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ON-ROAD REMOTE SENSING OF AUTOMOBILE EMISSIONS IN THE TULSA AREA: FALL 2019

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On-Road Remote Sensing of Automobile Emissions in the Tulsa Area: Fall 2019

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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 2019. The remote sensor used in this study measures the molar ratios of CO, HC, NO, SO₂, NH₃ and NO₂ to CO₂ in motor vehicle exhaust. From these ratios, we calculate the percent concentrations of CO, CO₂, HC, NO, SO₂, NH₃ and NO₂ 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 SO₂ emissions have followed suit and while we collected vehicle SO₂ measurements we did not calibrate those readings and they are not included in the discussion of the results.

Five days of fieldwork, September 9 – 13, 2019, 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, 2015 and 2017. A database was compiled containing 23,376 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 CO₂, 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 online at www.feet.biochem.du.edu.

The 2019 mean CO, HC, NO, NH₃ and NO₂ emissions for the fleet measured in this study were 11.6 gCO/kg of fuel (0.09%), 1.9 gHC/kg of fuel (69 ppm), 1.1 gNO/kg of fuel (76 ppm), 0.34 gNH₃/kg of fuel (42 ppm) and 0.02 g/kg of fuel (1 ppm) respectively. When compared with previous measurements from 2017 we find that mean CO (+5%) and HC (+12%) emissions slightly increased though the differences are not statistically significant. NO and NH₃ emissions in 2019 show statistically significant reductions when compared with the 2017 data with mean NO emissions decreasing by 21% and NH₃ emissions by 8%. Figure ES1 shows 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 error of the mean calculated using the daily means. Since 2003 the fuel specific CO emissions have decreased by 66%, HC by 41% and NO by 70%. As seen in the plot the largest absolute reductions occurred between the 2005 and 2013 measurements.

The average Tulsa fleet age again increased by 0.1 years (2011.9) which is approximately 8.1 years old. Fleet mean emissions are still dominated by a few high emitting vehicles and for the 2019 data set the highest emitting 1% of the measurements (99th percentile) is responsible for 30%, 32%, 35%, 16 % and 100% of the CO, HC, NO, NH₃ and NO₂ emissions, respectively.

The Tulsa site was one of the first in which the University of Denver collected NH₃ emissions from light-duty vehicles in 2005 and now has one of the longest running NH₃ measurement

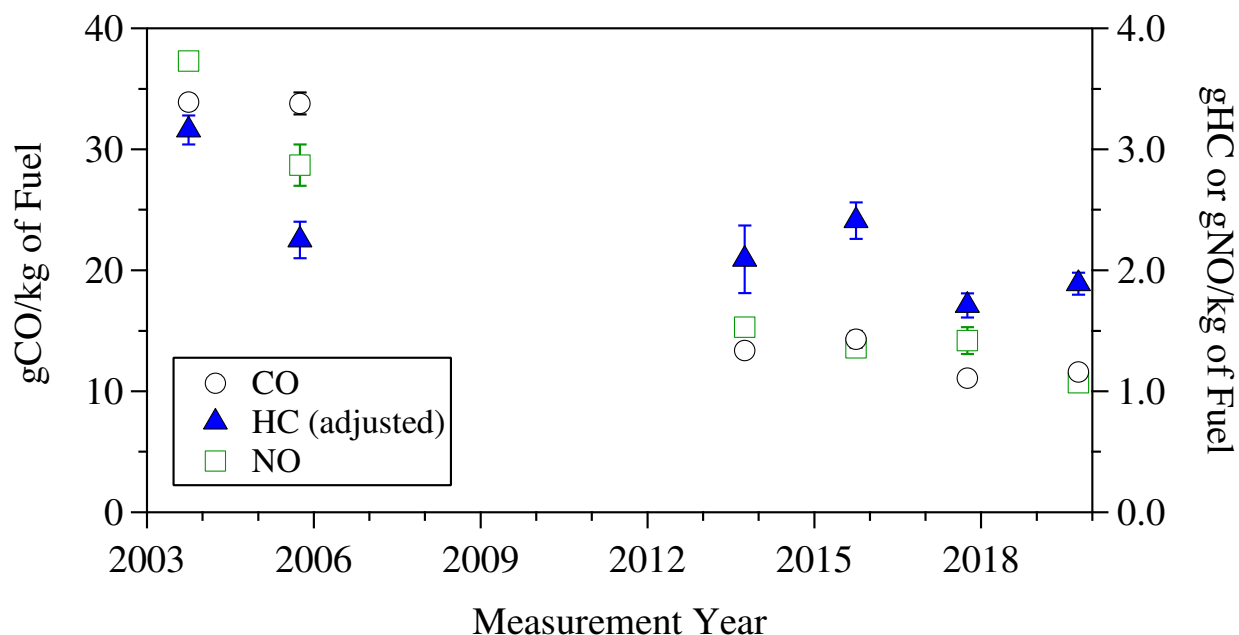


Figure ES1. Tulsa area historical fuel specific fleet mean emissions for CO (○, left axis), HC (▲, right axis) and NO (□, right axis) by measurement year. Uncertainties are standard error of the mean calculated using the daily measurements. The fuel specific HC means have been adjusted as described in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

trends. With this measurement campaign we have now collected 5 data sets with fuel specific NH_3 emissions and the means and standard error of the mean uncertainties are listed in Table ES1.

Table ES1. Mean Fuel Specific Ammonia Emissions with Standard Error of the Mean Uncertainties for the Five Tulsa Measurement Campaigns.

Measurement Year	Mean gNH_3/kg of Fuel
2005	0.5 ± 0.01
2013	0.43 ± 0.01
2015	0.37 ± 0.001
2017	0.37 ± 0.005
2019	0.34 ± 0.01

Ammonia emissions have experienced an overall 32% reduction in emissions over these fourteen years (-1.2% year over year change). Figure ES2 compares the five Tulsa data sets versus vehicle age where year 0 vehicles are 2020, 2018, 2016, 2014 and 2006 models for the 2019, 2017, 2015, 2013 and 2005 data sets. The uncertainties plotted are standard error of the mean calculated from distributing the daily means for each age groups data. 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 2019 data. Tier 3 vehicles phased into the vehicle fleet with the 2017 model year and these vehicles appear to continue the trend of lower NH_3 emissions in the 1 to 4 year old

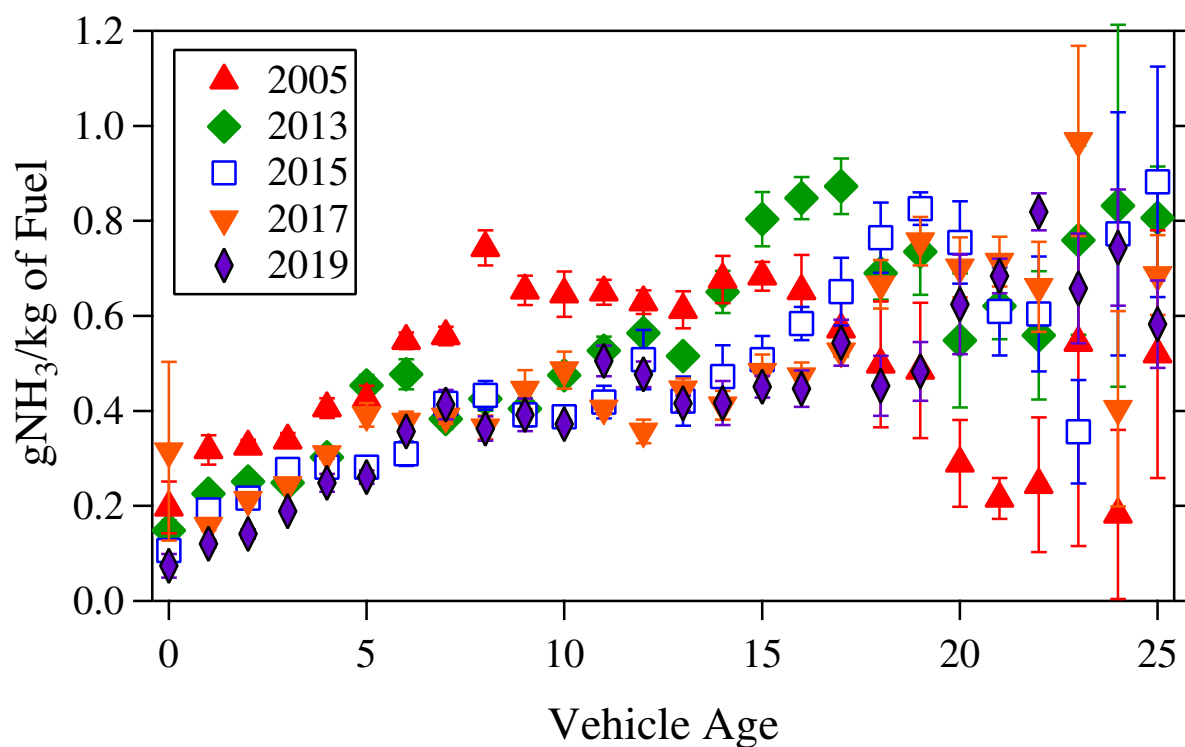


Figure ES2. Mean gNH_3/kg emissions plotted against vehicle age for the 2019, 2017, 2015, 2013 and 2005 measurements at the Tulsa site. The uncertainty bars plotted are the standard error of the mean determined from the daily samples.

vehicles. For example NH_3 emissions of one year old vehicles have declined by 47% (0.23 to 0.12 gNH_3/kg of fuel) since 2013. The location of the peak NH_3 emissions is not possible to definitively assign in the current data set but it has certainly been pushed beyond the 20 year mark for an estimated 3-way catalyst lifetime.

Over the same fourteen year period NO emissions have decreased by 62% (2.9 gNO/kg of fuel in 2005 to 1.1 gNO/kg of fuel in 2019), almost twice the decreases observed for NH_3 . It is not understood why NO emissions have decreased more during this fourteen year period than NH_3 since they have a common origination point in engine out NO emissions. With the disparity in these reductions NH_3 is now the dominate reactive nitrogen compound emitted at the tailpipe.

We again investigated potential differences between vehicles registered with the Cherokee Nation and those registered in the State of Oklahoma. The Cherokee Nation fleet observed at this location is smaller making up only 6.8% of the overall matched plates but is more than a year newer (mean model year of 2013.1 versus 2011.8). Because of its age the Cherokee Nation fleet has lower mean emission for all of the species measured, 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 have lower or similar emissions for every species but NO and NH_3 .

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 (NO₂). 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 (NH₃) 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 (CO₂), 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, subsequently lowered in 2008 and again in 2015) 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 in 2013. 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 2019. Measurements were made on five consecutive weekdays, from Monday, September 9, to Friday, September 13, 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, CO₂, and HC, and twin dispersive ultraviolet (UV) spectrometers for measuring oxides of nitrogen (NO and NO₂), SO₂ and NH₃ (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, CO₂, 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 SO₂ and NH₃ and continue to measure the 227nm peak from NO. The absorbance from each respective UV spectrum of SO₂, NH₃, 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 NO₂ 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 SO₂ emissions have become negligibly small and as such, while SO₂ measurements were collected as a part of this study, they will not be reported or discussed because the sensor was not calibrated for SO₂ 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, NH₃ or NO₂ to CO₂. The molar ratios of CO, HC, NO, NH₃ or NO₂ to CO₂, termed Q^{CO} , Q^{HC} , Q^{NO} , Q^{NH_3} and Q^{NO_2} 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, %NH₃ and %NO₂ in the exhaust gas, corrected for water and excess air not used in combustion. The HC measurement is calibrated with propane, a C₃ hydrocarbon. But based on measurements using flame ionization detection (FID) of gasoline vehicle exhaust, the remote sensor is only half as sensitive to exhaust hydrocarbons on a per carbon atom basis as it is to

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

$$\text{gm CO/gallon} = 5506 \cdot \% \text{CO} / (15 + 0.285 \cdot \% \text{CO} + 2(2.87 \cdot \% \text{HC})) \quad (1a)$$

$$\text{gm HC/gallon} = 2(8644 \cdot \% \text{HC}) / (15 + 0.285 \cdot \% \text{CO} + 2(2.87 \cdot \% \text{HC})) \quad (1b)$$

$$\text{gm NO/gallon} = 5900 \cdot \% \text{NO} / (15 + 0.285 \cdot \% \text{CO} + 2(2.87 \cdot \% \text{HC})) \quad (1c)$$

$$\text{gm NH}_3/\text{gallon} = 3343 \cdot \% \text{NH}_3 / (15 + 0.285 \cdot \% \text{CO} + 2(2.87 \cdot \% \text{HC})) \quad (1d)$$

$$\text{gm NO}_2/\text{gallon} = 9045 \cdot \% \text{NO}_2 / (15 + 0.285 \cdot \% \text{CO} + 2(2.87 \cdot \% \text{HC})) \quad (1e)$$

These equations show that the relationships between emission concentrations and mass emissions are: (a) linear for NO₂ and NH₃, (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 NO₂, 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:

$$\frac{\text{moles pollutant}}{\text{moles C}} = \frac{\text{pollutant}}{\text{CO} + \text{CO}_2 + 6\text{HC}} = \frac{(\text{pollutant}/\text{CO}_2)}{(\text{CO}/\text{CO}_2) + 1 + 6(\text{HC}/\text{CO}_2)} = \frac{(Q^{\text{CO}}, 2Q^{\text{HC}}, Q^{\text{NO}} \dots)}{Q^{\text{CO}} + 1 + 6Q^{\text{HC}}} \quad (2)$$

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 CH₂. Again, the HC/CO₂ 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

$$\text{gm CO/kg} = (28Q^{\text{CO}} / (1 + Q^{\text{CO}} + 6Q^{\text{HC}})) / 0.014 \quad (3a)$$

$$\text{gm HC/kg} = (2(44Q^{\text{HC}}) / (1 + Q^{\text{CO}} + 6Q^{\text{HC}})) / 0.014 \quad (3b)$$

$$\text{gm NO/kg} = (30Q^{\text{NO}} / (1 + Q^{\text{CO}} + 6Q^{\text{HC}})) / 0.014 \quad (3c)$$

$$\text{gm NH}_3/\text{kg} = (17Q^{\text{NH}_3} / (1 + Q^{\text{CO}} + 6Q^{\text{HC}})) / 0.014 \quad (3d)$$

$$\text{gm NO}_2/\text{kg} = (46Q^{\text{NO}_2} / (1 + Q^{\text{CO}} + 6Q^{\text{HC}})) / 0.014 \quad (3e)$$

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, CO₂, propane

and NO, the second contains NH₃ and propane and the final cylinder contains NO₂ and CO₂. 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 CO₂ 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 $\pm 5\%$ of the values reported by an on-board gas analyzer, and within $\pm 15\%$ 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 inter-comparison to have it independently validated. Tests involving a late-model low-emitting vehicle indicate a detection limit (3σ) of 25 ppm for NO, with an error measurement of $\pm 5\%$ 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 0.1 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. 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 2019, from Monday, September 9, to Friday, September 13, 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.

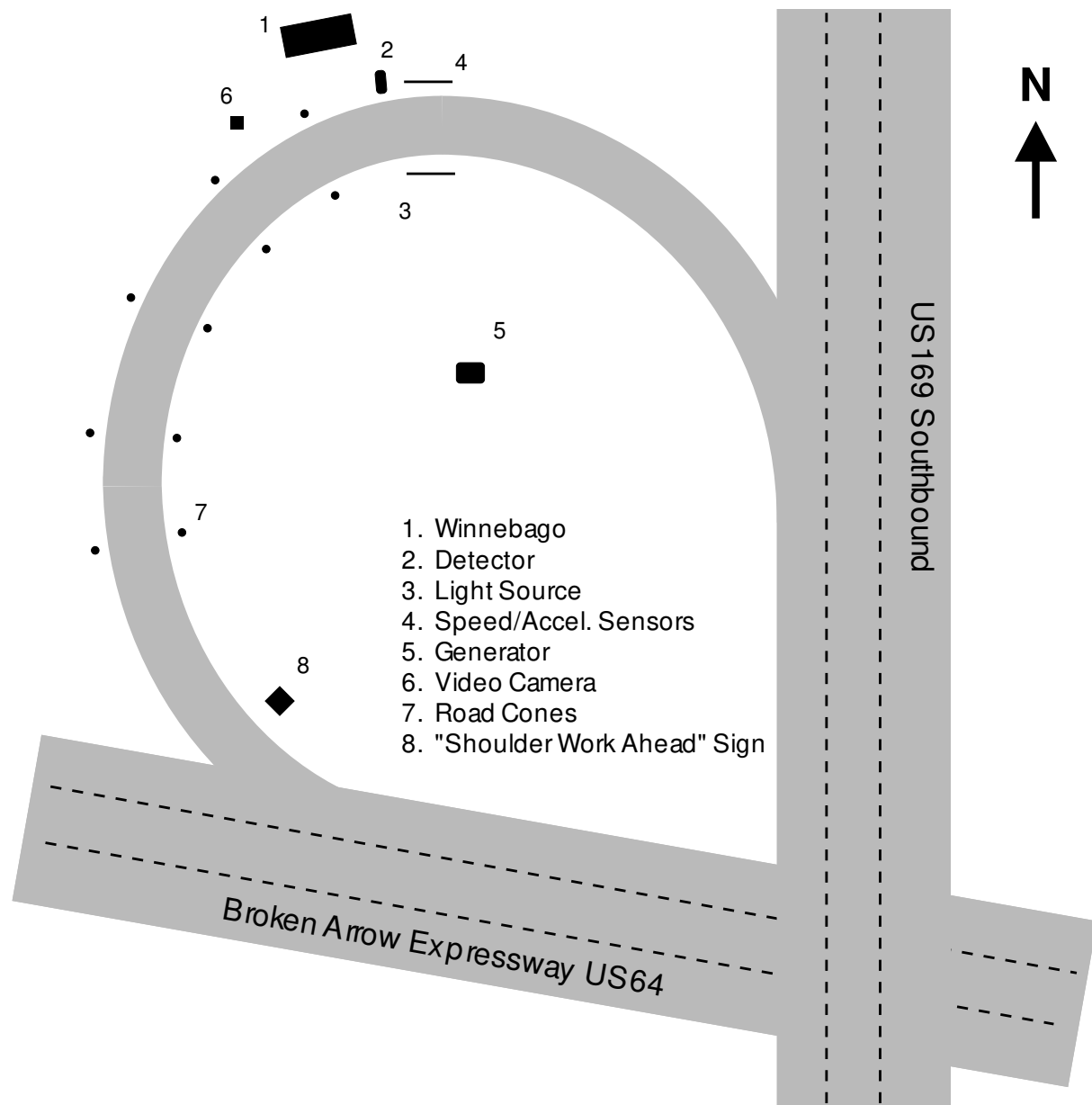


Figure 1. A schematic drawing of the ramp from Westbound US64 (Broken Arrow Expressway) to Southbound US169. The location and safety equipment configuration was for all five days of measurements.



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. The resulting 2019 database contains records (from Oklahoma and the Cherokee Nation) with make and model year information and valid measurements for at least CO and CO₂. Most of these records also contain valid measurements for HC, NO, NH₃ and NO₂. This database and all previous databases compiled for CRC E-23 and E-106 campaigns can be found online 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 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 CO₂ exceeds a preset limit (see Appendix A). The greatest loss of data in this process

Table 1. Validity Summary.

	CO	HC	NO	NH ₃	NO ₂
Attempted Measurements	31,305				
Valid Measurements	29,371	29,296	29,371	29,347	28,217
Percent of Attempts	93.8%	93.6%	93.8%	93.7%	90.1%
Submitted Plates	23,757	23,707	23,757	23,741	22,839
Percent of Attempts	75.9%	75.7%	75.9%	75.8%	73.0%
Percent of Valid Measurements	80.9%	80.9%	80.9%	80.9%	80.9%
Matched Plates	23,376	23,326	23,376	23,362	22,479
Percent of Attempts	74.7%	74.5%	74.7%	74.6%	71.8%
Percent of Valid Measurements	79.6%	79.6%	79.6%	79.6%	79.7%
Percent of Submitted Plates	98.4%	98.4%	98.4%	98.4%	98.4%

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 records used in this fleet analysis, (52.9%) were contributed by vehicles measured only once, and the remaining (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	12,364
2	2,407
3	975
4	483
5	155
6	45
7	24
>7	14

Table 3 summarizes the data for the current and all of the previous measurements collected at this site in 2019, 2017, 2015, 2013, 2005 and 2003. 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

Table 3. Data Summary.

Study Year Location	Tulsa 2003	Tulsa 2005	Tulsa 2013	Tulsa 2015	Tulsa 2017	Tulsa 2019
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)	0.09 (11.6)
Median CO (%)	0.06	0.11	0.028	0.046	0.020	0.025
Percent of Total CO from the 99 th Percentile	21.9%	20.8%	31.2%	26.2%	30.7%	29.6%
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	69 (1.9) 20
Median HC (ppm) ^a	40	40	35	17	19	42
Percent of Total HC from the 99 th Percentile	18.5%	34.1%	41.7%	33.8%	39.9%	32.2%
Mean NO (ppm) (g/kg of fuel)	265 (3.7)	202 (2.9)	109 (1.5)	96 (1.4)	100 (1.4)	76 (1.1)
Median NO (ppm)	53	33	5	2	8	3
Percent of Total NO from the 99 th Percentile	12.3%	13.9%	25.1%	27.8%	29%	35.1%
Mean NH ₃ (ppm) (g/kg of fuel)	NA	62 (0.5)	54 (0.43)	46 (0.37)	47 (0.37)	42 (0.34)
Median NH ₃ (ppm)	NA	25	19	15	16	14
Percent of Total NH ₃ from the 99 th Percentile	NA	12.2%	14.5%	16.3%	15.7%	16.0%
Mean NO ₂ (ppm) (g/kg of fuel)	NA	NA	6 (0.14)	6 (0.13)	1 (0.03)	1 (0.02)
Median NO ₂ (ppm)	NA	NA	3	3	0	0
Percent of Total NO ₂ from the 99 th Percentile	NA	NA	49.7%	29.6%	100%	100%
Mean Model Year	1997.6	1999.3	2006.3	2008.2	2010.1	2011.9
Mean Fleet Age ^c	6.4	6.7	7.8	7.9	8.0	8.1
Mean Speed (mph)	24.1	24.4	24.3	24.2	24.2	23.4
Mean Acceleration (mph/s)	0.06	-0.4	-0.01	-0.07	0.02	0.55
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°	10.3 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.						

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 2019 Tulsa measurements have again given indications that fleet average emissions are reaching a leveling out point, especially for CO and HC. In 2015 mean emission levels for CO and HC increased slightly for the first time only to be followed by modest reductions in 2017. Again in 2019 we see slight increases for CO (+5%) and HC (+12%) though the differences are not statistically different from the 2017 means. However, both are still well below the 2015 means. NO and NH₃ emissions in 2019 show the largest reductions with mean NO emissions decreasing by 21% and NH₃ emissions by 8%. Both of these reductions are statistically different from the 2017 means. The percent of emissions contributed by the highest emitting 1% of the fleet (the 99th percentile) moved opposite of the mean emissions and decreased for CO, HC and increased for NO and NH₃.

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, 2017 and 2019. The HC data have been offset adjusted for comparison and the y-axis has been split for all species. In general for model years 2005 and older, fleet model year emission 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 in the latest data set because of the small sample sizes (less than 58 measurements per model year). All three species graphed in Figure 3 show an 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 2 (2009 - 2016) and Tier 3 certified vehicles (2017 & newer) have now significantly reduced the fleet average NO emissions deterioration rate.

Following the data analysis and presentation format originally shown by Ashbaugh et al.,²² the vehicle emissions data by model year from the 2019 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 that still shows 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 1999 and not graphed account for 1.9% of the measurements and contribute between 10.7% (HC) and 16.8% (NO) of the total emissions. The bottom graph for each species is the combination of the top and middle figures. These figures illustrate that at least the cleanest 60% of the vehicles,

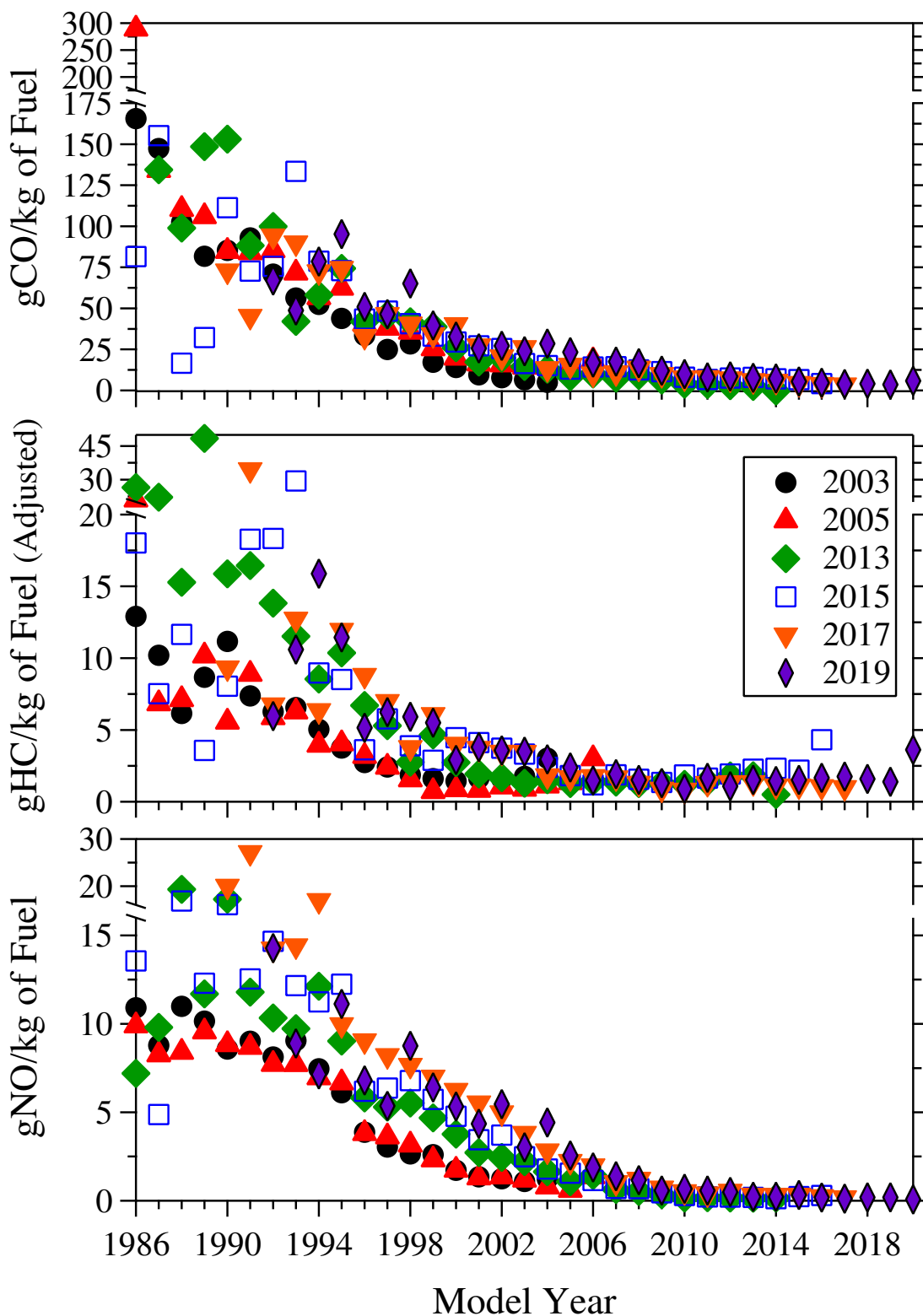


Figure 3. Mean fuel specific vehicle emissions plotted as a function of model year for the five Tulsa data sets, 2003 (circles), 2005 (triangles), 2013 (diamonds), 2015 (squares), 2017 (inverted triangle) and 2019 (thin diamonds). HC data have been offset adjusted as described in the text and the y-axis have been split.

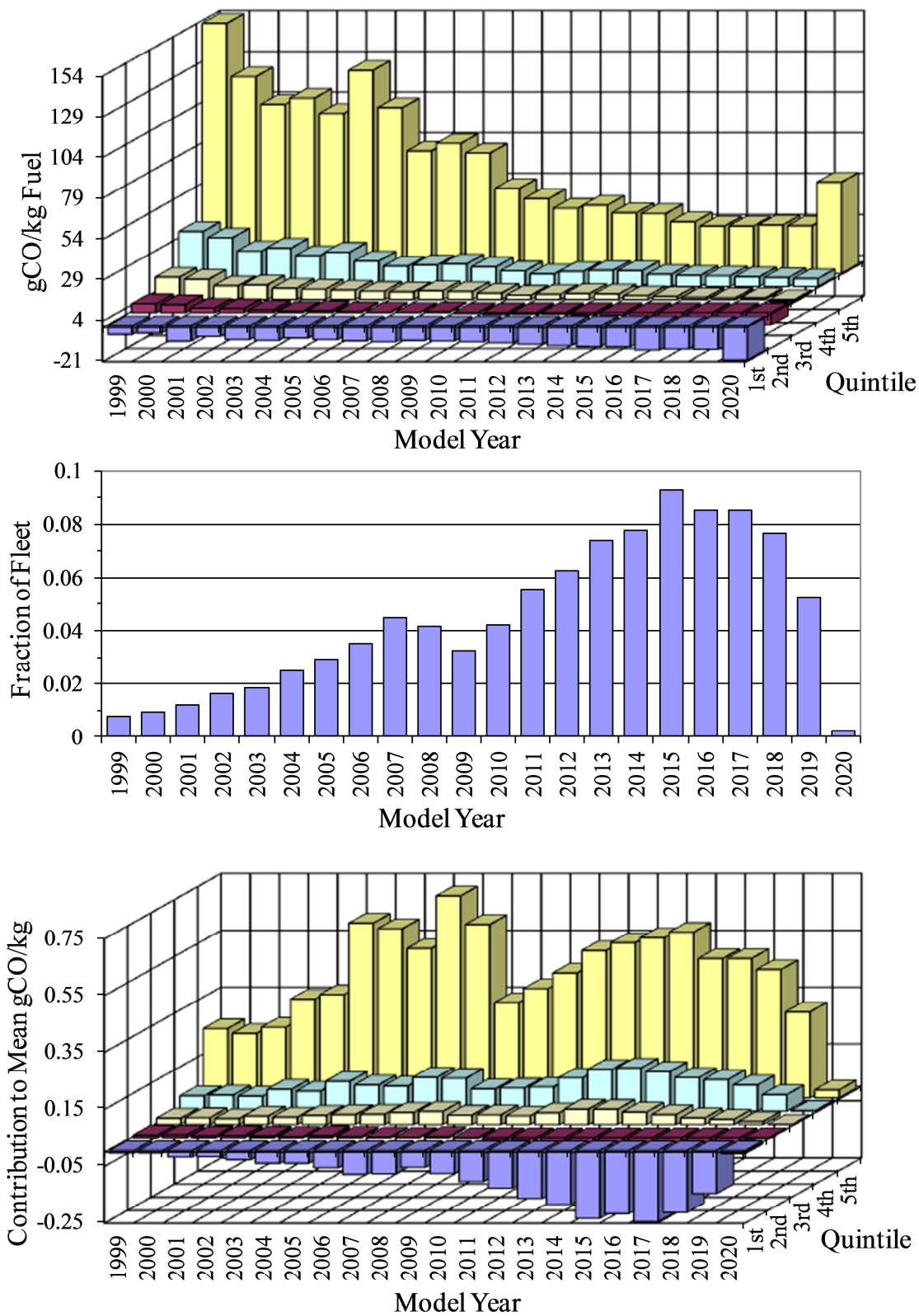


Figure 4. Mean gCO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gCO/kg of fuel emissions by model year and quintile (bottom).

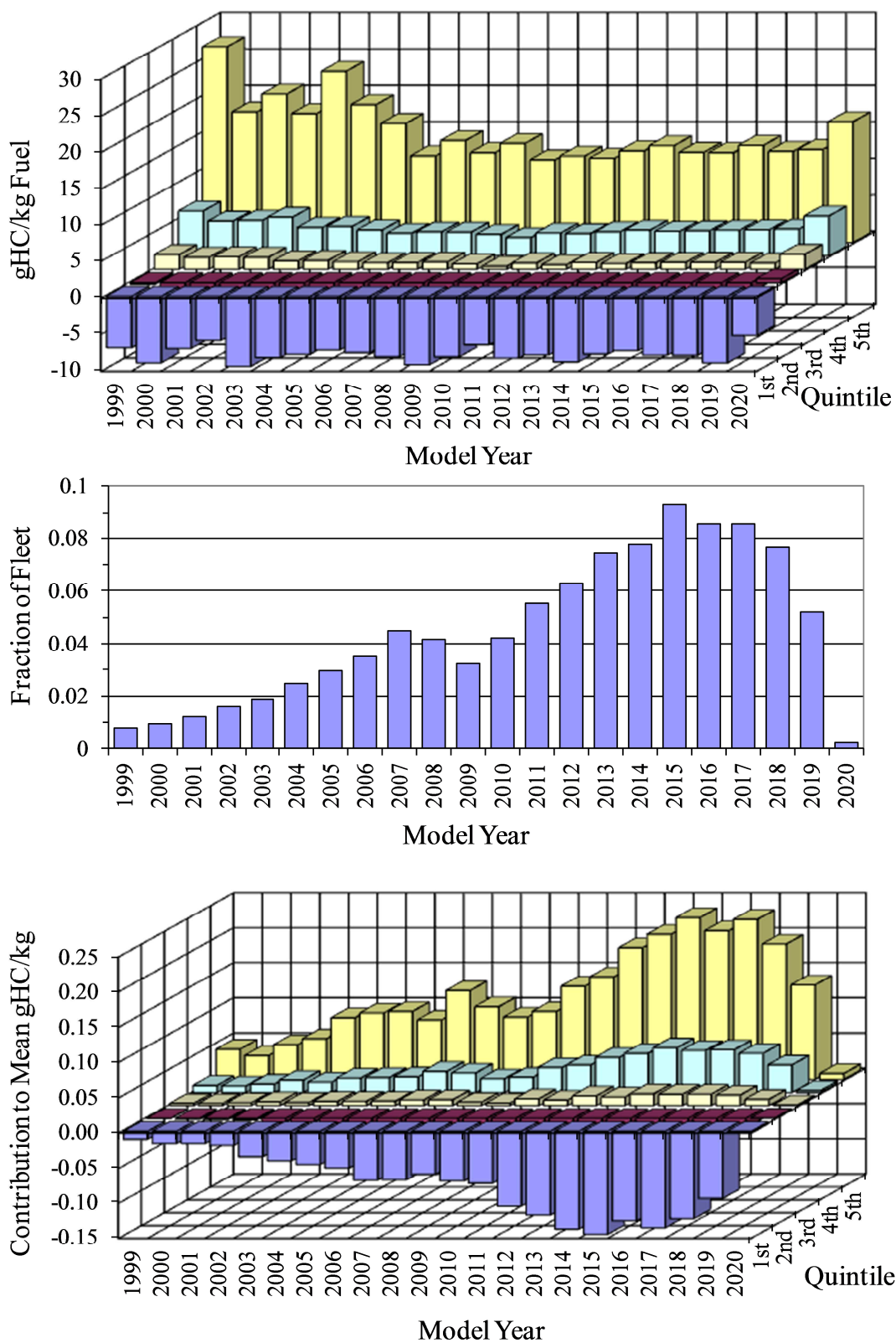


Figure 5. Mean gHC/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gHC/kg of fuel emissions by model year and quintile (bottom).

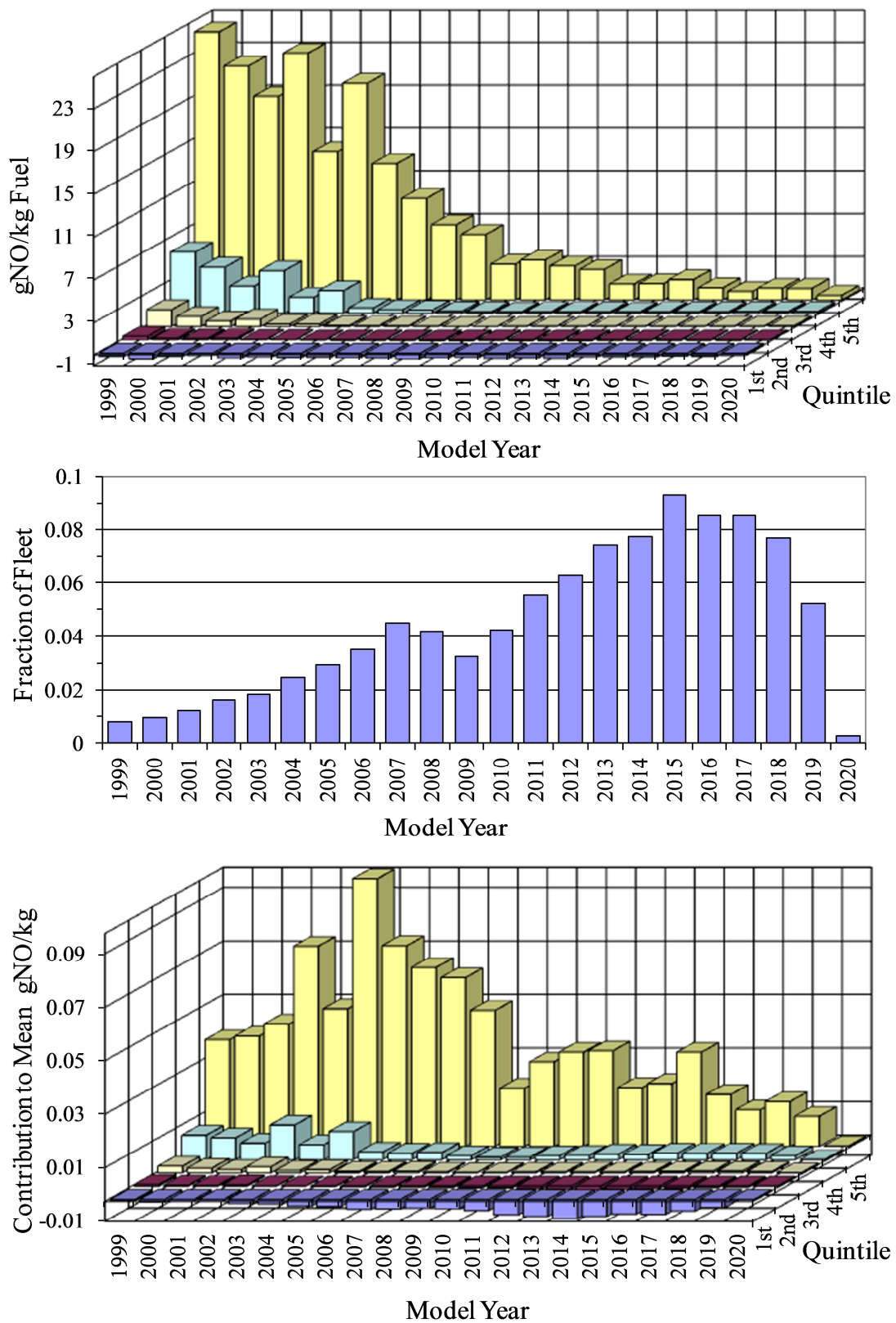


Figure 6. Mean gNO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gNO/kg of fuel emissions by model year and quintile (bottom).

regardless of model year, make an essentially negligible contribution to the overall fleet mean emissions. The top and bottom graph for the NO emissions is perhaps the most striking. As previously mentioned, the introduction of Tier 2 vehicles in 2009 and Tier 3 in 2017 has essentially eliminated NO emission increases due to age. This has resulted in prior model years now responsible for the majority of fleet NO emissions (see top graph in Figure 6). The emission levels of the highest emitting Tier 1 vehicles in the top quintile have expanded the y-axis so that the contribution of all the model years in the first four quintiles appears insignificant (see bottom graph in Figure 6). Selective catalytic reduction systems were introduced starting with 2009 diesel vehicles and one can see the differences in emission levels in the fifth quintile where those vehicles first appeared.

The accumulations of negative emissions in the first two quintiles are the result of continuing decreases in emission levels. Our instrument is designed such that when measuring true zero emission plumes (a ratio of zero), a normal distribution around zero will occur with approximately half of the readings negative and half positive. As the lowest emitting segments of the fleets continue to trend toward zero emissions, the negative emission readings will continue to grow toward half of the measurements. This is best seen in the HC quintile plot where the newest model years have essentially reached this distribution.

The middle graph in Figures 4 – 6 shows the fleet fractions by model year for the 2019 Tulsa database. The impact of the 2008 recession and the resultant reduction in light-duty vehicle sales is still visible in the 2019 data (for a review of this impact, please see the 2013 Tulsa report and other recent publications).^{23, 24} The Tulsa fleet was more resilient at the time than either fleets in Denver or West Los Angeles 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 2019 fleet's age increasing again by 0.1 model years to 8.1 years old.

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 a vehicle's engine'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 NO or hydrogen 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

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 2019 data set we now have 5 Tulsa data sets that can be used to look at the changes in NH_3 emissions. Figure 7 compares gNH_3/kg of fuel emissions collected at the Tulsa site for all five measurement campaigns by model year. The earliest data sets show the characteristic shape with NH_3 emissions increasing with model year until the vehicles reach an age where the catalyst can no longer catalyze the reduction reaction and emissions start decreasing. 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 four data sets for which those model years are present which suggests it is a real difference and we currently have no explanation for this observation.

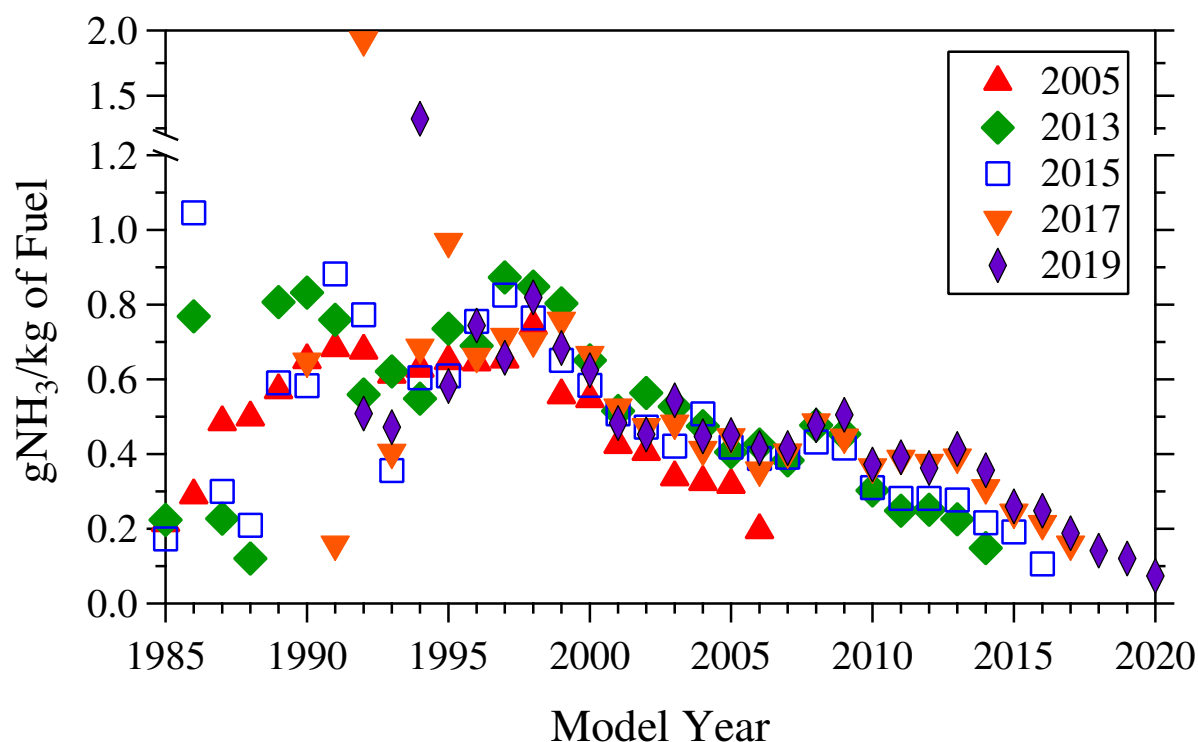


Figure 7. Mean gNH_3/kg of fuel emissions plotted against vehicle model year for the five measurement data sets collected at the Tulsa site with a split y-axis.

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 8 compares the five Tulsa data sets in this way where year 0 vehicles are 2020, 2018, 2016, 2014 and 2006 models for the 2019, 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.

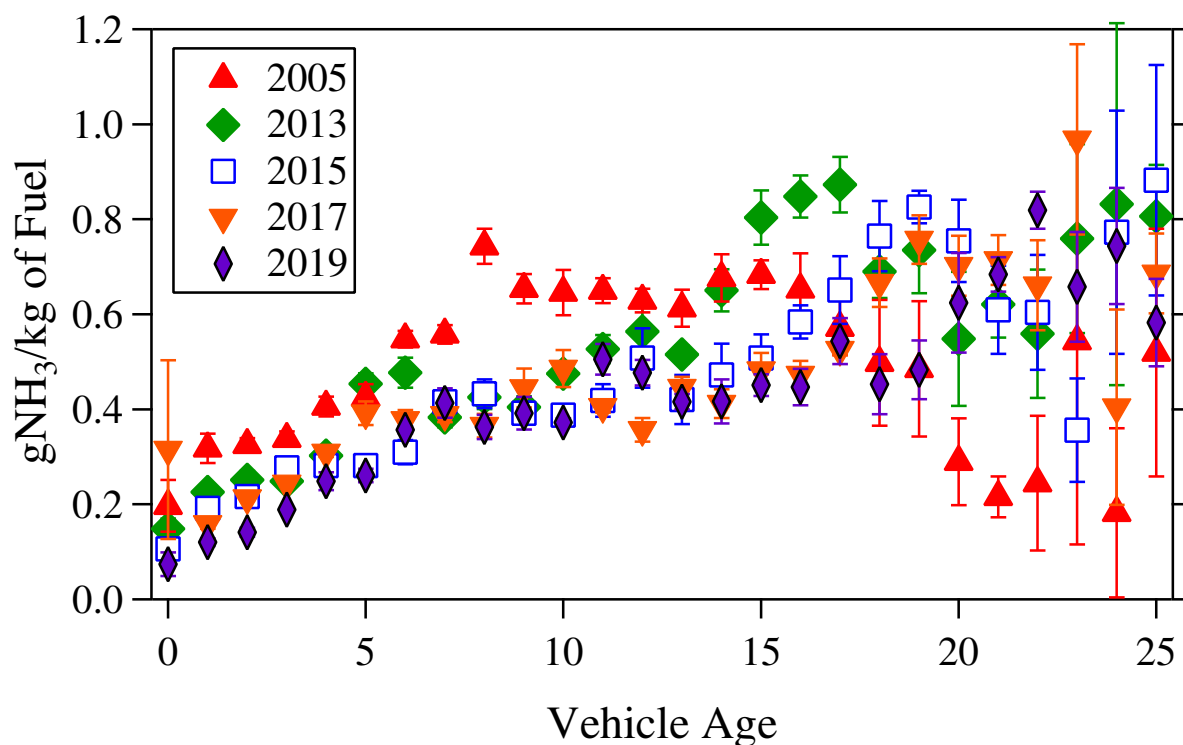


Figure 8. Mean gNH₃/kg emissions plotted against vehicle age for the 2019, 2017, 2015, 2013 and 2005 measurements at the Tulsa site. The uncertainty bars plotted are the standard error of the mean determined from the daily samples.

The differences between the data sets in Figure 8 are more obvious. The lower rate of increase in NH₃ emissions as a function of vehicle age seen initially with the 2013 data set is still a feature of the 2019 data. Tier 3 vehicles phased into the vehicle fleet with the 2017 model year and these vehicles appear to continue the trend of lower NH₃ emissions in the 1 to 4 year old vehicles. For example since 2013 NH₃ emissions of one year old vehicles have declined by 47% (0.23 to 0.12 gNH₃/kg of fuel). Since NO emissions have also remained extremely low (see Figure 3) in these models it suggests that control of engine out NO emissions have been further improved.

While the rate of increase has slowed it appears that the average vehicle age at which NH₃ emissions peak and then begin to decrease keeps getting older. The unique shape of the NH₃ 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 converters follow. The period of increasing NH₃ emissions has grown with each successive measurement campaign since 2005. 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 at other sites since 2008.³³ The 2015 and 2017 data sets appear to not peak until at least ~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. It is debatable whether the 2019 data set has a peak emissions indicating catalyst lifetimes well beyond 20 years. Certainly declining fuel sulfur levels have improved the

longevity of catalytic converters, and sulfur levels were again decreased with the introduction of Tier 3 fuels. This undoubtedly is a contributing factor in these NH₃ emission trends.

With the 2019 measurement campaign we have now collected 5 data sets with fuel specific NH₃ emissions and the means and standard error of the mean uncertainties are listed in Table 4. Ammonia emissions have experienced an overall 32% reduction in emissions over these fourteen years. This translates to a -1.2% year over year percent change in NH₃ emissions. During this same time span NO emissions at this Tulsa site have decreased by 62% (2.9 gNO/kg in 2005 to 1.1 gNO/kg in 2019). It is not understood why NO emissions have decreased more during this same time period than NH₃ since they have a common origination point in engine out NO emissions. Unlike NO emissions, NH₃ emissions are not near zero in the newest vehicles (see Figures 7 and 8) and with longer catalyst life more vehicles are contributing to the mean emissions today. Fuel changes might also be a contributing factor, as fuel sulfur levels have decreased significantly during this period, but laboratory research on the fuel effects of NH₃ emissions is contradictory, due in part to the small number of vehicles tested.^{26, 35} Driving mode and catalyst age and formulation are two additional factors discussed in the literature that impact NH₃ emissions and might be involved in the answer to this question.^{27, 35} Also as previously mentioned NH₃ 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.

Table 4. Mean Fuel Specific Ammonia Emissions with Standard Error of the Mean Uncertainties for the Five Tulsa Measurement Campaigns.

Measurement Year	Mean gNH ₃ /kg of Fuel
2005	0.5 ± 0.01
2013	0.43 ± 0.01
2015	0.37 ± 0.001
2017	0.37 ± 0.005
2019	0.34 ± 0.01

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

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

where VSP is the vehicle specific power in kW/metric tonne, *slope* is the slope of the roadway (in degrees), *v* is vehicle speed in mph, and *a* is vehicle acceleration in mph/s. 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 six 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 9. Each of the specific power bins contains at least 125 measurements, except

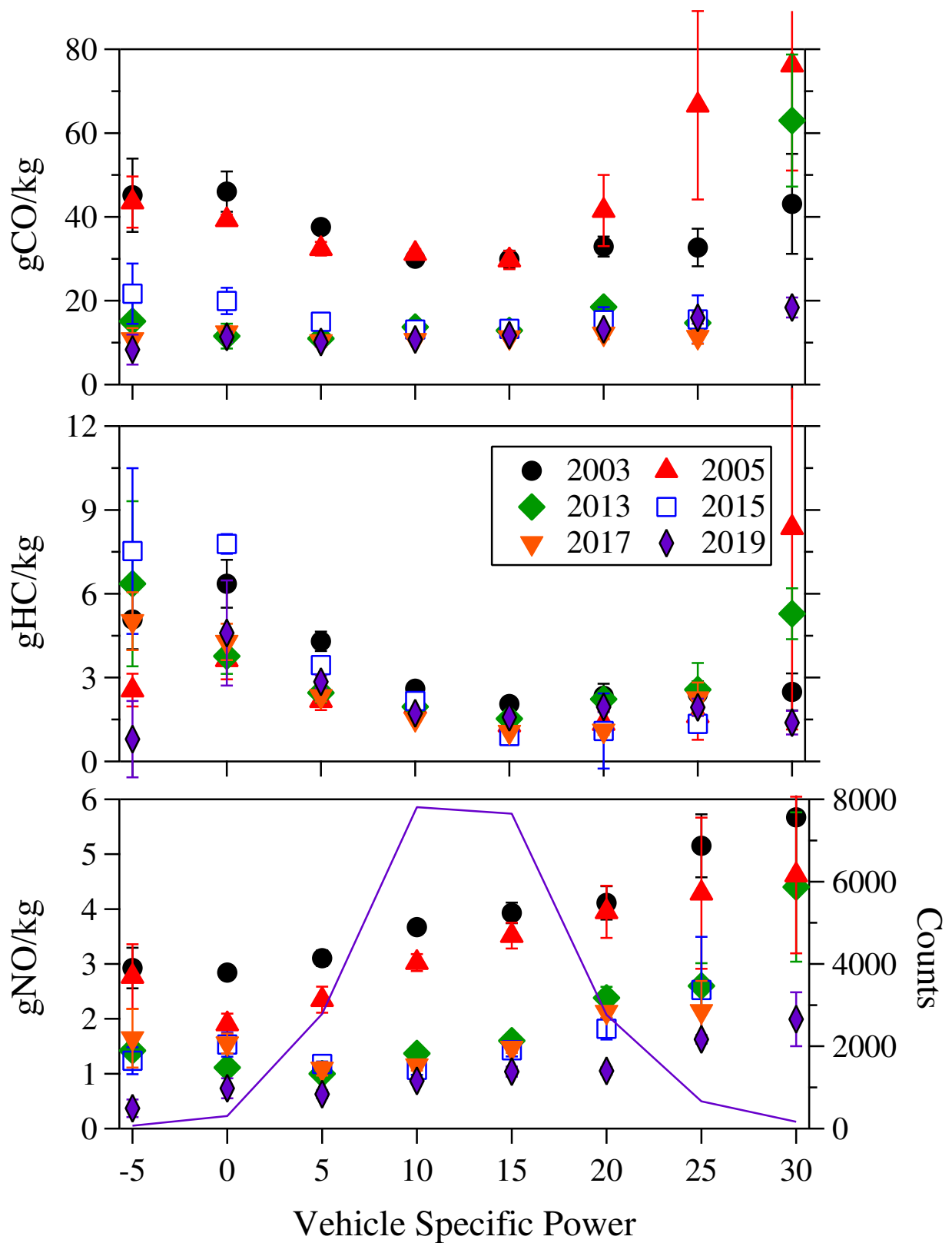


Figure 9. Vehicle emissions as a function of vehicle specific power for all of the Tulsa data sets. Uncertainties plotted are standard error of the mean calculated from the daily samples. The solid line without markers in the bottom graph is the vehicle count profile for the 2019 data.

for the 25 VSP bin in 2005 which only contains 57 measurements and the -5 VSP bin in 2019 which contains 69 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. The solid line in the bottom graph is the frequency count distribution of vehicles in the 2019 dataset sorted by specific power bin.

Within each vehicle specific power bin there have been significant reductions in mean emissions of CO and NO with the largest occurring between the 2003 and 2013 datasets. Between VSP bins 5 and 20, where the majority of the measurement occur, there have been significantly smaller reductions for CO since 2013. However, NO has continued to see significant emission reductions between these VSP's that have lowered the rate of emission increases with increasing VSP. This can be seen in that even though the 2019 fleet had a 24% increase in mean VSP, driven by an increase in the average acceleration (see Table 3), mean NO emissions still decreased. There have been smaller reductions observed between the various HC data sets.

To emphasize the small influence that VSP now has on mean emissions Table 5 compares the mean emissions for the last 4 Tulsa campaigns. Listed are the measured mean emissions for the vehicles with a valid speed measurement and an adjusted mean that has been calculated to match the driving mode observed in the 2013 campaign. This makes the 2013 values equal since there is no adjustment for that year. In general all of the campaigns prior to 2019 had similar VSP driving distributions and the adjusted mean emissions change little. However, despite the larger change in VSP between the 2017 and 2019 campaigns the differences in the 2019 adjusted means are all still less than 10% (4.3% CO, 9.5% HC and 8.4% NO) and are not statistically different from the measured means.

Table 5. Vehicle specific power emissions with standard error of the mean calculated using daily averages and means adjusted to the 2013 VSP distribution^a.

Year	Mean gCO/kg Measured (Adjusted)	Mean gHC/kg ^a Measured (Adjusted)	Mean gNO/kg Measured (Adjusted)
2013	13.2 ± 1.3 (13.2 ± 1.3)	2.1 ± 0.3 (2.1 ± 0.3)	1.4 ± 0.2 (1.4 ± 0.2)
2015	14.3 ± 1.3 (14.2 ± 1.3)	2.5 ± 0.8 (2.4 ± 0.8)	1.3 ± 0.2 (1.3 ± 0.2)
2017	10.9 ± 0.3 (10.9 ± 0.3)	1.7 ± 0.4 (1.7 ± 0.4)	1.3 ± 0.2 (1.3 ± 0.2)
2019	11.6 ± 0.3 (11.1 ± 0.3)	1.9 ± 0.3 (2.1 ± 0.3)	0.95 ± 0.15 (0.87 ± 0.14)

^a2013 VSP distribution constructed combining all readings below -5 into the -5 bin and all readings above 25 into the 25 bin (see Appendix E).

The Cherokee Nation has kindly provided us with vehicle information in 2019 and we have repeated the emission comparison with Oklahoma plates that was included in previous reports. Table 6 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 6.8% of the matched plates and is newer. Mean fuel specific emissions are similar between the two fleets with all of the means except NO and NO_x 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 has lower or the same emissions for CO, HC and NO_x.

Table 6. 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	21,779	2011.8	15,288	11.7±0.3	1.9±0.1	1.1±0.05	0.34±0.01	1.7±0.1
Cherokee	1,597	2013.1	1597	10.7±1.1	1.8±0.2	0.7±0.1	0.3±0.01	1.2±0.2
US Age Adjusted to Cherokee Fleet				9.0	1.7	0.76	0.31	1.2

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 6.3, 3.9, 0.15, 0.04 and 0.22 for CO, HC, NO, NH₃ and NO₂, respectively. These values indicate standard deviations of 8.8 g/kg (0.07%), 5.5 g/kg (124ppm), 0.22 g/kg (17ppm), 0.057 g/kg (6ppm) and 0.32 g/kg (14ppm) for individual measurements of CO, HC, NO, NH₃ and NO₂, respectively. Noise levels for all species except NO₂ increased from the levels observed in the 2017 measurements. However, for CO and HC these levels still remain lower than the low noise level discussed in the Phoenix report.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 0.6 g/kg, 0.4 g/kg, 0.02 g/kg, 0.004 g/kg and 0.02 g/kg, respectively.

CONCLUSIONS

The University of Denver successfully completed the sixth year of a multi-year remote sensing study in Tulsa. Five days of fieldwork, September 9 – 13, 2019, were conducted on the uphill interchange ramp from westbound US64 (Broken Arrow Expressway) to southbound US169. A database was compiled containing 23,376 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 CO₂, and most records contained valid measurements for the other species as well. Of these measurements, 12,364 (52.9%) were contributed by vehicles measured only once, and the remaining 11,012 (47.1%) records were from vehicles measured at least twice.

The mean CO, HC, NO, NH₃ and NO₂ emissions for the fleet measured in this study were 11.6 gCO/kg of fuel (0.09%), 1.9 gHC/kg of fuel (69 ppm), 1.1 gNO/kg of fuel (76 ppm), 0.34 gNH₃/kg of fuel (42 ppm) and 0.02 g/kg of fuel (1 ppm) respectively. When compared with previous measurements from 2017 we find that mean CO (+5%) and HC (+12%) emissions increased while NO (-21%) and NH₃ (-8%) emissions changed showed the largest year over year decreases. The average fleet age again increased by 0.1 model years (2011.9) which is approximately 8.1 years old. 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 30%, 32%, 35%, 16 % and 100% of the CO, HC, NO, NH₃ and NO₂ emissions, respectively.

The Tulsa site was one of the first that the University of Denver collected NH₃ emissions from light-duty vehicles in 2005 and now has one of the longest running NH₃ measurement trends. With the 2019 measurement campaign we have now collected 5 data sets (2005, 2013, 2015, 2017 and 2019) and fuel specific NH₃ emissions have experienced an overall 32% reduction in emissions over these fourteen year (0.5 ± 0.01 to 0.34 ± 0.01 gNH₃/kg of fuel). This represents a percent year over year reduction of 1.2%. The peak NH₃ emissions are difficult to detect in the current data set but have certainly extended beyond the 20 year mark for estimated 3-way catalyst lifetimes. The NH₃ reduction rates are much smaller than observed for the tailpipe NO emissions which have decreased by 62% (2.9 to 1.1 gNO/kg of fuel) over the same time period.

We again investigated potential differences between vehicles registered with the Cherokee Nation and those registered in the State of Oklahoma. The Cherokee Nation fleet observed at this location is smaller making up only 6.8% of the overall matched plates but is more than a year newer (mean model year of 2013.1 versus 2011.8). Because of its age the Cherokee Nation fleet has lower mean emission for all of the species measured, 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 have lower or similar emissions for every species but NO and NH₃.

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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 $>0.25\%$ CO₂ in 8 cm path length. Often heavy-duty diesel trucks, bicycles.
- 2) Too much error on CO/CO₂ 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/CO₂ slope, equivalent to $\pm 20\%$ for HC >2500 ppm propane, 500ppm propane for HC <2500 ppm.
- 5) Reported HC <-1000 ppm propane or $>40,000$ ppm. HC “invalid”.
- 6) Too much error on NO/CO₂ slope, equivalent to $\pm 20\%$ for NO >1500 ppm, 300ppm for NO <1500 ppm.
- 7) Reported NO <-700 ppm or >7000 ppm. NO “invalid”.
- 8) Excessive error on NH₃/CO₂ slope, equivalent to ± 50 ppm.
- 9) Reported NH₃ <-80 ppm or >7000 ppm. NH₃ “invalid”.
- 10) Excessive error on NO₂/CO₂ slope, equivalent to $\pm 20\%$ for NO₂ >200 ppm, 40ppm for NO₂ <200 ppm
- 11) Reported NO₂ <-500 ppm or >7000 ppm. 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 $100\text{mph} > \text{speed} > 5\text{mph}$ and $14\text{mph/s} > \text{accel} > -13\text{mph/s}$ 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_19.dbf database.

The Tulsa_19.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.
V_class	Vin decoded vehicle type classification.
V_year	Vin decoded model year.
V_make	Vin decoded make.
V_model	Vin decoded model information
V_engine	Vin decoded engine type/model information
V_disp	Vin decoded engine displacement in liters
V_cylinder	Vin decoded number of engine cylinders
V_fuel	Vin decoded fuel (G, D, F (flex), N)
V_wtclass	Vin decoded weight class designation
V_type	Vin decoded Passenger (P) or Truck (T) type
Wt_class	Numeric weight class extracted from V_wtclass

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

Tulsa 2019 Temperature and Humidity Data										
Time	9/9 °F	9/9 %RH	9/10 °F	9/10 %RH	9/11 °F	9/11 %RH	9/12 °F	9/12 %RH	9/13 °F	9/13 %RH
5:53	76	74	75	79	77	77	76	79	70	100
6:53	76	74	76	77	77	77	77	79	71	96
7:53	80	64	77	77	79	74	79	74	72	97
8:53	85	59	81	69	82	67	82	67	73	94
9:53	88	55	82	69	85	59	85	63	75	90
10:53	88	57	85	63	87	57	88	57	77	82
11:53	91	50	86	63	89	53	91	52	78	82
12:53	93	46	88	59	91	50	91	52	78	82
13:53	92	49	90	52	90	50	92	51	79	74
14:53	92	49	90	54	90	50	92	51	79	77
15:53	93	44	91	50	91	49	91	52	81	67
16:53	92	43	91	50	90	48	91	52	80	64
17:53	91	42	89	53	89	52	89	53	79	72
18:53	88	48	83	72	87	57	73	89	76	79

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: 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 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 F: 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

2019 Tulsa (FEAT 3002)						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH ₃ Cal Factor	NO ₂ Cal Factor
9/9	8:30	1.60	1.58	1.38	0.86	0.86
9/9	10:35	1.32	1.31	1.22	0.89	0.81
9/9	13:10	1.18	1.15	1.08	0.91	0.81
9/10	7:15	1.72	1.67	1.47	0.89	1.19
9/10	8:40	1.58	1.53	1.37	0.94	1.16
9/10	11:10	1.34	1.32	1.15	0.96	0.98
9/10	13:50	1.22	1.21	1.06	0.96	0.89
9/11	7:15	1.77	1.72	1.44	0.79	1.31
9/11	8:40	1.53	1.51	1.33	0.91	1.12
9/11	11:00	1.30	1.27	1.17	0.91	0.94
9/11	13:25	1.22	1.20	1.13	0.94	0.95
9/12	7:15	1.71	1.67	1.38	0.79	1.38
9/12	8:40	1.58	1.53	1.30	0.89	1.15
9/12	11:00	1.29	1.25	1.15	0.97	0.94
9/12	13:15	1.20	1.19	1.10	1.01	0.95
9/13	7:25	2.12	2.04	1.86	0.82	1.55
9/13	8:45	1.77	1.70	1.57	0.86	1.35
9/13	11:00	1.63	1.61	1.45	0.88	1.25
9/13	12:20	1.54	1.52	1.34	0.91	1.12