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# ON-ROAD REMOTE SENSING OF AUTOMOBILE EMISSIONS IN THE TULSA AREA: FALL 2015

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# On-Road Remote Sensing of Automobile Emissions in the Tulsa Area: Fall 2015

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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 2015. The remote sensor used in this study measures the ratios of CO, HC, NO, $SO_2$ and $NH_3$ to $CO_2$ in motor vehicle exhaust. From these ratios, we calculate the percent concentrations of CO, $CO_2$, HC, NO, $SO_2$ and $NH_3$ 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. 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 14 – 18, 2015, 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 and 2013. We did experience an equipment failure on Friday morning September 18 which cut the sampling week short by about a half day. A database was compiled containing 19,601 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 mean CO, HC, NO, $NH_3$ and $NO_2$ emissions for the fleet measured in this study was 14.3 g/kg (0.11%), 2.4 g/kg (64ppm), 1.4 g/kg (96ppm), 0.37 g/kg (46ppm) and 0.13 g/kg (6ppm) respectively. When compared with previous measurements from 2013 we find that mean CO (+6%) and HC (+13%) emissions slightly increased while NO (-7%) and $NH_3$ (-14%) emissions have slightly declined. The average fleet age increased 0.1 model years (2008.2) to 7.9 years. 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 new slowdown in new car purchases with the percentage of one year old vehicles lagging the 2013 levels. While the fleet age increase is part of the explanation for mixed results in emission changes the 2015 measurements most significant contributor is the simple fact that there are more 14 year old and older vehicles in this database than previously seen. Fleet mean emissions are still dominated by a few high emitting vehicles and for the 2015 data set the highest emitting 1% of the measurements are responsible for 26%, 34%, 28%, 16 % and 30% 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. The $NH_3$ mean emissions observed in 2005, 2013 and 2015 were 0.5 ± 0.01, 0.43 ± 0.01 and 0.37 ± 0.001 g/kg of fuel respectively, which is a 26% reduction in emissions over ten years. In addition the peak $NH_3$ emissions increased by an additional two years with the peak occurring now around 19 year old vehicles. The emissions reductions have likely been negatively impacted by the aging of the light-duty fleet due to the 2008-2010 recession. We attempted to estimate these impacts by applying the age distribution from the 2005 measurements to the 2015 data to produce a 2015 fleet with the same age as the 2005 fleet and

this lowers the 2015 measured mean $gNH_3$/kg of fuel to 0.34, an additional 7% reduction when compared with the 2015 mean. The rate of reduction measured in Tulsa over a ten year period is smaller than reduction rates previously reported by Kean et al. in the Caldecott tunnel in California between 1999 and 2006 of 38% ± 6%. 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 2015) over the same time period.

We 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 4.2% of the matched plates and newer (mean model year of 2009.7 versus 2008.1). One interesting observation is that the oldest model year vehicle from the Cherokee fleet is from only 1992. Why they seem to stop at this point is curious but does not seem to be related to a poor registration match as only 2 out of the 650 plates that were submitted came back as unmatchable. Because of the younger fleet the Cherokee Nation fleet has lower mean emission for all of the species however, they have larger uncertainties due to the small sample size and the differences appear to only be statistically significant for $NH_3$. In addition when the Oklahoma plated vehicles are age adjusted to match the age of the Cherokee fleet the Oklahoma fleet is actually slightly lower emitting for every species but $NH_3$.

Tulsa is unique in the emissions measurement world because it is one of the few large metropolitan areas whose vehicles have never been subject to any type of emissions inspection and maintenance program (I/M). Because of that fact it is always interesting to see how Tulsa's fleet compares to other cities fleets that do have programs. We therefore compared the 2015 Tulsa data with recent data collected in Denver CO by plotting mean emissions by model year for each city against one another. The Denver I/M program exempts vehicles from testing for their first six years of life and then they are tested every other year after that. The Tulsa site has slightly higher CO emissions for all model years and Denver has higher HC emissions for most model years. For both species the trends observed in the first six model years are carried through the remaining model years indicating that site driving mode is the most likely explanation for the differences observed. For NO the data more closely hug the 1:1 line and the Denver site has higher $NH_3$ emissions though $NH_3$ is an unregulated species.

We also compared each cities $99^{th}$ percentiles for CO and HC. Finding statistically significant differences in fleet means is difficult as not all of the vehicles measured in the Denver area participate in the program because they are not registered within the six county program area. However, because of this fact if a program is to be successful it should not be sufficient for it to just reduce emission from vehicles that agree to participate but should actually reduce fleet emissions for the program area. The $99^{th}$ percentile is an extreme statistic that for vehicle CO and HC emissions is occupied entirely by broken or mal-maintained vehicles that have excess emissions. If a regions I/M program has any effect on reducing fleet emissions it should be apparent by reducing the magnitude of the $99^{th}$ percentile vehicles. Both plots for CO and HC emissions show similar $99^{th}$ percentiles between the two cities indicating that broken vehicles in Tulsa look much like broken vehicles in Denver.

## 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, and ground-level ozone, a major component of urban smog, is produced by the photochemical reaction of nitrogen oxides ($NO_x$) and hydrocarbons (HC). Ambient levels of particulate emissions can result either from direct emissions of particles or semi-volatile species or from secondary reactions between gaseous species, such as ammonia and nitrogen dioxide. As of 2010, on-road vehicles were estimated to still be one of the larger sources for the major atmospheric pollutants, contributing approximately 44% of the CO, 34% of the VOC's, 8% of the $NH_3$ and 34% 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 of course 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, 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, and with the new 8 hour ozone standards introduced by the EPA in 1997 and tightened again in 2008, many more locations are likely to have some 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 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.

Reflecting a desire to continue evaluating the historical and recent emissions trends several of the previous E-23 sites have been chosen for additional data collection. This report describes the on-road emission measurements taken in the Tulsa, OK area in the fall of 2013, under CRC Contract No. E-106. Measurements were made on five consecutive weekdays, from Monday, September 30, to Friday, October 4, between the hours of 7:00 and 19:00 on the uphill interchange ramp from westbound US64 (Broken Arrow Expressway) to southbound US169. Measurements have previously been collected at this same location in 2003 and 2005 with the only differences being

that the 2005 measurements utilized a different Fuel Efficiency Automobile Test (FEAT) NDIR detector (No. 3004).

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 I/M program. 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.[7-9] 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.[10] 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.[11] 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:

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

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, 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.[11]

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

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). These calibrations account for day-to-day variations in instrument sensitivity and variations in ambient $CO_2$ levels caused by local sources, atmospheric pressure and instrument path length. Since propane is used to calibrate the instrument, all hydrocarbon measurements reported by the remote sensor are reported as propane equivalents.

Studies sponsored by the California Air Resources Board and General Motors Research Laboratories have shown that the remote sensor is capable of CO measurements that are correct to within ±5% of the values reported by an on-board gas analyzer, and within ±15% for HC.[12, 13] The NO channel used in this study has been extensively tested by the University of Denver, but we are still awaiting the opportunity to participate in an extensive blind study and instrument intercomparison to have it independently validated. Tests involving a late-model low-emitting vehicle indicate a detection limit ($3\sigma$) of 25 ppm for NO, with an error measurement of ±5% of the reading at higher concentrations.[8] 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.[14] 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 2015, from Monday, September 14, to Friday, September 18, 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 is shown in Figure 2.

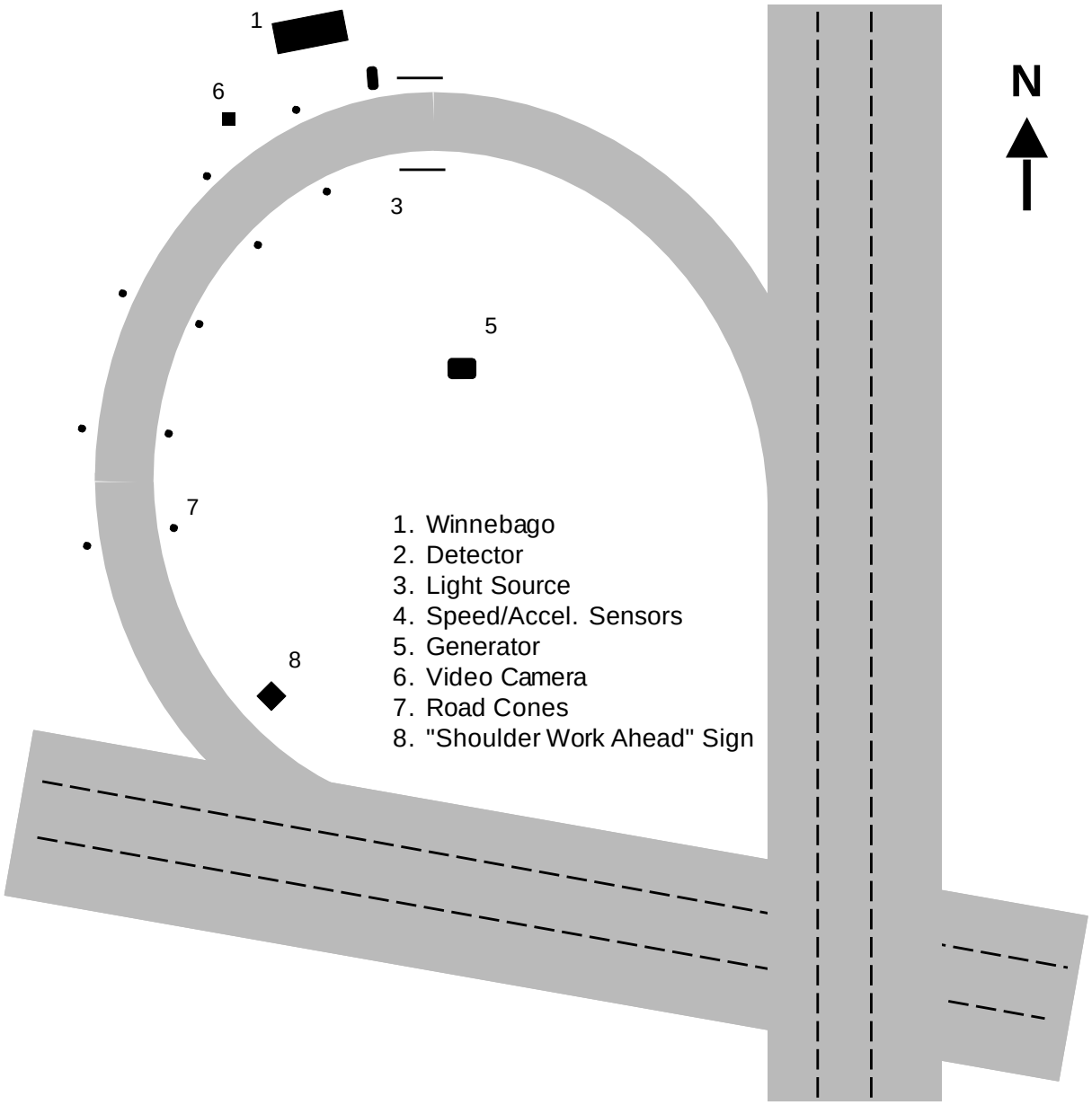


Figure 1. A schematic drawing of the ramp from Westbound US64 (Broken Arrow Expressway) to Southbound US169. The location and safety equipment configuration was for all five days of measurements.

Figure 2. Tulsa 2013 monitoring site looking west toward downtown Tulsa.

Appendix C gives temperature and humidity data for the study obtained from Tulsa International Airport, approximately ten miles north of the measurement site. Data collection was cut short on Friday September 18 due to equipment failure with what turned out to be a dead power supply.

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. 2003 was the last year that we made an effort to code for the various tribal nations. At that time we had success working with two nations, the Cherokee and the Muskogee Creek. Because of the equipment problems that cut short measurements on the last day we decided to transcribe and match Cherokee nation plates, which was the largest fleet from 2003, to bolster the number of total measurements in the database. The resulting 2015 database contains 19,601 records (19,306 from Oklahoma and 827 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 $NO_2$. The database and all previous databases compiled for CRC E-23 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 data collection. If the data collection period is interrupted by another beam block from a closely following vehicle, the 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 and vehicles with unreadable plates (obscured, missing, dealer, out of camera field of view) 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.

**Table 1.** Validity Summary.

| | CO | HC | NO | $NH_3$ | $NO_2$ |
|---|---|---|---|---|---|
| Attempted Measurements | 27,024 | | | | |
| Valid Measurements | 25,199 | 25,008 | 25,196 | 25,181 | 24,898 |
| Percent of Attempts | 93.2% | 92.5% | 93.2% | 93.2% | 92.1% |
| Submitted Plates | 20,133 | 20,004 | 20,131 | 20,119 | 19,894 |
| Percent of Attempts | 74.5% | 74.0% | 74.5% | 74.4% | 73.6% |
| Percent of Valid Measurements | 79.9% | 80.0% | 79.9% | 79.9% | 79.9% |
| Matched Plates | 19,601 | 19,475 | 19,599 | 19,587 | 19,367 |
| Percent of Attempts | 72.5% | 72.1% | 72.5% | 72.5% | 71.7% |
| Percent of Valid Measurements | 77.8% | 77.9% | 77.8% | 77.8% | 77.8% |
| Percent of Submitted Plates | 97.4% | 97.4% | 97.4% | 97.4% | 97.4% |

Table 2 provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured. Of the 19,601 records used in this fleet analysis, 10,496 (53.5%) were contributed by vehicles measured only once, and the remaining 9,105 (46.5%) records were from vehicles measured at least twice.

**Table 2.** Number of measurements of repeat vehicles.

| Number of Times Measured | Number of Vehicles |
|---|---|
| 1 | 10,496 |
| 2 | 2,013 |
| 3 | 895 |
| 4 | 374 |
| 5 | 95 |
| 6 | 42 |
| 7 | 17 |
| >7 | 6 |

Table 3 summarizes the data from the current and previous measurements collected at the same site in 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 vehicles, and assuming that these vehicles emit negligible levels of hydrocarbons, using the lowest of either of these values as the offset. The offset adjustment subtracts this value from all of the hydrocarbon data. This normalizes each data set to a similar emissions point since we assume the cleanest vehicles to 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, but are not included in the finalized databases.

The 2015 Tulsa measurements show inconsistent changes in mean emission levels for the first time. CO and HC emissions both show slight increases along with the mean age of the fleet (7.8 to 7.9 years old). The HC offset to normalize the 2015 Tulsa data set is much larger than usual and we cannot help but wonder if this is related to the instrument hardware problems that we experienced during sampling. NO and $NH_3$ show slight decreases of 7 and 14%. The percent of emissions contributed by the highest emitting 1% of the fleet (the $99^{th}$ percentile) is consistent with the pattern of the mean emissions with the contribution for CO and HC dropping and NO and $NH_3$ increasing.

An inverse relationship between vehicle emissions and model year is shown in Figure 3 for the four periods sampled in calendar years 2003, 2005, 2013 and 2015. The HC data have been offset adjusted here for comparison. Since 2005 fleet average emissions in Tulsa by model year have crept up slowly. The two most recent data sets have considerable uncertainty in the mean emission levels for model years 1995 and older because of the small sample sizes. All three species graphed in Figure 3 show an ever increasing number of years with emission levels that are not significantly different from zero. NO emissions are the quickest to rise but as more and more Tier II certified vehicles enter the fleet we would expect this graph to begin to look more and more like the CO and HC graphs.

Following the data analysis and presentation format originally shown by Ashbaugh et al.,[15] the vehicle emissions data by model year from the 2015 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 20 model years showing the impacts the last recession had on car sales between 2009 and 2010 and the likely effects of the oil and gas downturn on 2015 models. Model years older than 1996 and not graphed account for ~2% of the measurements and contribute between 9.6% (HC) and 16% (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 emissions. The

**Table 3.** Data Summary.

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

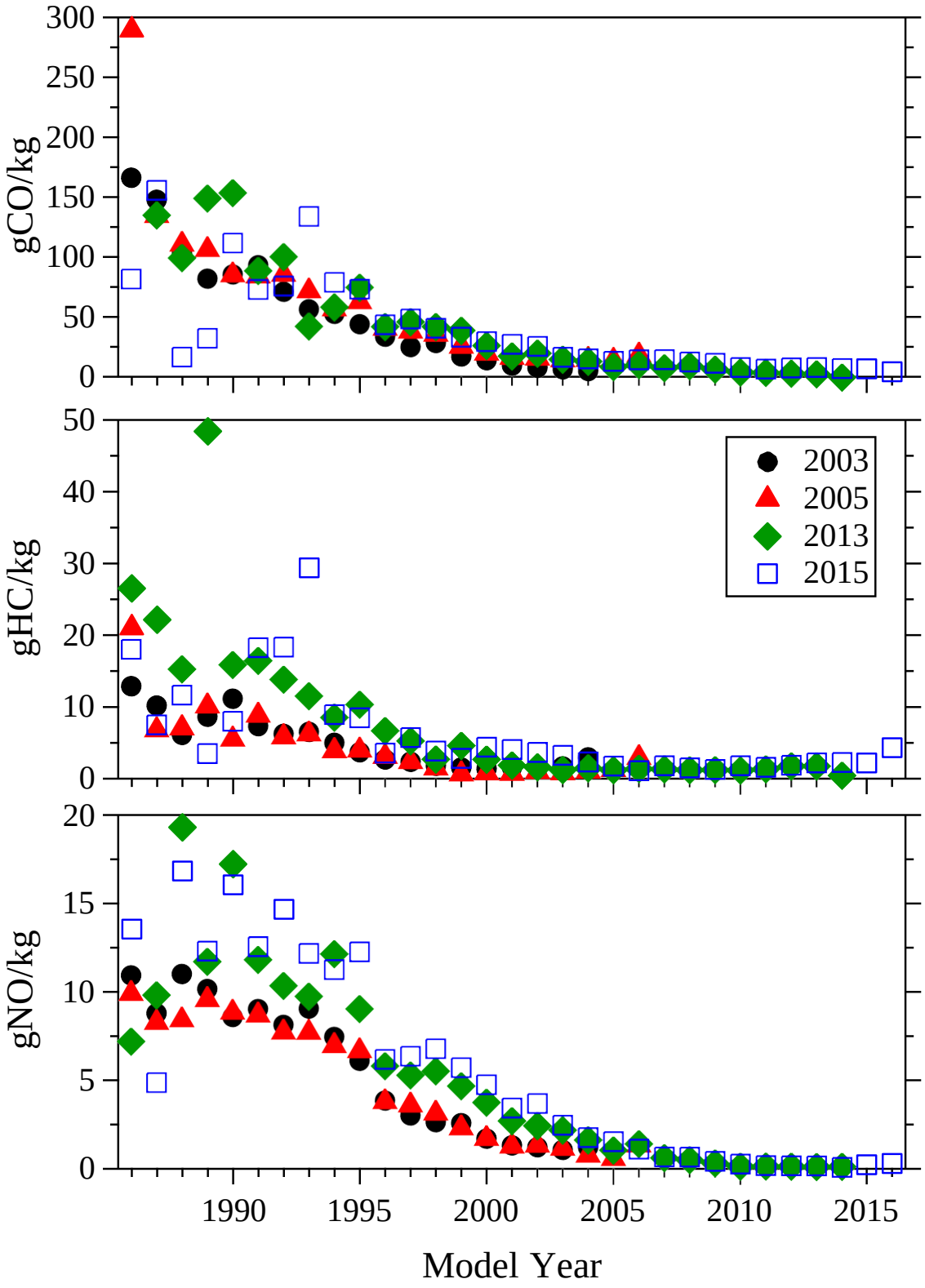


Figure 3. Mean fuel specific vehicle emissions plotted as a function of model year for the four Tulsa data sets, 2003 (circles), 2005 (triangles), 2013 (diamonds) and 2015 (squares). HC data have been offset adjusted as described in the text.

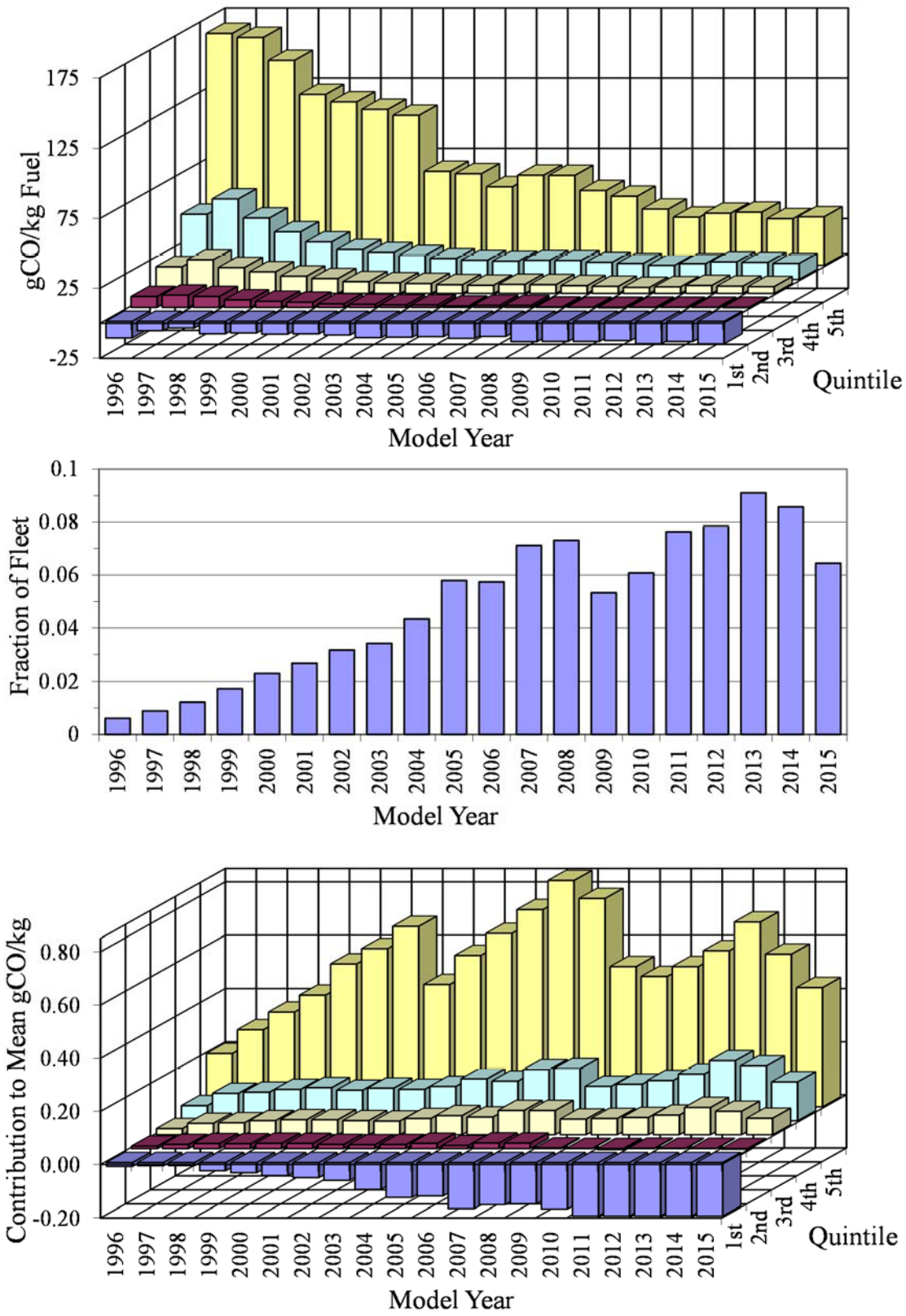


Figure 4. Mean gCO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gCO/kg of fuel emissions by model year and quintile (bottom).

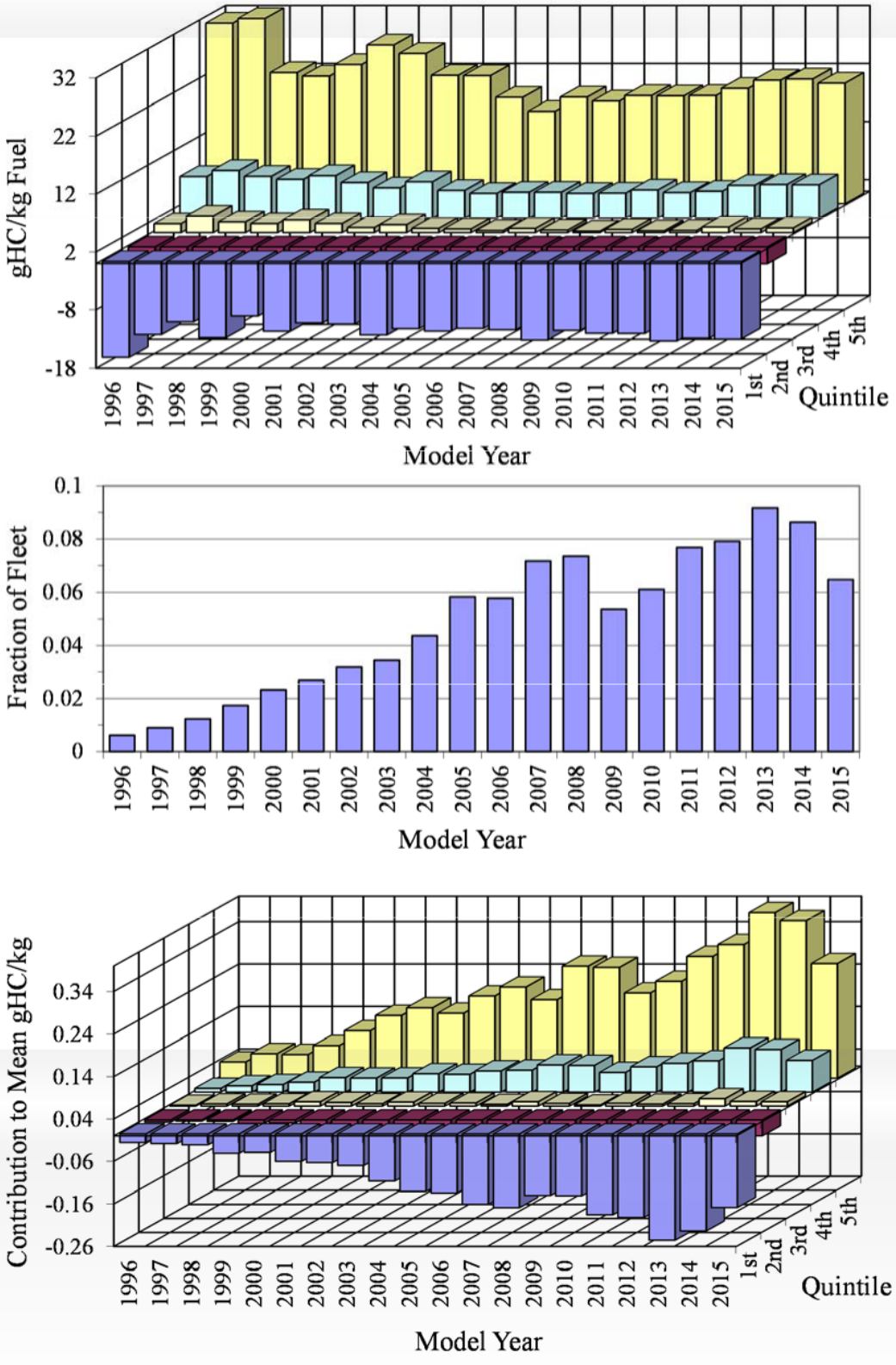


Figure 5. Mean gHC/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gHC/kg of fuel emissions by model year and quintile (bottom).

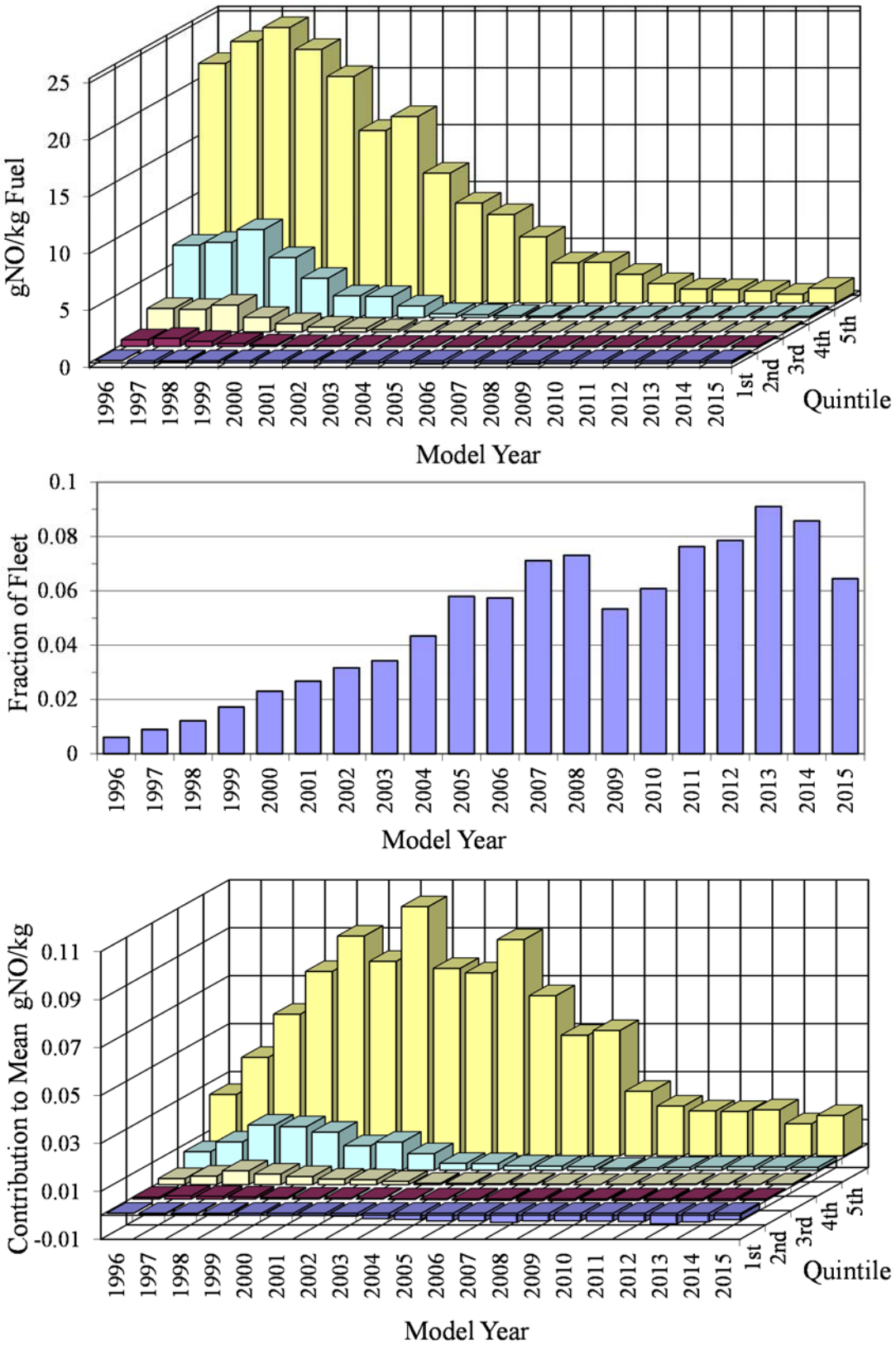


Figure 6. Mean gNO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gNO/kg of fuel emissions by model year and quintile (bottom).

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), half of the readings will be negative and half will be positive. As the lowest emitting segments of the fleets continue to dive toward zero emissions, the negative emission readings will continue to grow toward half of the measurements.

The middle graph in Figures 4 – 6 shows the fleet fractions by model year for the 2015 Tulsa database. The impact of the 2008 recession and the resultant reduction in light-duty vehicle sales was discussed extensively in the 2013 Tulsa report and a recent publication.[16] Of the three cities discussed, Tulsa was the most resilient 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. We have recent data from the west Los Angeles site showing a slow recovery with fleet ages decreasing slightly (0.2 model years between 2013 and 2015). However, the 2015 Tulsa data show that this fleet did not keep up with the passing of time and its age has increased slightly (0.1 model years) since the last visit in 2013.

Figure 7 is a plot of fleet percentage by vehicle age for the 2013 and 2015 Tulsa data sets. The cavity created by the 2008 recession has moved 2 years with the 2009 model year vehicles now being 7 years old. Figure 8 is a plot of cumulative fleet age in year's verses vehicle age in years to help show where the age differences lie between the 2013 and 2015 data sets. Starting with 7 year old vehicles the 2015 data set is a slightly younger fleet but starting around 14 year old vehicles the 2015 data set has consistently more vehicles than the 2013 data set leading to a slightly older fleet (If you compare the bars in Figure 7 carefully you can see this). The location of these age differences is a major contributing factor to the slight increases in CO and HC emissions observed in the 2015 data set.

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.[17] Ammonia is most often associated with farming and livestock operations but it can also be produced by 3-way catalyst equipped vehicles.[18] 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 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.[19] 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 Tulsa and by Kean et al in 1999 and 2006 from the Caldecott tunnel near Oakland.[20-23] 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.[24, 25] In addition air borne measurements of ammonia were collected in 2010 over the South Coast Air Basin as part of the CalNex campaign.[26] Most recently we have reported on ammonia emissions that we collected in 2013 from the West LA site, Denver and this Tulsa site.[27]

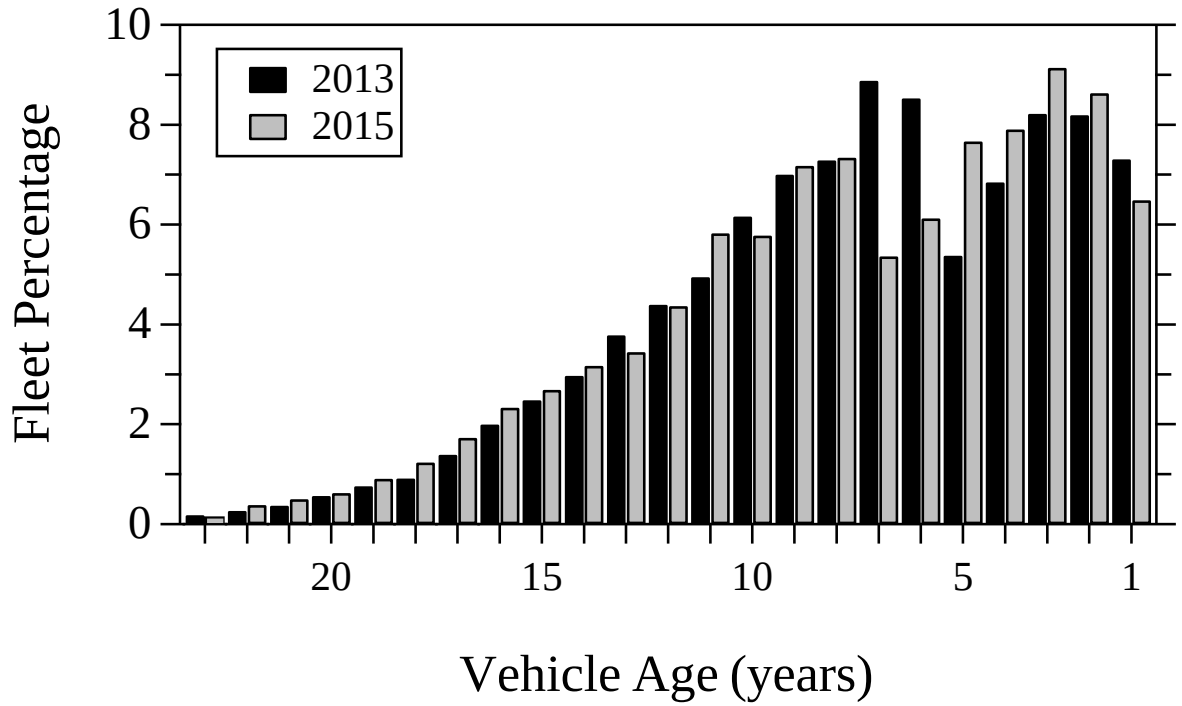


Figure 7. Fleet percentages plotted by vehicle age for the 2013 (black bars) and 2015 (grey bars) Tulsa data sets. One year old vehicles represent the 2013 and 2015 model years in the 2013 and 2015 data sets, respectively.

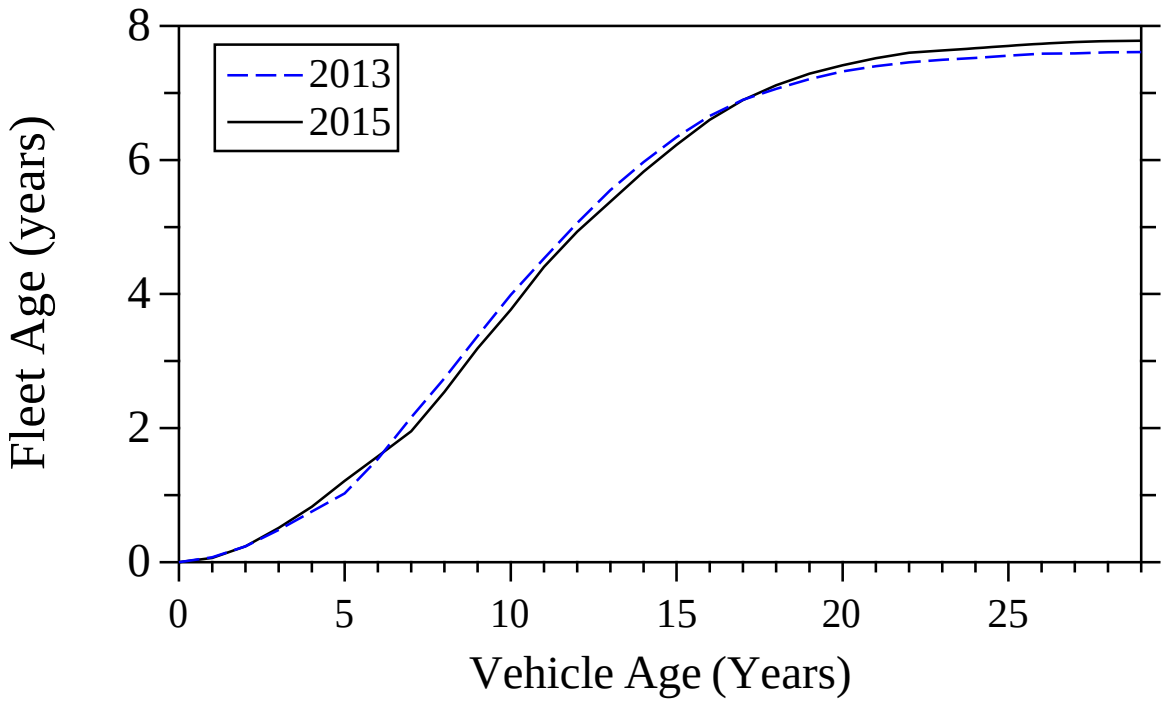


Figure 8. Cumulative fleet Age (years) versus vehicle age in years for the 2013 (dashed line) and 2015 (solid line) Tulsa data sets.

With the collection of the 2015 data set we now have 3 data sets that can be used to look at the changes in $NH_3$ emissions. Figure 9 compares $gNH_3/kg$ emissions collected at the Tulsa site for all three measurement campaigns by model year. The data show the characteristic shape with $NH_3$ emissions increasing with age until vehicles reach about 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 back to back data sets which suggests it is a real difference. There are similar, though smaller increases seen in data from Los Angeles and Chicago that confirms this observation but we currently have no explanation for this observation.

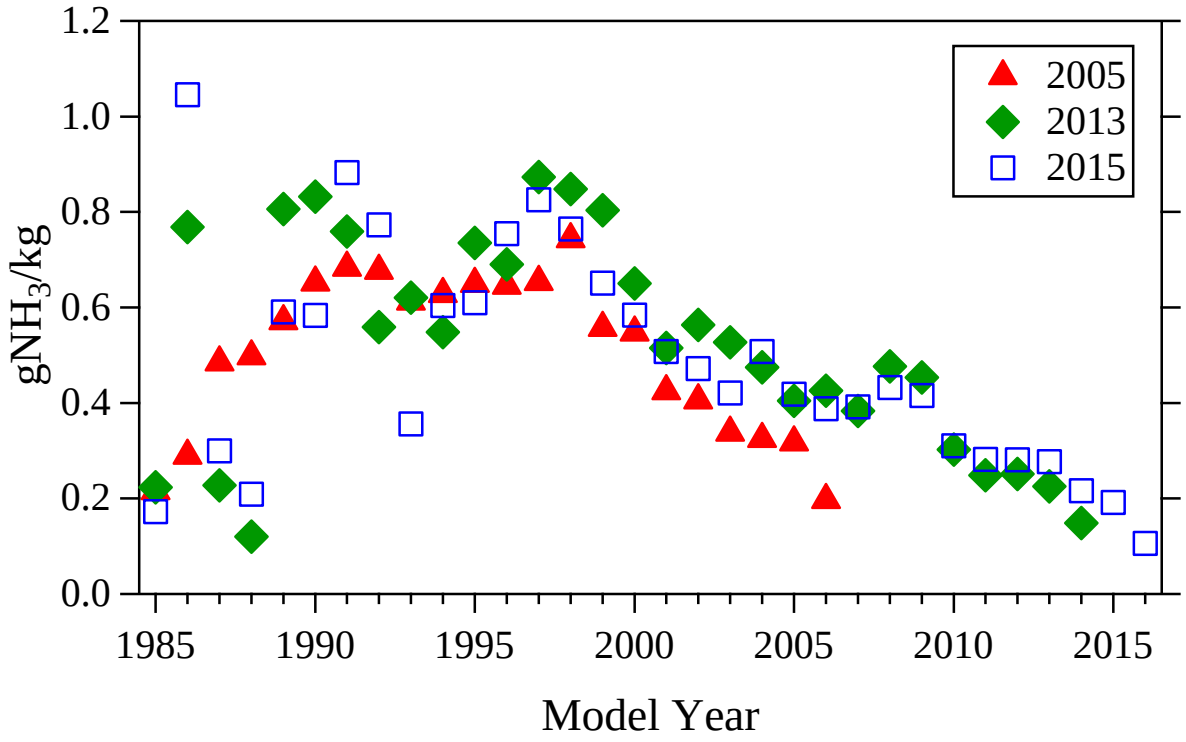


Figure 9. Mean $gNH_3/kg$ emissions plotted against vehicle model year for the 2015, 2013 and 2005 measurements at the Tulsa site.

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 three Tulsa data sets in this way where year 0 vehicles are 2016, 2014 and 2006 models for the 2015, 2013 and 2005 data sets. The errors plotted are standard errors of the mean calculated from distributing the daily means for each year's data.

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 continues in the 2015 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

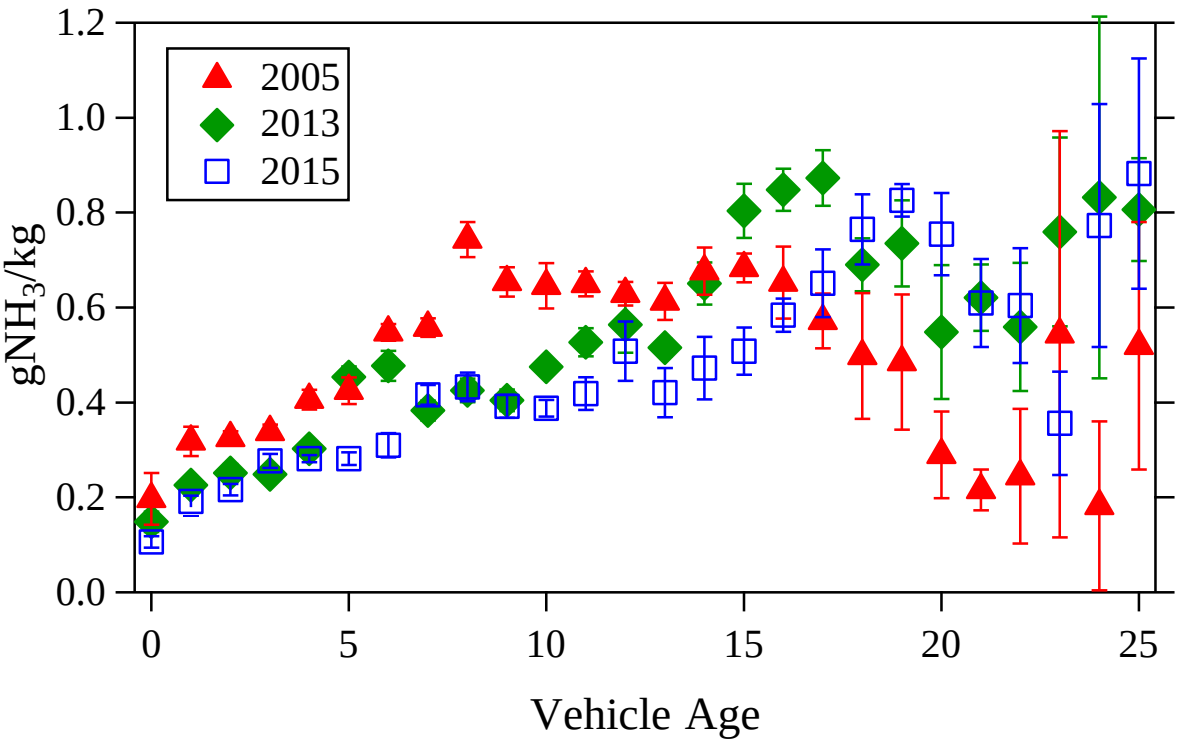


Figure 10. Mean $gNH_3/kg$ emissions plotted against vehicle age for the 2015, 2013 and 2005 measurements at the Tulsa site. The uncertainty bars plotted are the standard error of the mean determined from the daily samples.

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.[25] The 2015 data set appears to not peak until 19 year old vehicles though the increased uncertainty because of the small sample sizes complicates that determination. One possible explanation for this longer period of rising $NH_3$ emissions might be that OBDII vehicle catalysts age slower than 1995 and earlier models and 1996 models are now 20 years old.

The $NH_3$ mean emissions observed in 2005, 2013 and 2015 were 0.5 ± 0.01, 0.43 ± 0.01 and 0.37 ± 0.001 g/kg of fuel respectively, which is a 26% reduction in emissions over ten years. This difference has likely been negatively impacted by the aging of the light-duty fleet due to the 2008-2010 recession and the slow recovery as previously discussed. We can estimate these impacts by applying the age distribution from the 2005 measurements to the 2015 data which lowers the 2015 measured mean $gNH_3/kg$ of fuel to 0.34, an additional 7% reduction when compared with the 2015 mean. The rate of reduction measured in Tulsa over a ten year period is smaller than reduction rates previously reported by Kean et al. in the Caldecott tunnel in California between 1999 and 2006 of 38% ± 6%.[20] In addition NO emissions at this Tulsa site have decreased by 51% (2.9 gNO/kg in 2005 to 1.4 gNO/kg in 2015) 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 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.[18, 28] 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.[19, 28]

An equation for determining the instantaneous power of an on-road vehicle has been proposed by Jimenez,[29] 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 three 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 11. Each of the specific power bins contains at least 57 measurements and the HC data have been offset adjusted for this comparison. Within each vehicle specific power bin there were significant reductions in mean emissions of CO and NO between the 2003 and 2015 datasets. There were smaller reductions observed between the HC data sets. All of the data sets have similar NO emissions trends with increasing NO emissions with increasing VSP with the 2015 data still showing some emission reductions. The error 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 2015 dataset sorted by specific power bin.

Because the 2015 data set has data from the Cherokee Nation we thought we would investigate what if any differences with the Oklahoma plated vehicles. Table 4 provides a summary of 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 4.2% of the matched plates and newer. One interesting observation is that the oldest model year vehicle from the Cherokee fleet is from only 1992. Why they seem to stop at this point is curious but does not seem to be related to a poor registration match as only 2 out of the 650 plates that were submitted came back as unmatchable. Because of the younger fleet the Cherokee Nation fleet has lower mean emission for all of the species listed in Table 4. However, the uncertainties associated with the Cherokee fleet are large due to its small size and the difference appear to only be statistical for $NH_3$. In addition when the Oklahoma plated vehicles are age adjusted so that they match the age of the Cherokee fleet one can see that similarly aged Cherokee vehicles are actually slightly higher emitting than there Oklahoma counterparts again with the exception for $NH_3$.

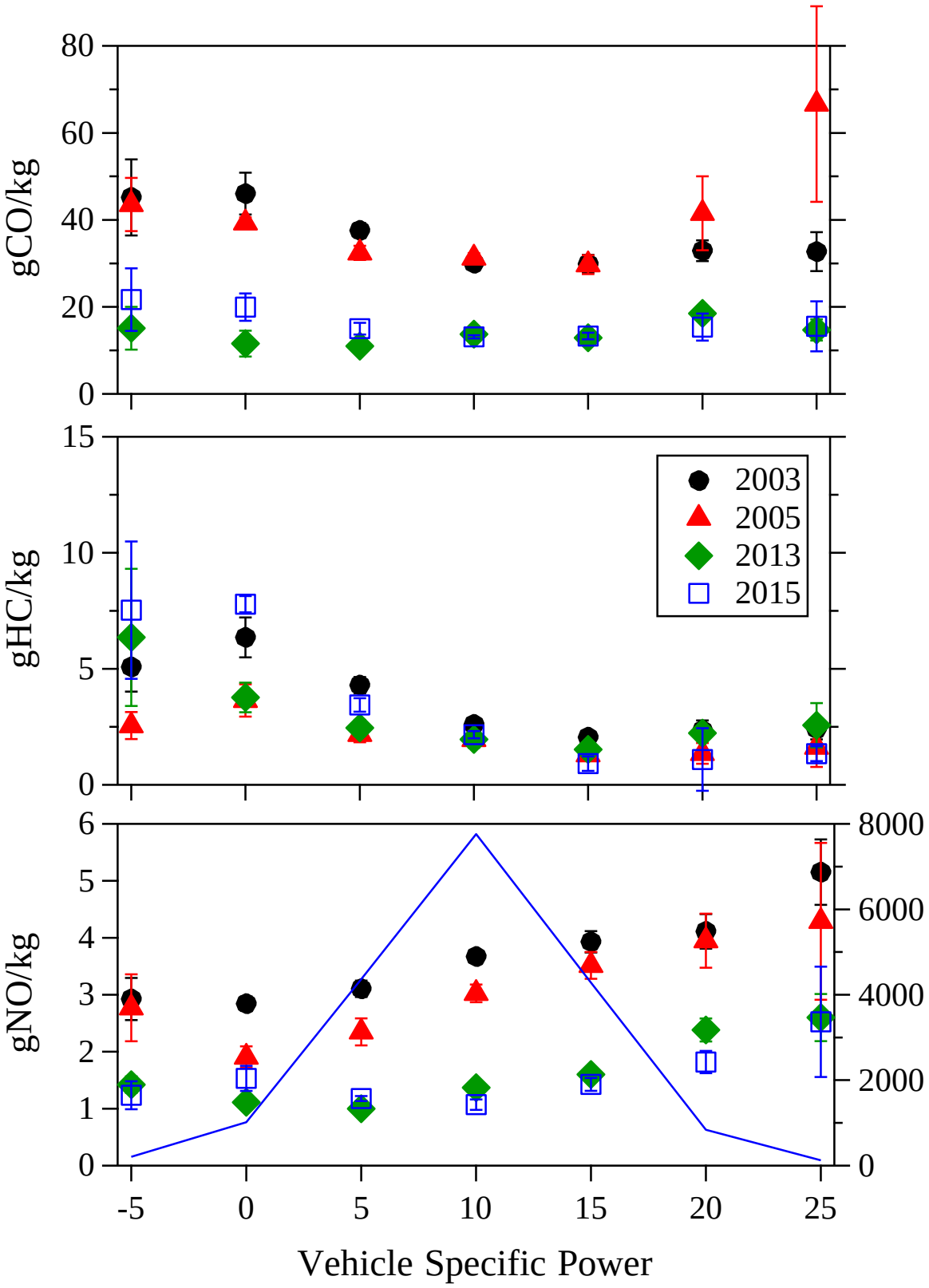


Figure 13. Vehicle emissions as a function of vehicle specific power for all of the Tulsa data sets. Uncertainties plotted are standard errors of the mean calculated from the daily samples. The solid line without markers is the vehicle count profile for the 2015 data.

**Table 4.** Comparison of Vehicle Measurements by Nation

| 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 | 19,306 | 2008.1 | 13,290 | 14.3±0.6 | 2.4±0.2 | 1.4±0.1 | 0.37±0.001 | 2.2±0.1 |
| Cherokee | 827 | 2009.7 | 648 | 13.5±2.6 | 2.2±0.6 | 1.2±0.2 | 0.31±0.03 | 2.1±0.3 |
| US Aged Adjusted to Cherokee Fleet | | | | 11.7 | 2.2 | 0.9 | 0.34 | 1.5 |

Figures 14 and 15 are a comparison of mean fuel specific emissions for CO, HC, NO and $NH_3$ grouped by model year for the 2015 Tulsa and Denver data sets. These means are calculated for the entire data set and diesel vehicles are included to the extent they are represented in each fleet. The uncertainties plotted are standard errors of the mean determined from each sites daily measurements. The solid line is the 1:1 line drawn to indicate agreement. One major difference between the Tulsa and Denver sites is that Tulsa has never had a vehicle emissions inspection and maintenance program (I/M) while Denver has had various types of programs going back to the mid 1980's. Because vehicles that fail I/M have been shown to migrate out of program areas to neighboring communities, Tulsa was specifically chosen because it is regionally isolated from other metropolitan areas that currently have I/M programs.[30] For example Oklahoma City is between Tulsa and Dallas to the south, Springfield is between Tulsa and the St. Louis area to the east and Tulsa is separated by a considerable distance from Denver to the west. This of course does not completely eliminate cars migrating to Tulsa from these program areas but should serve to greatly reduce their numbers.

The Denver I/M program currently does not require vehicles to report for its first I/M test until its seventh years and test are required every other year after that. The Denver program is a mix of onboard diagnostic testing and IM240 tailpipe testing. Figures 14 and 15 show the first six vehicle model years (2010 – 2015) as black squares and any differences in emissions observed in this group are not the result of any I/M testing but are more likely differences in driving modes between the two sites. Uncertainties increase substantially for model years older than 1996 in Tulsa because of the decrease in the sample size. For Tulsa those values range from only 25 measurements in 1992 to 72 measurements for 1995 models. The statistics are better for Denver because of a larger database where those same model years have 77 to 183 measurements respectively. A For CO the Tulsa means are consistently higher than those observed in Denver including the first six model years. For HC the Denver means are generally higher than the same model years in Tulsa which is likely explained by the fact that the Denver 2015 site is a higher speed site with a larger fraction of vehicles measured during decelerations which will increase HC emissions. Neither the CO nor HC plot show any significant deviations relative to the 1:1 line after the first six model years. Figure 15 shows NO and $NH_3$ for completeness as we do not expect Denver's I/M program to have any measureable effect on these emissions.

The stated purpose of any I/M program is to identify vehicles with excessive emissions and force their removal or repair to correct the problem. Finding statistically significant differences in fleet means is difficult as not all of the vehicles measured in the Denver area participate in the program because they are not registered within the six county program area. However, because

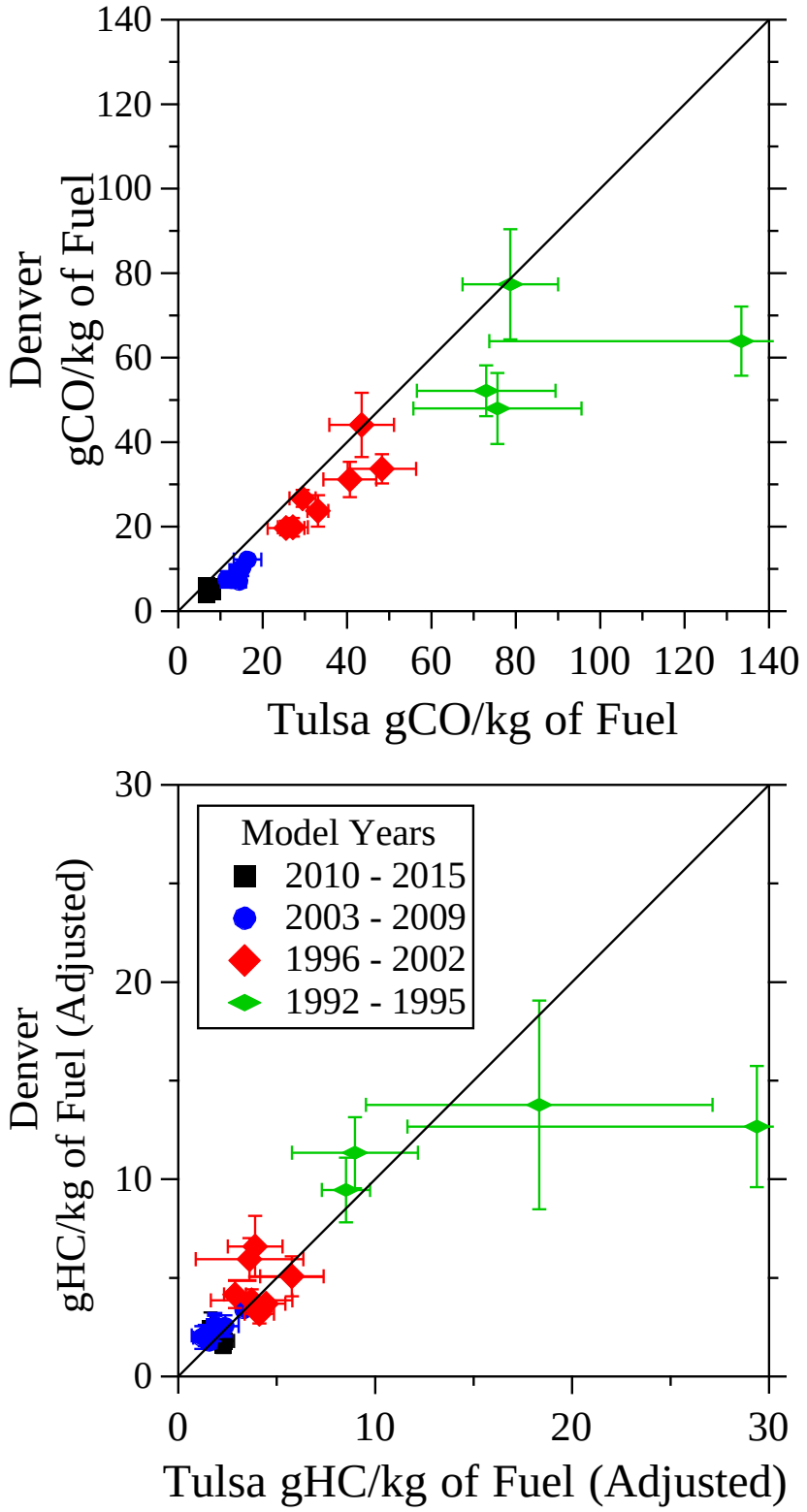


Figure 14. Mean model year fuel specific emissions comparison for CO and HC between the 2015 Denver and Tulsa data sets. Uncertainties plotted are standard errors of the mean calculated from each sites daily samples. Solid 1:1 line is drawn to indicate agreement.

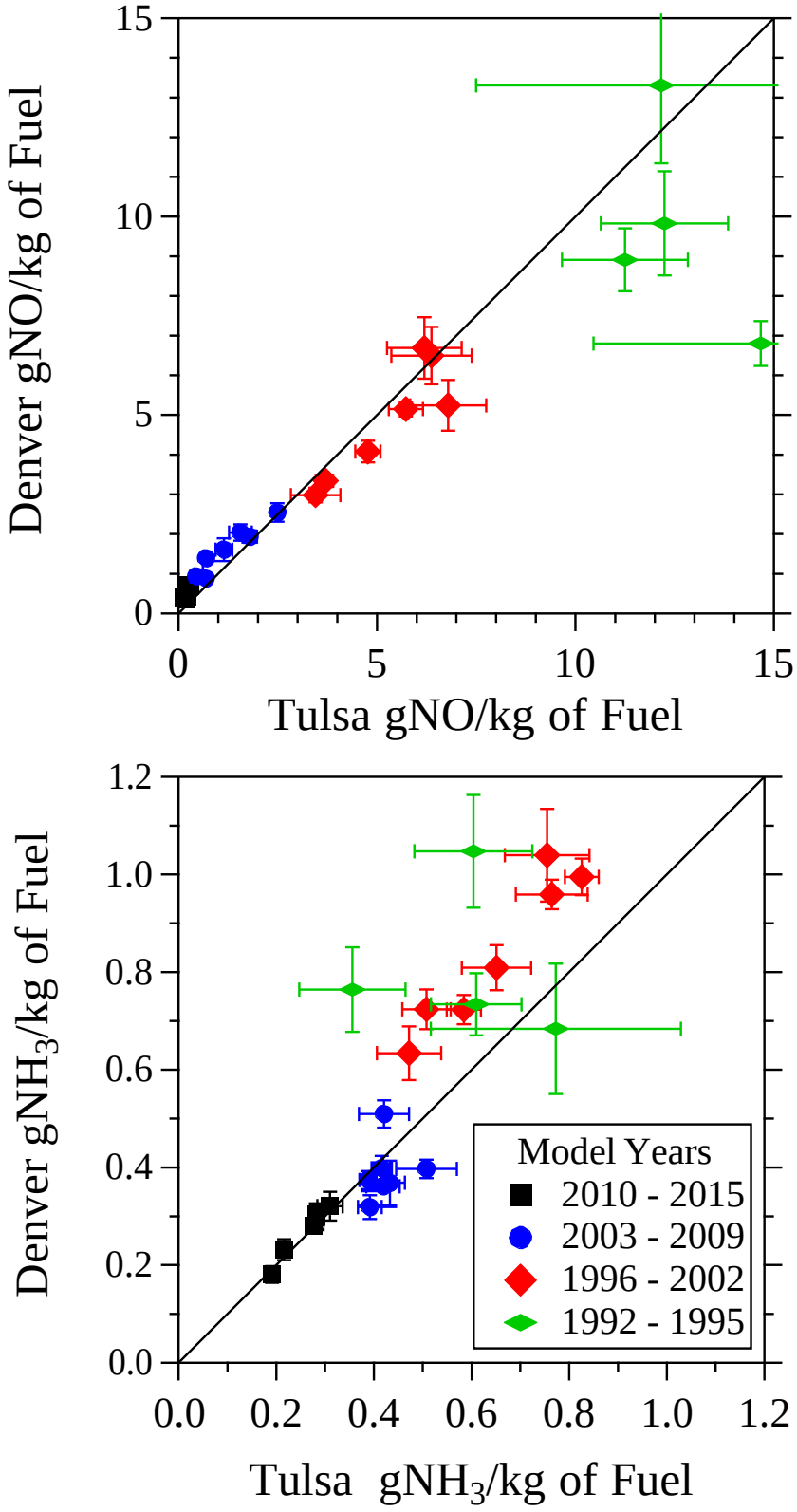


Figure 15. Mean model year fuel specific emissions comparison for NO and $NH_3$ between the 2015 Denver and Tulsa data sets. Uncertainties plotted are standard errors of the mean calculated from each sites daily samples. Solid 1:1 line is drawn to indicate agreement.

of this fact if a program is to be successful it should not be sufficient for it to just reduce emission from vehicles that agree to participate but should actually reduce fleet emissions for the program area. The 99$^{th}$ percentile is an extreme statistic that for vehicle CO and HC emissions is occupied entirely by broken or mal-maintained vehicles that have excess emissions. If a regions I/M program has any effect on reducing fleet emissions it should be apparent by reducing the magnitude of the 99$^{th}$ percentile vehicles. Figure 16 is a plot of the 99$^{th}$ percentiles for CO and HC emissions by model years using the same groupings as the previous two figures. The solid line is the 1:1 line indicating agreement. The plots for both species show that there is considerable agreement between the 99$^{th}$ percentile emissions observed in the two cities and a lack of any major on-road emissions reduction as a result Denver's I/M program. We have not included the 99$^{th}$ percentile plots for NO due to a lack of fuel type information in the Tulsa data set which precludes us from eliminating diesel vehicles. Unlike CO and HC the 99$^{th}$ percentile for NO will be dominated by diesel vehicles which are not subject to Denver's I/M program. The 99$^{th}$ percentile plots are not shown for $NH_3$ as it is not subject to I/M tested nor regulated at all.

In the manner described in the E-23 Phoenix, Year 2 report, instrument noise was measured using the slope of the negative portion of a plot of the natural log of the binned emission measurement frequency versus the emission level.[31] Such plots were constructed for the three 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 7.6, 5.4, 0.11, 0.02 and 0.2 for CO, HC, NO, $NH_3$ and $NO_2$, respectively. These values indicate standard deviations of 10.8 g/kg (0.08%), 7.6 g/kg (181ppm), 0.15 g/kg (12ppm), 0.02 g/kg (4ppm) and 0.3 g/kg (13ppm) 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.[31] This of course indicates that any power supply problems we may have had during the sampling it does not seem to have introduced any appreciable noise in the measurements. 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 1.1 g/kg, 0.8 g/kg, 0.02 g/kg, 0.002 g/kg and 0.03 g/kg, respectively.

## ACKNOWLEDGEMENTS

The successful outcome of this project would not be possible without the assistance of the Oklahoma Department of Transportation, Brandon Welborn of the Oklahoma Tax Commission, Ms. Sharon Swepston of the Cherokee Nation Tax Commission and Mrs. Annette Bishop. Comments from the various reviewers of this report were also invaluable.

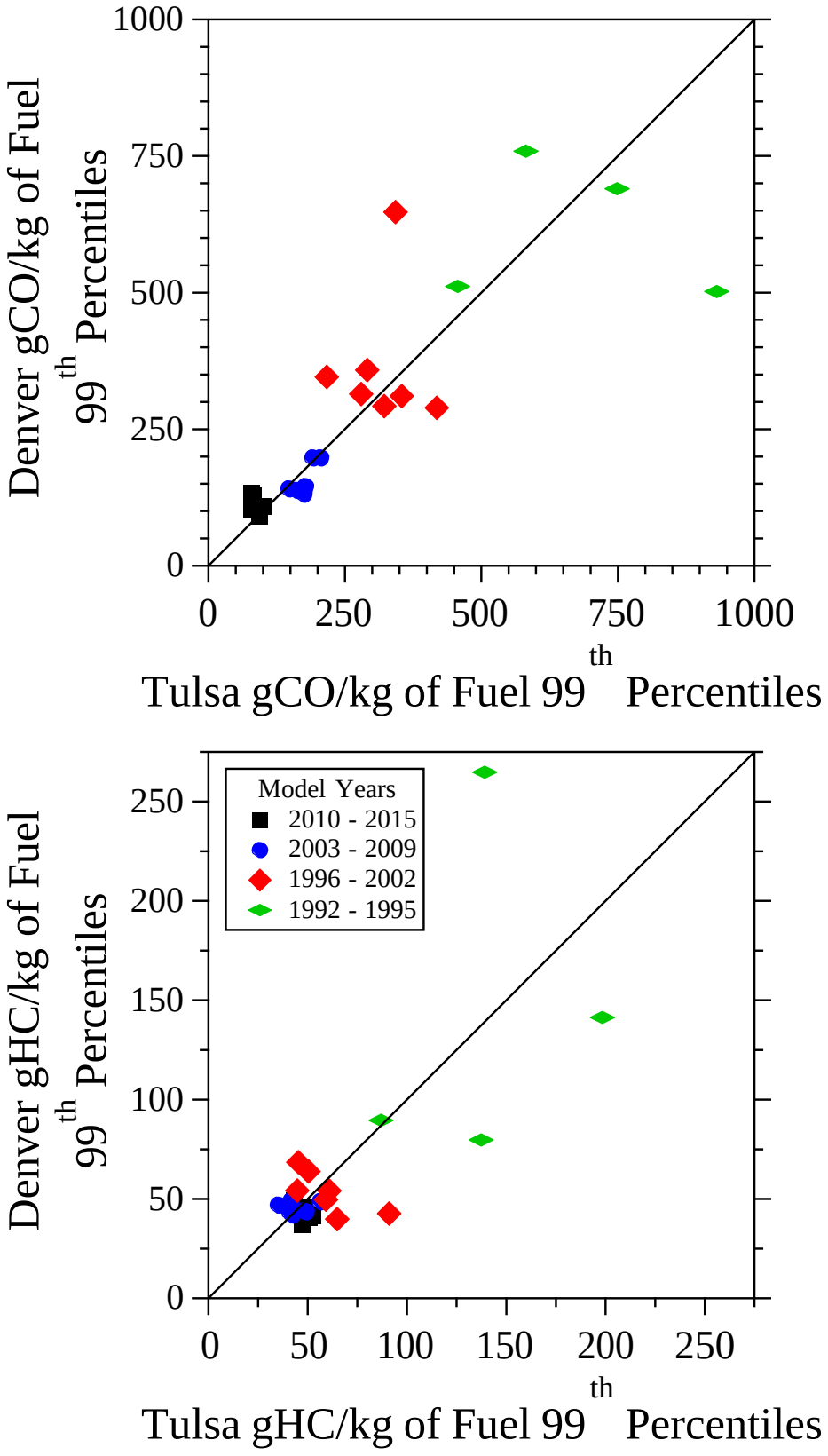


Figure 16. Fuel specific model year 99th percentile emissions comparison for CO and HC between the 2015 Denver and Tulsa data sets. Solid 1:1 line is drawn for a visual reference.

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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_15.dbf database.**

The Tulsa_15.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. |
| **Year** | Model year. |

| | |
|---|---|
| **Vin** | Vehicle identification number. |
| **Title_date** | Oklahoma DMV date of title for vehicle. |
| **Make** | Manufacturer of the vehicle. |
| **Model** | Oklahoma model designation. |
| **Body** | Oklahoma designated body style |
| **City** | Registrant’s mailing city. |
| **State** | Registrant’s mailing State. |
| **Exp_date** | Cherokee Nation plate expiration date. |

## 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 | | |

**APPENDIX D: 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 |