/kg of fuel (1 ppm) respectively. When compared with previous measurements from 2015 we find that mean CO (-22%) and HC (-29%) emissions decreased while NO (+4%) and NH_3 (0%) emissions changed very little. The average fleet age again increased by 0.1 model years (2010.1) which is approximately 8 years old. Unlike recent data from Los Angles showing a rebound from the 2008 recession with a slightly younger fleet, the Tulsa fleet shows signs of a slowdown in new car purchases with the percentage of one year old vehicles dropping again in

the 2017 measurements. Fleet mean emissions are still dominated by a few high emitting vehicles and for the 2017 data set the highest emitting 1% of the measurements (99th percentile) are responsible for 31%, 40%, 29%, 16 % and 100% of the CO, HC, NO, NH_3 and NO_2 emissions, respectively.

The Tulsa site was one of the first in which the University of Denver collected NH_3 emissions from light-duty vehicles in 2005 and now has one of the longest running NH_3 measurement trends. The NH_3 mean emissions observed in 2005, 2013, 2015 and 2017 were 0.5 ± 0.01, 0.43 ± 0.01, 0.37 ± 0.001 and 0.37 ± 0.005 g/kg of fuel respectively, which is an overall 26% reduction in emissions over twelve years but as previously mentioned no change since 2015. The peak NH_3 emissions remain around the 19 year old vehicles as observed in 2015 but the increase in noise due to fewer measurements in the older model years makes an exact assignment difficult. The NH_3 reduction rates are much smaller than observed for the tailpipe NO emissions which have decreased by 51% (2.9 gNO/kg of fuel in 2005 to 1.4 gNO/kg of fuel in 2017) over the same time period.

We investigated potential differences there were between vehicles registered with the Cherokee Nation and those registered in the State of Oklahoma. The Cherokee Nation fleet is smaller making up only 5.8% of the overall matched plates and the fleet is newer (mean model year of 2011.3 versus 2010). Because of the younger fleet the Cherokee Nation fleet has lower mean emission for all of the species except for HC, however, they are accompanied with larger uncertainties. When the Oklahoma plated vehicles are age adjusted to match the age distribution of the Cherokee Nation fleet the Oklahoma fleet turns out to be lower emitting for every species but NH_3.

ACKNOWLEDGEMENTS

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

Not measured:

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

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

Invalid :

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

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

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

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

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

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

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

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

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

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

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

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

APPENDIX B: Explanation of the Tulsa_17.dbf database.

The Tulsa_17.dbf is a Microsoft FoxPro database file, and can be opened by any version of MS FoxPro. The file can be read by a number of other database management programs as well, and is available on our website at www.feat.biochem.du.edu. The following is an explanation of the data fields found in this database:

License	License plate.
Nation	Nation of license plate, US (Oklahoma) or CN (Cherokee)
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.
Percent_CO2	Carbon dioxide concentration, in percent.
CO2_err	Standard error of the carbon dioxide measurement.
Opacity	Opacity measurement, in percent.
Opac_err	Standard error of the opacity measurement.
Restart	Number of times data collection is interrupted and restarted by a close-following vehicle, or the rear wheels of tractor trailer.
HC_flag	Indicates a valid hydrocarbon measurement by a “V”, invalid by an “X”.
NO_flag	Indicates a valid nitric oxide measurement by a “V”, invalid by an “X”.
NH3_flag	Indicates a valid ammonia measurement by a “V”, invalid by an “X”.
NO2_flag	Indicates a valid nitrogen dioxide measurement by a “V”, invalid by an “X”.
Opac_flag	Indicates a valid opacity measurement by a “V”, invalid by an “X”.
Max_CO2	Reports the highest absolute concentration of carbon dioxide measured by the remote sensor over an 8 cm path; indicates plume strength.
Speed_flag	Indicates a valid speed measurement by a “V”, an invalid by an “X”, and slow speed (excluded from the data analysis) by an “S”.
Speed	Measured speed of the vehicle, in mph.
Accel	Measured acceleration of the vehicle, in mph/s.
Tag_name	File name for the digital picture of the vehicle.
Vin	Vehicle identification number.

Title_date	Oklahoma DMV date of title for vehicle.
Year	Model year.
Make	Manufacturer of the vehicle.
Model	Oklahoma model designation.
Body	Oklahoma designated body style
City	Registrant's mailing city.
State	Registrant's mailing State.
Zipcode	Cherokee Nation registration zip code.
CO_gkg	Grams of CO per kilogram of fuel using 860 gC/kg of fuel.
HC_gkg	Grams of HC per kilogram of fuel using 860 gC/kg of fuel and the molecular weight of propane which is our calibration gas.
NO_gkg	Grams of NO per kilogram of fuel using 860 gC/kg of fuel.
NH3_gkg	Grams of NH_3 per kilogram of fuel using 860 gC/kg of fuel.
NO2_gkg	Grams of NO_2 per kilogram of fuel using 860 gC/kg of fuel.
NOx_gkg	Grams of NO_x per kilogram of fuel using 860 gC/kg of fuel.
HC_offset	Hydrocarbon concentration after offset adjustment.
Hcgkg_off	Grams of HC per kilogram of fuel using 860 gC/kg of fuel and using the HC_offset value for this calculation.
VSP	Vehicles specific power calculated using the equation provided in the report.

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

Tulsa 2003 Temperature and Humidity Data										
Time	9/8 °F	9/8 %RH	9/9 °F	9/9 %RH	9/10 °F	9/10 %RH	9/11 °F	9/11 %RH	9/12 °F	9/12 %RH
5:53	61	93	70	84	71	81	76	79	65	90
6:53	63	90	71	84	71	81	76	79	65	90
7:53	67	87	72	82	74	76	71	94	65	90
8:53	72	79	76	72	78	67	69	96	64	96
9:53	78	69	79	65	80	64	69	96	64	96
10:53	79	67	82	60	83	59	70	97	65	93
11:53	82	58	84	57	85	57	71	94	66	90
12:53	83	53	85	57	87	50	71	90	67	87
13:53	84	53	87	51	87	51	72	87	68	87
14:53	83	57	85	51	89	47	73	81	68	87
15:53	85	50	86	53	88	46	74	82	68	90
16:53	81	61	85	57	87	46	74	82	68	93
17:53	79	67	83	61	85	53	74	85	67	97
18:53	76	77	79	69	82	58	72	87	67	97

Tulsa 2005 Temperature and Humidity Data										
Time	9/19 °F	9/19 %RH	9/20 °F	9/20 %RH	9/21 °F	9/21 %RH	9/22 °F	9/22 %RH	9/23 °F	9/23 %RH
5:53	74	74	76	79	71	93	73	74	68	90
6:53	76	71	73	90	72	90	74	69	69	87
7:53	79	67	76	87	79	77	77	62	73	82
8:53	84	57	80	79	84	61	81	56	79	69
9:53	87	55	83	72	87	55	86	50	84	57
10:53	90	50	85	70	90	47	89	47	87	52
11:53	93	47	88	63	93	41	92	42	89	50
12:53	93	47	90	56	94	37	94	38	91	45
13:53	94	46	93	52	95	37	94	36	92	41
14:53	94	44	92	50	95	35	95	34	91	47
15:53	94	43	92	49	95	34	95	32	91	47
16:53	93	44	92	49	94	35	93	34	88	52
17:53	91	47	89	55	89	42	91	35	84	65
18:53	88	52	86	57	87	48	88	42	85	59

Tulsa 2013 Temperature and Humidity Data										
Time	9/30 °F	9/30 %RH	10/1 °F	10/1 %RH	10/2 °F	10/2 %RH	10/3 °F	10/3 %RH	10/4 °F	10/4 %RH
5:53	54	93	62	100	72	93	72	90	74	87
6:53	53	96	66	100	73	90	72	90	74	90
7:53	59	84	71	97	74	90	73	90	76	85
8:53	64	81	74	90	76	87	75	85	77	79
9:53	71	61	77	79	77	82	77	82	82	65
10:53	75	52	80	69	81	72	81	74	84	59
11:53	77	42	83	61	83	63	83	67	85	57
12:53	79	41	84	55	85	57	85	65	86	53
13:53	81	47	86	53	85	57	86	63	86	53
14:53	81	42	86	48	86	57	87	61	87	52
15:53	82	38	86	48	85	57	86	61	87	52
16:53	80	41	85	46	84	57	85	61	85	59
17:53	78	47	82	51	82	63	83	63	83	63
18:53	73	57	78	60	80	67	81	67	82	63

Tulsa 2015 Temperature and Humidity Data										
Time	9/14 °F	9/14 %RH	9/15 °F	9/15 %RH	9/16 °F	9/16 %RH	9/17 °F	9/17 %RH	9/18 °F	9/18 %RH
5:53	65	78	67	61	73	84	74	84	75	79
6:53	65	78	67	63	73	87	75	82	76	76
7:53	68	71	70	59	76	82	78	77	79	72
8:53	70	66	73	59	79	77	81	72	80	72
9:53	74	60	77	62	82	72	85	63	83	67
10:53	74	60	80	56	85	63	88	57	86	59
11:53	76	58	82	55	87	59	88	57	87	59
12:53	79	52	83	53	87	59	91	52	87	61
13:53	79	52	84	55	87	57	91	52		
14:53	81	51	85	53	86	59	90	52		
15:53	81	51	84	55	87	59	91	52		
16:53	81	51	84	55	86	59	91	50		
17:53	79	52	82	58	85	59	88	55		
18:53	77	56	80	65	83	63	85	61		

Tulsa 2017 Temperature and Humidity Data										
Time	9/11 °F	9/11 %RH	9/12 °F	9/12 %RH	9/13 °F	9/13 %RH	9/14 °F	9/14 %RH	9/15 °F	9/15 %RH
5:53	57	93	54	97	60	84	57	87	71	81
6:53	58	93	56	93	61	81	63	78	72	79
7:53	64	81	60	86	65	73	69	59	75	74
8:53	70	64	63	78	71	57	73	51	79	67
9:53	75	55	69	61	75	46	79	44	82	63
10:53	80	42	74	48	80	41	82	41	86	57
11:53	83	37	75	41	82	32	85	36	88	52
12:53	84	34	76	42	84	32	88	31	90	47
13:53	85	32	78	35	86	30	89	29	90	45
14:53	86	32	78	36	86	28	90	29	91	42
15:53	85	30	78	35	88	26	89	31	91	42
16:53	84	30	78	31	85	31	88	35	89	43
17:53	81	35	76	39	82	42	85	40	87	46
18:53	73	50	72	50	80	35	77	52	83	51

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

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

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

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

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

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

2014 Chicago Mode Calculations
For model year 2009 and newer vehicles

Table D1. HC Normalization Mode Calculation.

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

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

APPENDIX E: Field Calibration Record.

2003 (FEAT 3002)				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/8	7:10	1.71	1.43	1.78
9/8	10:35	1.295	1.051	1.102
9/8	13:00	1.173	0.971	1.141
9/9	6:40	1.507	1.215	1.55
9/9	10:00	1.25	1.016	1.271
9/9	13:35	1.087	0.893	0.941
9/10	6:40	1.48	1.19	1.38
9/10	9:30	1.254	1.018	1.153
9/10	13:40	1.121	0.93	1.055
9/11	6:45	1.35	1.08	1.29
9/11	13:54	1.31	1.10	1.20
9/12	6:50	1.536	1.225	1.592
9/12	13:30	1.455	1.214	1.525

2005 (FEAT 3004)					
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor
9/19	8:15	1.66	1.75	1.50	1.08
9/19	11:30	1.25	1.25	1.06	1.09
9/20	7:15	1.71	1.74	2.24	1.09
9/20	9:30	1.52	1.55	1.88	1.09
9/20	11:30	1.38	1.35	1.52	1.09
9/21	7:10	2.46	2.58	3.9	1.09
9/21	8:20	1.91	2.03	3.07	1.09
9/21	10:00	1.31	1.35	1.49	1.09
9/21	13:30	1.23	1.26	1.55	1.09
9/22	7:00	1.92	2.13	2.85	1.17
9/22	9:15	1.65	1.85	2.22	1.24
9/22	11:30	1.28	1.33	1.33	1.14
9/23	7:00	2.17	2.29	2.19	1.24
9/23	9:30	1.66	1.69	1.50	1.22
9/23	11:20	1.31	1.35	1.28	1.22

2013 Tulsa (FEAT 3002)						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
9/30	9:20	1.72	1.58	1.61	0.86	0.67
9/30	11:15	1.35	1.26	1.26	0.95	0.51
10/1	7:00	1.87	1.70	1.74	0.83	0.75
10/1	9:30	1.54	1.41	1.46	0.83	0.67
10/1	12:00	1.31	1.22	1.30	0.95	0.57
10/2	7:00	1.67	1.52	1.60	0.85	0.66
10/2	9:30	1.53	1.42	1.40	0.77	0.60
10/2	12:00	1.38	1.29	1.31	0.85	0.70
10/3	7:00	1.57	1.43	1.54	0.88	0.63
10/3	9:23	1.41	1.28	1.40	0.90	0.66
10/3	12:00	1.28	1.19	1.25	0.95	0.61
10/4	6:50	1.55	1.43	1.49	0.91	0.67
10/4	9:15	1.44	1.33	1.47	0.93	0.75
10/4	12:00	1.24	1.16	1.21	1	0.63

2015 Tulsa (FEAT 3002)						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
9/14	8:45	1.57	1.46	1.38	0.94	1.17
9/14	12:25	1.47	1.34	1.376	0.96	1.02
9/14	15:11	1.31	1.20	1.26	1.1	0.91
9/15	7:10	1.82	1.67	1.68	0.9	1.37
9/15	9:30	1.49	1.40	1.48	1.07	1.14
9/15	12:30	1.29	1.22	1.34	1.03	0.93
9/16	7:18	1.75	1.63	1.69	0.87	1.28
9/16	9:30	1.44	1.36	1.46	0.97	1.05
9/16	12:37	1.28	1.19	1.27	0.98	0.91
9/17	7:00	1.74	1.63	1.79	0.87	1.28
9/17	9:30	1.39	1.32	1.46	1.02	1.02
9/17	12:30	1.19	1.14	1.24	1.06	0.84
9/18	7:18	1.70	1.61	1.68	0.89	1.23
9/18	9:30	1.43	1.36	1.39	0.94	0.99

2017 Tulsa (FEAT 3002)						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
9/11	8:17	1.98	1.87	1.67	0.87	1.44
9/11	10:47	1.44	1.37	1.38	0.95	1.09
9/11	12:50	1.31	1.25	1.25	0.95	0.94
9/12	7:45	1.92	1.84	1.79	0.89	1.77
9/12	9:35	1.70	1.62	1.52	0.93	1.43
9/12	11:50	1.41	1.39	1.31	0.96	1.12
9/12	14:00	1.38	1.36	1.25	0.98	1.11
9/13	7:30	2.34	2.30	2.27	0.91	2.05
9/13	8:46	1.77	1.72	1.73	0.97	1.51
9/13	10:20	1.43	1.41	1.37	1.00	1.12
9/13	12:30	1.28	1.27	1.27	1.01	0.94
9/14	7:30	2.16	2.10	2.11	0.92	2.04
9/14	8:45	1.79	1.75	1.78	0.93	1.54
9/14	10:10	1.43	1.38	1.42	1.02	1.13
9/14	12:30	1.26	1.25	1.31	1.03	0.92
9/15	7:35	1.72	1.65	1.61	0.88	1.47
9/15	8:50	1.54	1.49	1.46	0.94	1.29
9/15	10:40	1.30	1.28	1.30	1.00	0.99