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July 2014

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On-Road Remote Sensing of Automobile Emissions in the Tulsa Area: Fall 2013

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EXECUTIVE SUMMARY

The University of Denver conducted a five-day remote sensing study in the Tulsa, Oklahoma area in late September and early October of 2013. 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 30 – October 4, 2013, 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 and 2005. A database was compiled containing 21,115 records for which the State of Oklahoma 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 13.4 g/kg (0.11%), 2.1 g/kg (57ppm), 1.5 g/kg (109ppm), 0.43 g/kg (54ppm) and 0.14 g/kg (6ppm) respectively. When compared with previous measurements from 2005 we find that mean CO (-60%) and NO (-46%) emissions have experienced significant reductions while HC (-4.5%) and NH_3 (-14%) emissions have declined less. Emission deterioration between similar model years during the intervening eight years is remarkably low, especially for CO where there is statistically no difference between 10 to 30 year old vehicles. The emissions measurements in this study exhibit a gamma distribution and the skewedness has increased since the last measurements in 2005. The highest emitting 1% of the measurements is responsible for 31%, 42%, 25%, 15 and 50% of the CO, HC, NO, NH_3 and NO_2 emissions, respectively.

The recent recession has had a measurable effect on the age of this Tulsa vehicle fleet. The dramatic economic downturn that began in late 2008 and continued through 2010 reduced both new vehicle sales and the retirement (scrappage) of older vehicles. Consequently, the average age of the Tulsa fleet increased from 6.7 (last measured in 2005) to 7.8 years. The largest loss in sales occurred in model year 2009 (37% lower than 2007) and 2010 (23% less than 2007). As a result of the aging of the fleet, tailpipe emissions have not decreased over this time period as fast as they might have done in the absence of the economic downturn. If we adjust the 2013 data using the fleet age distribution seen in 2005 we find that CO, HC, NO and NH_3 emissions would have been 17% lower for CO (2.3 g/kg), 9% lower for HC (0.2 g/kg), 26% lower for NO (0.4 g/kg) and 6% lower for NH_3 (0.03 g/kg) emissions. These differences are statistically significant for all of these species but the HC emissions. The on-road emissions that would otherwise have been replaced by the purchase of newer vehicles were found in the 10 to 20 year old vehicles.

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 mean value of the NH_3 emissions measured in 2013 was 0.43 ± 0.01 g/kg in comparison to a mean of 0.5 ± 0.01 g/kg for measurements made at the same location in 2005 using the same equipment. This is a 14% reduction in NH_3 emissions over eight years which represents a slower rate of change than that evidenced by the 38% ± 6% reduction between 1999 and 2006 previously reported by Kean et al. for data collected at the California Caldecott tunnel. The 2013 data show a slightly lower rate of increase in emissions with increasing age but the increases continue for a longer period (~17 years versus 13 or 14 years for the 2005 data) before starting their decline. The larger reductions observed in NO emissions suggests that a trade-off may be occurring in newer models that favors (unregulated) NH_3 production.

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.[7] 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.[8-10] 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.[11] 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.[12] To calculate mass emissions as described below, the %HC values reported first have to be multiplied by 2.0 to account for these "unseen" hydrocarbons as shown below, assuming that the fuel used is regular gasoline. These percent emissions can be directly converted into mass emissions by the equations shown below.

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

These equations show that the relationships between emission concentrations and mass emissions are: (a) linear for NO_2 and NH_3, (b) nearly linear for CO and NO and (c) linear at low concentrations for HC. Thus, the percent difference in emissions calculated from the concentrations of pollutants reported here is equivalent to a difference calculated from masses. Note that NO is reported as grams of NO, while vehicle emission factors for NO_x are normally reported as grams of NO_2, even when the actual compound emitted is close to 100% NO in the case of gasoline fueled vehicles.

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

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

Next, moles of pollutant are converted to grams by multiplying by molecular weight (e.g., 44 g/mole for HC since propane is measured), and the moles of carbon in the exhaust are converted to kilograms by multiplying (the denominator) by 0.014 kg of fuel per mole of carbon in fuel, 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.[12]

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

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.[13, 14] 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 (3σ) of 25 ppm for NO, with an error measurement of ±5% of the reading at higher concentrations.[9] 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 2013, 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. A schematic of the measurement location is shown in Figure 1 and a photograph of the setup is shown in Figure 2. It has been 8 years since remote sensing measurements were last made at this site in Tulsa and all of the paint marks used for marking the equipment set-up in the previous studies were no longer visible. Working from previous photos and notebook drawings we did our best to locate the

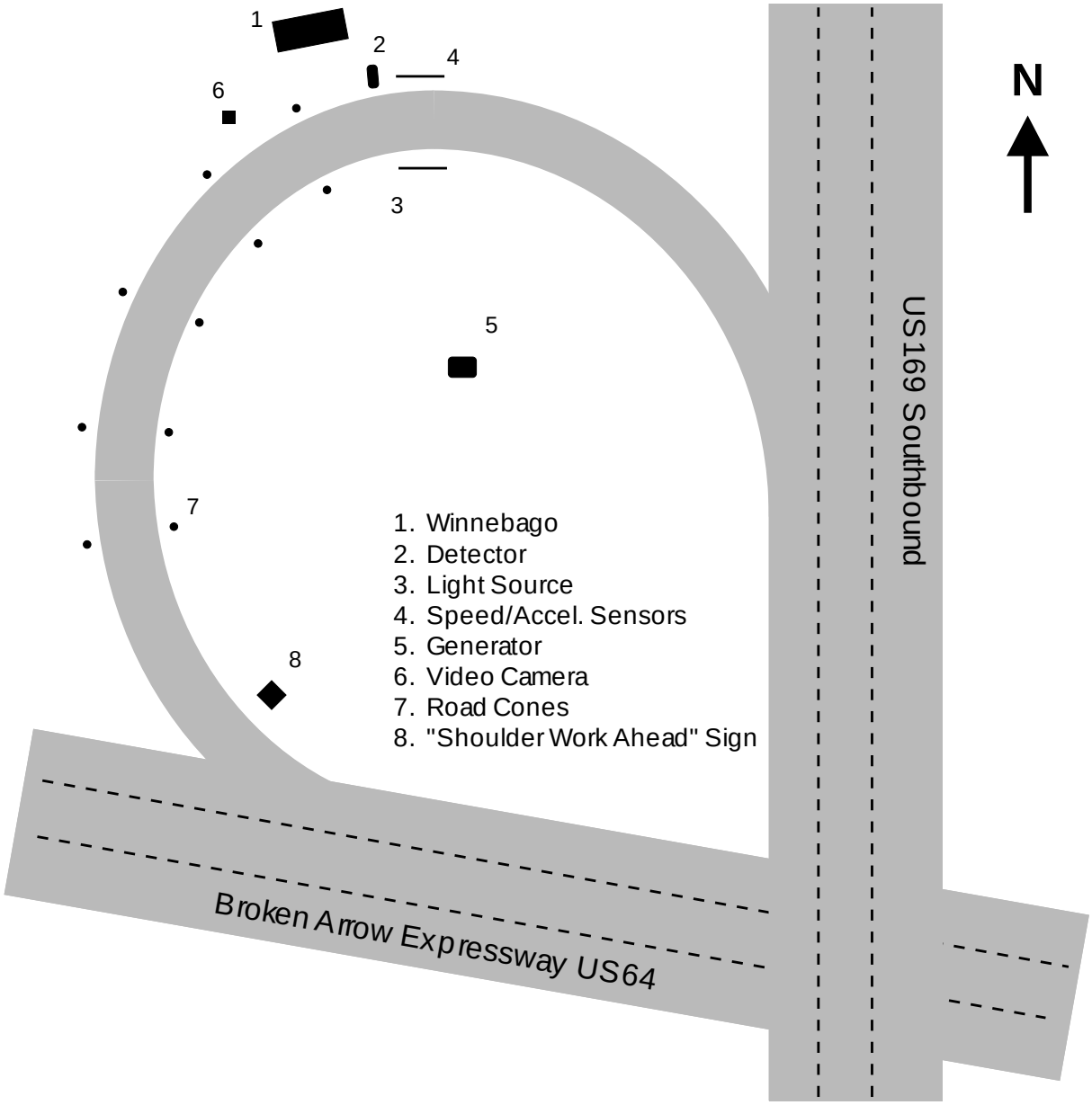

Figure 1. A schematic drawing of the ramp from Westbound US64 (Broken Arrow Expressway) to Southbound US169. The location and safety equipment configuration was for all five days of measurements.

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

remote sensor as close as possible to the original site. Appendix C gives temperature and humidity data for the study obtained from Tulsa International Airport, approximately ten miles north of the measurement site.

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. In 2003 we made the extra effort to code for the various tribal nations and found that out of 14,016 unique plates there were 429 (3%) that were issued by tribal nations. Because of the small number of tribal plates observed in 2003, we have subsequently only transcribed the Oklahoma issued plates when compiling final databases of the 2005 and the 2013 measurements. The resulting 2013 database contained 21,115 records 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

Table 1. Validity Summary.

	CO	HC	NO	NH_3	NO_2
Attempted Measurements	29,268				
Valid Measurements	26,971	26,461	26,970	26,953	23,494
Percent of Attempts	92.2%	90.4%	92.1%	92.1%	80.3%
Submitted Plates	21,988	21,605	21,987	21,975	19,206
Percent of Attempts	75.1%	73.8%	75.1%	75.1%	65.6%
Percent of Valid Measurements	81.5%	81.6%	81.5%	81.5%	81.7%
Matched Plates	21,115	20,745	21,115	21,104	18,443
Percent of Attempts	72.1%	70.9%	72.1%	72.1%	63.0%
Percent of Valid Measurements	78.3%	78.4%	78.3%	78.3%	78.5%
Percent of Submitted Plates	96.0%	96.0%	96.0%	96.0%	96.0%

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, successful transcription was particularly maddening this time.

Table 2 provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured. Of the 21,115 records used in this fleet analysis, 10,574 (50.1%) were contributed by vehicles measured once, and the remaining 10,541 (49.9%) records were from vehicles measured at least twice.

Table 2. Number of measurements of repeat vehicles.

Number of Times Measured	Number of Vehicles
1	10,574
2	2,102
3	968
4	495
5	161
6	63
7	19
>7	16

Table 3 summarizes the data from the current and previous measurements collected at the same site in 2003 and 2005. The average HC values have been adjusted to remove an artificial offset in

Table 3. Data Summary.

Study Year Location	Tulsa 2003	Tulsa 2005	Tulsa 2013
Mean CO (%) (g/kg of fuel)	0.27 (34.0)	0.27 (33.6)	0.11 (13.4)
Median CO (%)	0.06	0.11	0.028
Percent of Total CO from the 99th Percentile	21.9%	20.8%	31.2%
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
Median HC (ppm)[a]	40	40	35
Percent of Total HC from the 99th Percentile	18.5%	34.1%	41.7%
Mean NO (ppm) (g/kg of fuel)	265 (3.7)	202 (2.9)	109 (1.5)
Median NO (ppm)	53	33	5
Percent of Total NO from the 99th Percentile	12.3%	13.9%	25.1%
Mean NH_3 (ppm) (g/kg of fuel)	NA	62 (0.5)	54 (0.43)
Median NH_3 (ppm)	NA	25	19
Percent of Total NH_3 from the 99th Percentile	NA	12.2%	14.5%
Mean NO_2 (ppm) (g/kg of fuel)	NA	NA	6 (0.14)
Median NO_2 (ppm)	NA	NA	3
Percent of Total NO_2 from the 99th Percentile	NA	NA	49.7%
Mean Model Year	1997.6	1999.3	2006.3
Mean Fleet Age[c]	6.4	6.7	7.8
Mean Speed (mph)	24.1	24.4	24.3
Mean Acceleration (mph/s)	0.06	-0.4	-0.01
Mean VSP (kw/tonne) Slope (degrees)	7.8 2.6°	5.3 2.6°	7.7 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.

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. Since we assume the cleanest vehicles to emit little 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.

In the eight years since the last measurement study in Tulsa OK we find that mean CO (-60%) and NO (-46%) emissions have experienced significant reductions while HC (-4.5%) and NH_3 (-14%) emissions have declined much less. NO_2 emissions are only significant for diesel vehicles which only account for 2.8% of the Tulsa measurements. The percent of emissions contributed by the highest emitting 1% of the fleet (the 99^{th} percentile) increased for all of the species measured. The average age of the Tulsa fleet has also increased by one year likely due to the most recent recession.

An inverse relationship between vehicle emissions and model year is shown in Figure 3 for the three periods sampled in calendar years 2003, 2005 and 2013. The HC data have been offset adjusted here for comparison. Between 2005 and 2013 fleet average emissions in Tulsa have likely changed less than one might expect. CO emissions are statistically similar for the vast majority of the 30 model years plotted in Figure 3. With respect to HC measurements for the three time periods, there are no significant differences in the means by model year for the 1998 and newer models and some divergence (particularly in the CY 2013 data) observed in 1997 and older models. For NO, the 2013 measurements begin with the 2003 models to deviate from the comparable values recorded in the two earlier measurement years.

Following the data analysis and presentation format originally shown by Ashbaugh et al.,[15] the vehicle emissions data by model year from the 2013 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 years 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 19 model years and documents the negative impacts that the last recession had on car sales between 2009 and 2010. Model years older than 1995 and not graphed account for ~2% of the measurements and contribute between 15% (NO) and 16.6% (HC) of the 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 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.

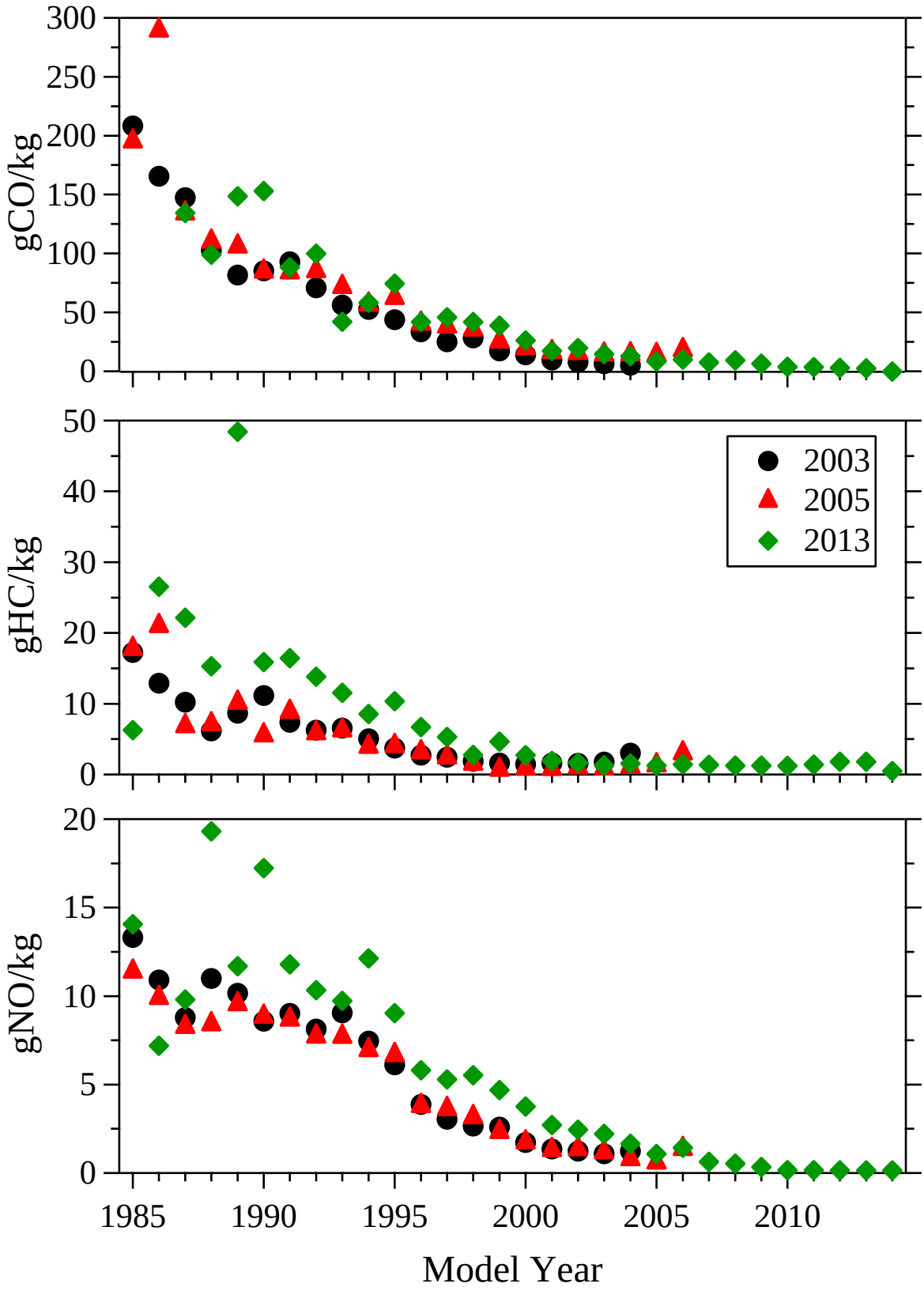

Figure 3. Mean vehicle emissions plotted as a function of model year for the three Tulsa data sets, 2003 (circles), 2005 (triangles) and 2013 (diamonds). HC data have been offset adjusted as described in the text.

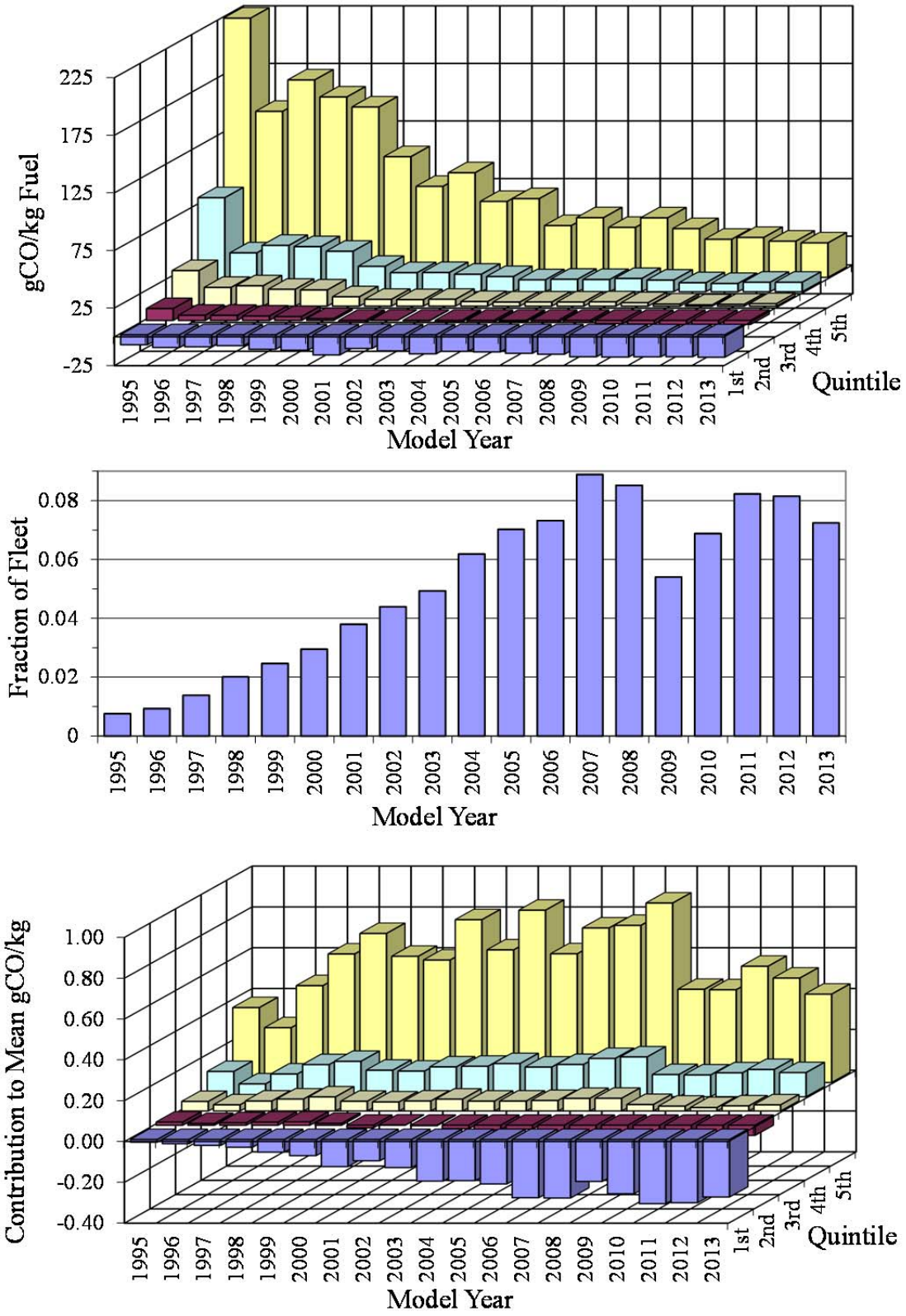

Figure 4. Mean gCO/kg emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gCO/kg emissions by model year and quintile (bottom).

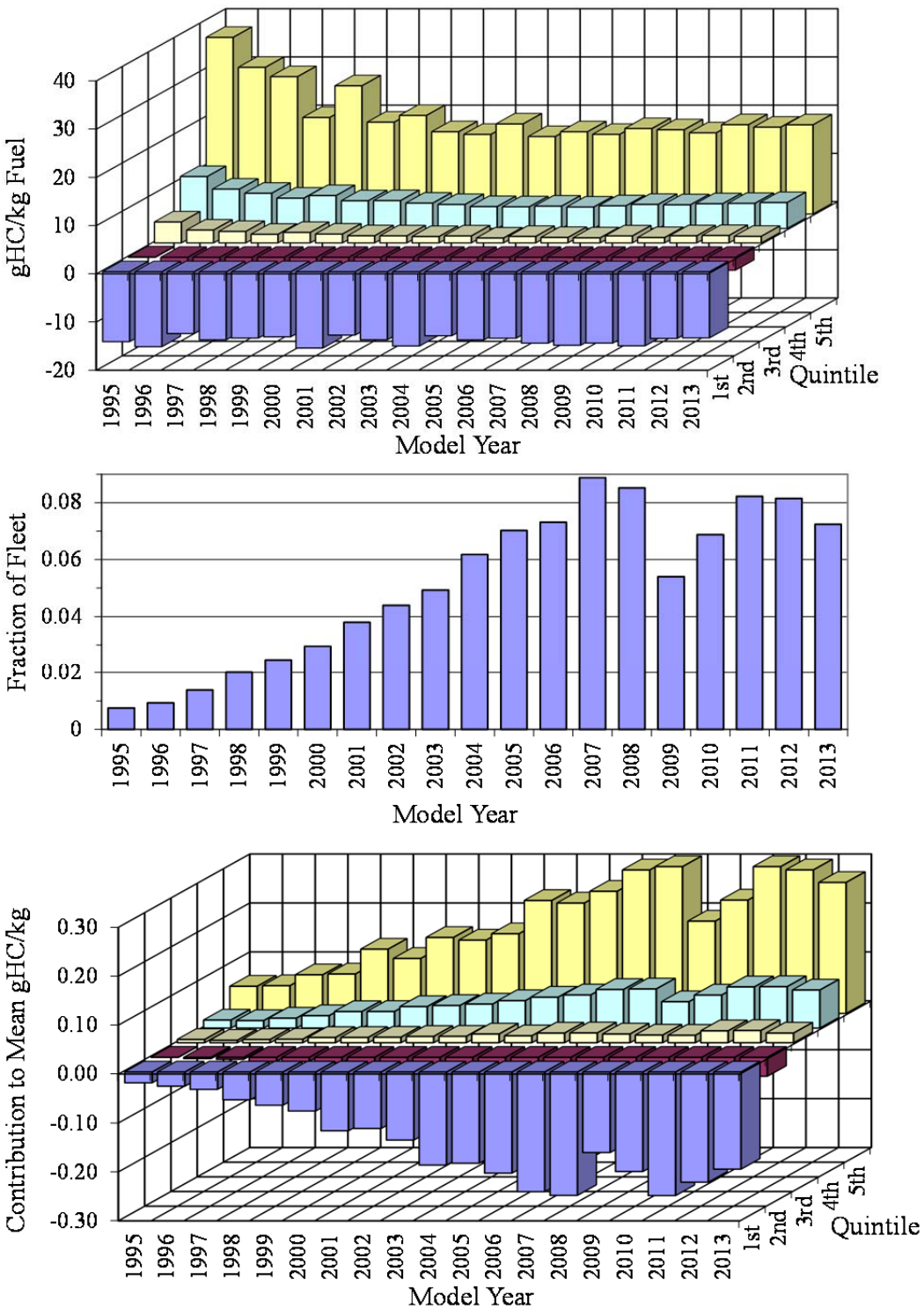

Figure 5. Mean gHC/kg emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gHC emissions by model year and quintile (bottom).

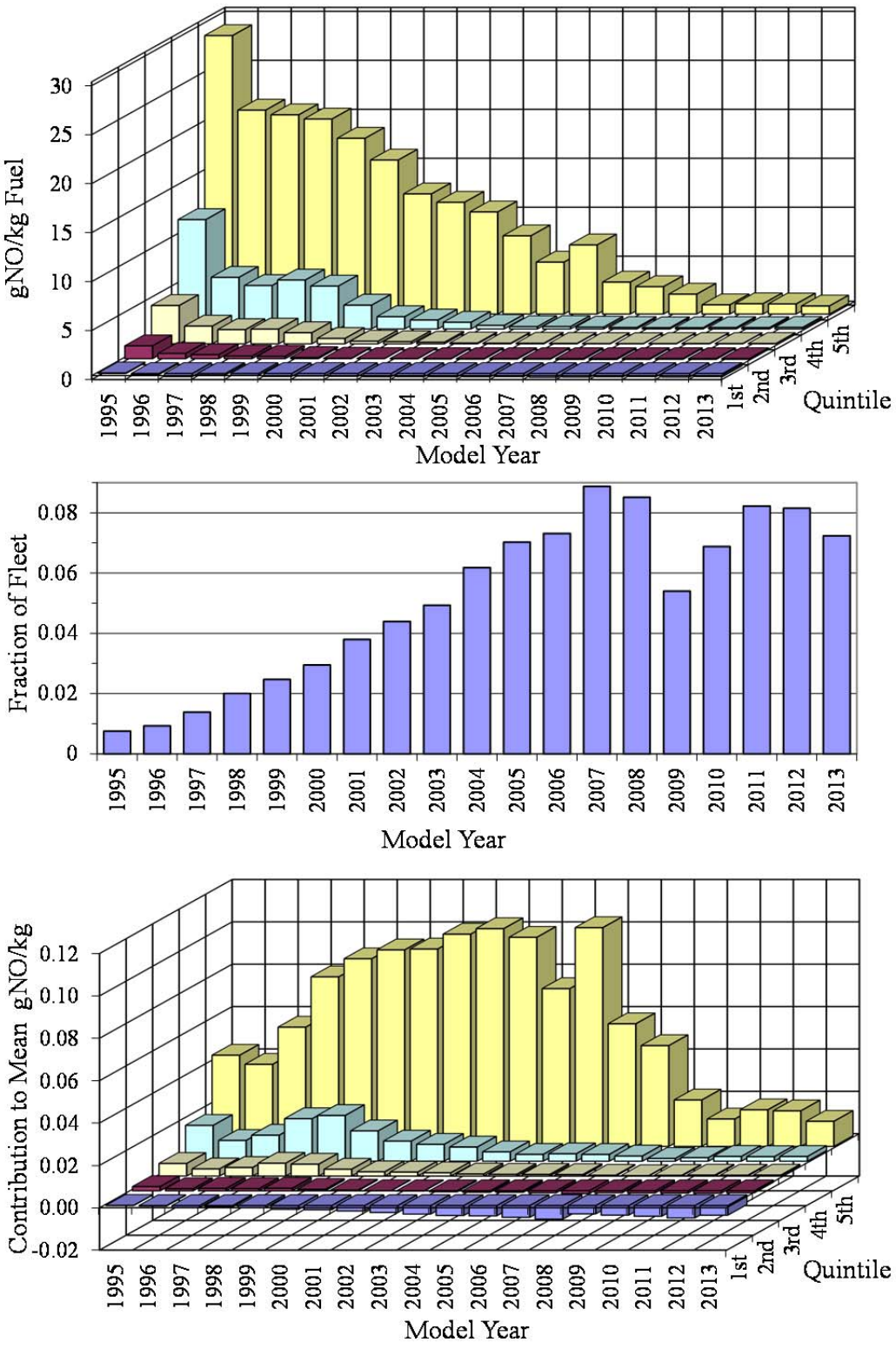

Figure 6. Mean gNO/kg emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gNO/kg emissions by model year and quintile (bottom).

The middle graph in Figures 4 – 6 shows the fleet fractions by model year for the 2013 Tulsa database. The impact of the recent reduction in light-duty vehicle sales due to the economic recession is clearly evident in the fleet model year fraction beginning in 2009 and continuing through 2011. The previous recession that occurred in 2001 is not noticeable in this data set though we have previously reported that data collected in the California cities of San Jose and Fresno clearly showed its effects.[16] Nationwide new vehicle sales, as reported by the National Automobile Dealers Association, for 2009 were the lowest per capita since World War II.[17, 18] For the 2013 Tulsa measurements the 2009 fleet fraction is 37% lower than the 2008 models and 39.5% lower than the 2007 model year. This reduction is similar to reductions seen at the West LA and Denver measurement sites.

The direct result is that the average age of the Tulsa fleet has increased between 2005 and 2013. Table 3 summarized the mean fleet ages for all of the previous data sets collected at the Tulsa site. The vehicle age has been estimated assuming that a vehicle model year starts in September. This site does not have as many data sets as some of the other E-23 sites, and it has been eight years between measurements, but the data show that the 2013 fleet is on average 1 model year older than that observed for the Tulsa fleet in 2005. It will be interesting going forward to see how the direction and magnitude of future vehicle sales and retirement will impact this trend in fleet average age.

We can estimate where those changes have taken place by comparing the fleet fractions between the 2013 and 2005 distributions. We cannot directly map model years between the two data sets because they were collected eight years apart so we have mapped all model years to vehicle age ignoring the week difference between sampling dates. Figure 7 is a bar chart which compares the fleet fraction distribution for the 2013 and 2005 Tulsa data sets. As expected 5 to 7 year old vehicles are underrepresented in the 2013 data and 9 to 20 year old vehicles are over represented.

While an economic recession may not directly result in an increase in tailpipe emissions, its impact on vehicle sales, vehicle scrappage and the rate of fleet turnover will likely lead to an increase in the average age of the on-road fleet and at the very least that age increase will offset the on-road emissions reductions observed during periods characterized by “normal” rates of fleet turnover and economic activity. If those increases in the average age of the fleet are attributable to a larger fraction of high emitters, then overall emissions may rise as well. To estimate the magnitude of this impact we used the fleet model year fractions from the 2005 data set to adjust the vehicle age fractions for the 2013 model year emissions. This age adjustment is accomplished by computing the fraction of 1 year old, 2 years old, 3 years old etc. vehicles in the 2005 database and applying those fractions to the 2013 emissions by age data. Figure 8 is a bar chart comparing the 2013 Tulsa measured fleet average emissions and the estimated emissions that would have been observed if the 2013 fleet had the same age (6.7 years old) distribution as the 2005 data set. The age adjusted data set has 17% lower CO (2.3 g/kg), 9% lower HC (0.2 g/kg), 26% lower NO (0.4 g/kg) and 6% lower NH_3 (0.03 g/kg) emissions. The errors plotted are standard errors of the means calculated from the 2013 daily means and have been plotted using the same error percentage for the age adjusted bars. All the emission differences except HC are statistically significant. These lost reductions are smaller than those observed at the West LA site and the fact that this data set was collected 5 months later in 2013 is likely a contributing factor.

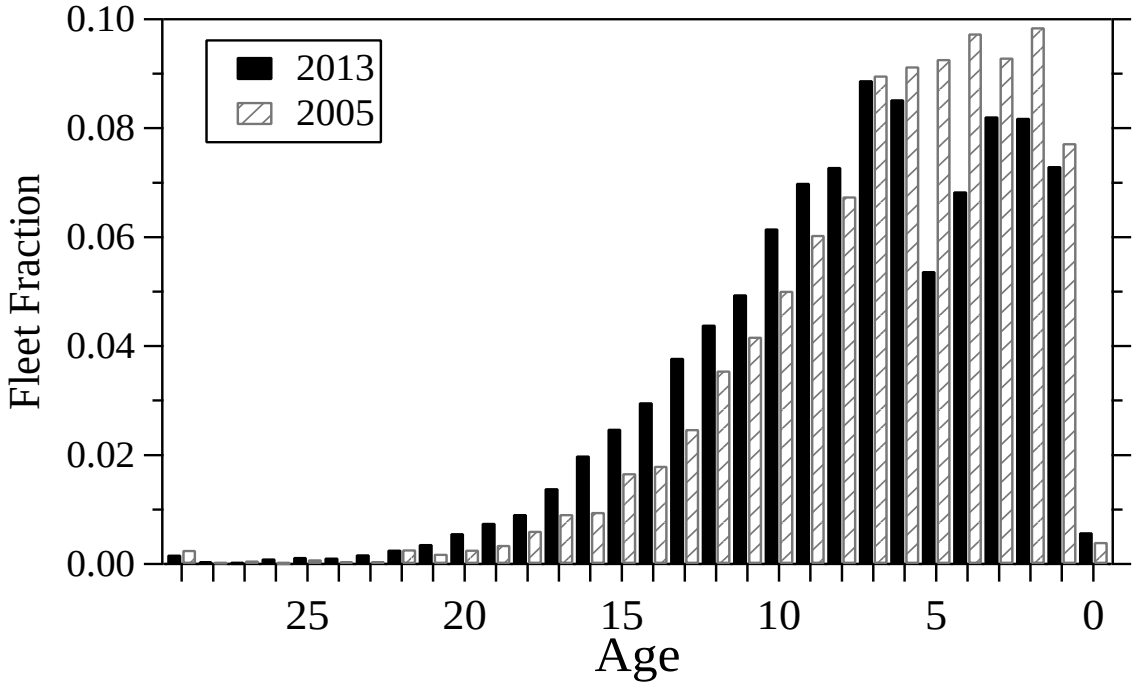

Figure 7. Fleet fractions plotted by vehicle age for the 2013 and 2005 Tulsa data sets. Age = 0 vehicles represent the 2014 and 2006 model years in the 2013 and 2005 data sets, respectively.

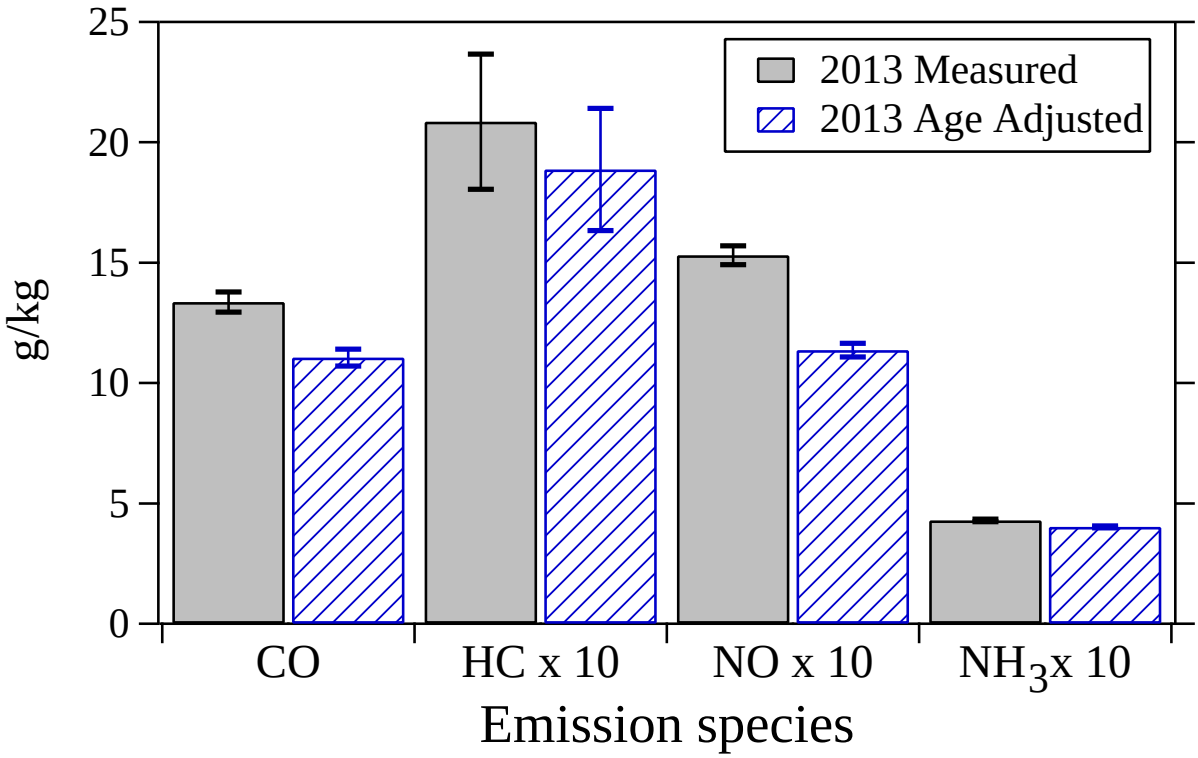

Figure 8. Fleet mean emission comparison for the 2013 Tulsa data set as collected (solid bars) and when age adjusted (hatched bars) to match the 2005 data (6.7 years old). Error bars are standard errors of the mean calculated from the daily means for the 2013 data and are the same for each species. HC, NO and NH_3 emissions values are multiplied by 10 for easier viewing.

We can distribute the emission species differences observed across the 2013 model years to see which years were affected the most by the changes in fleet turnover. Figures 9 and 10 display the measured minus modeled emission differences in grams per kilogram by model year for gCO/kg, gHC/kg, gNO/kg and gNH_3/kg. The total g/kg emissions difference for each species from Figure 8 is given in the upper right hand corner of each figure. The 1985 model year bar includes not only the 1985 model year vehicles but any older models as well.

A positive number in these figures indicates emissions that likely would have been eliminated if the rate of fleet turnover had not been slowed by the recession and the age distribution of the 2013 fleet was as measured in 2005. As expected from the fleet fraction differences shown in Figure 8 emissions for all of the species generally starts to accumulate around 9 year old vehicles (2005 to 2004 models) peaks around 15 year old vehicles (1998 to 1999 models) and then tails off. The differences observed for the first fifteen model years is largely driven by the differences in the fleet fractions while during the later fifteen years the magnitude of the emissions appears to play a more important role. The NH_3 differences are shifted toward the newer model years and have positive differences across fewer model years when compared to the other species. As will be discussed next tailpipe NH_3 emissions are the only species measured whose emissions increase with vehicle age, reach a maximum and then decrease back to low levels. As a result the tail of the NH_3 differences plotted in Figure 10 is a product of decreasing fleet fractions and decreasing emission factors.

The lost reduction in emissions is only part of the total emissions picture for inventory purposes. Since our measurements are fuel based, the total emissions emitted at this site are a product of the amount of fuel consumed. Tax data reported by the Oklahoma Tax Commission indicates that fuel sales have increased around 4% since before the recession which would further increase the total emissions produced at the Tulsa site.[19]

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.[20] Ammonia is most often associated with farming and livestock operations but it can also be produced by 3-way catalyst equipped vehicles.[21] The production of exhaust NH_3 emissions is contingent upon the vehicles 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.[22] 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.[23-26] 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.[16, 27] In addition air borne measurements of ammonia were collected in 2010 over the South Coast Air Basin as part of the CalNex campaign.[28]

Figure 11 compares gNH_3/kg emissions collected at the Tulsa site for the past two 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. Because NH_3 emissions are sensitive to vehicle age, and these

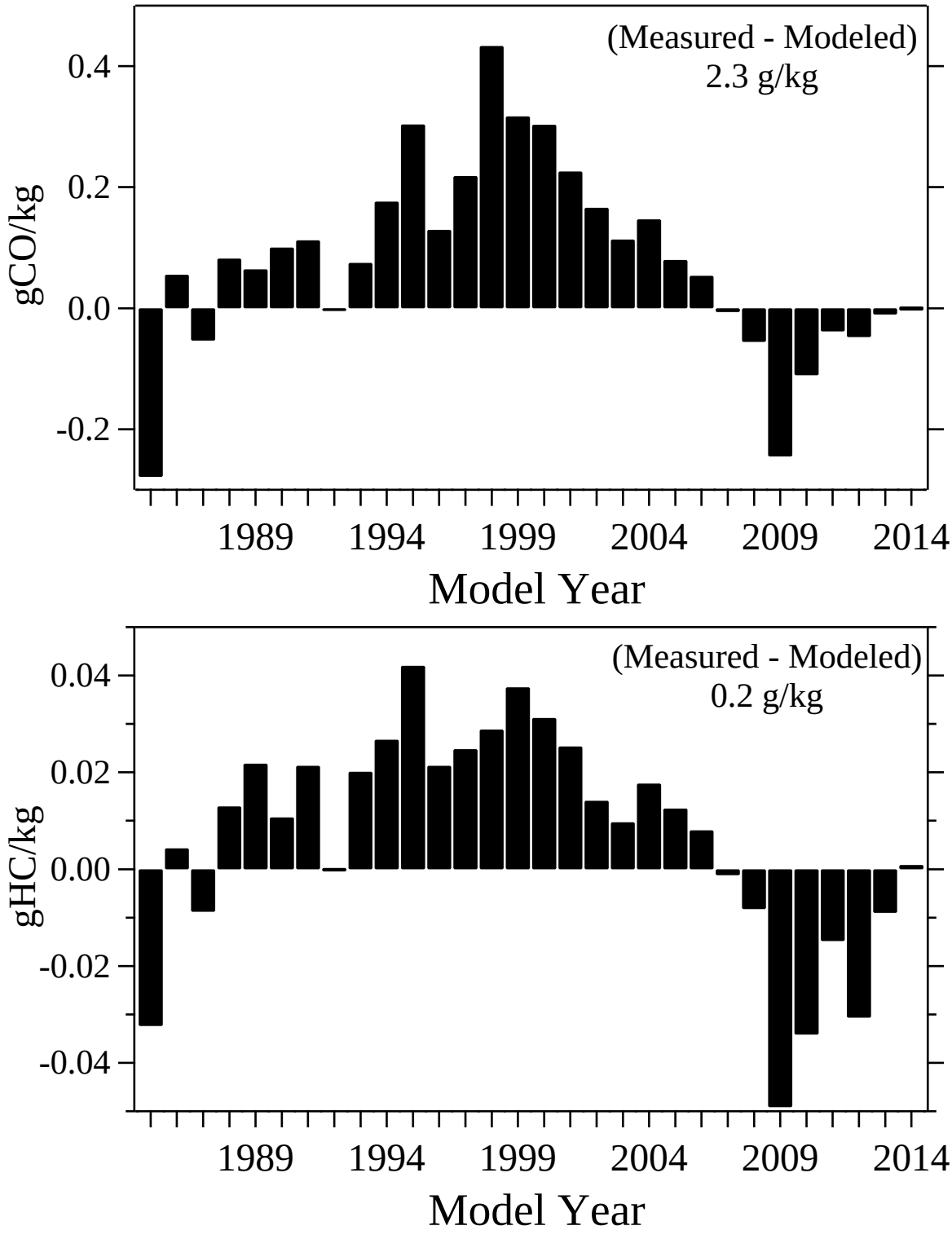

Figure 9. Plots of the measured minus modeled emission differences in grams per kilogram for CO (top) and HC (bottom) as a function of model year. A positive value indicates the presence of emissions that likely would have been eliminated if fleet turnover rates had not been slowed by the recession. The sum total of the difference in g/kg is listed in the upper right hand corner of each graph.

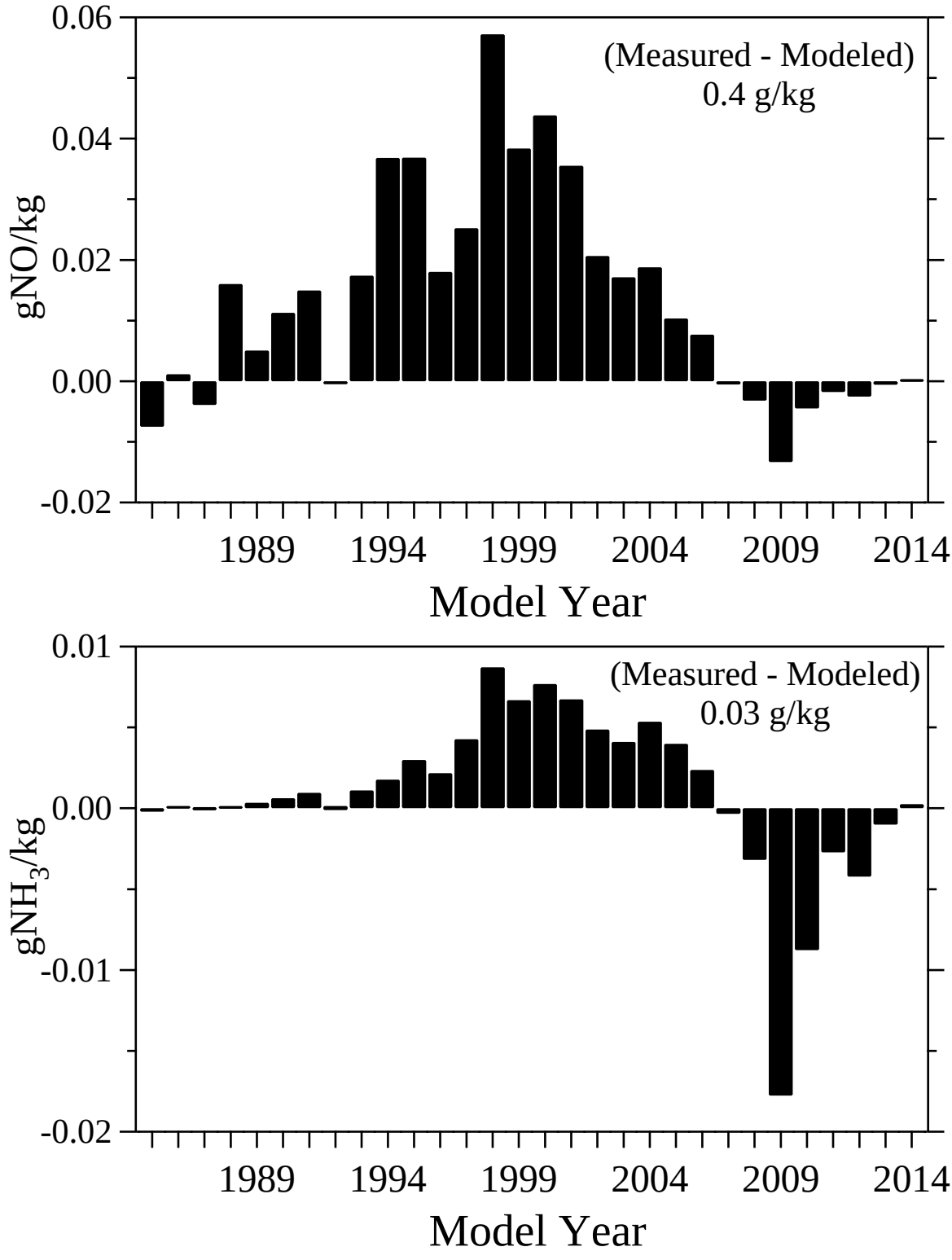

Figure 10. Plots of the measured minus modeled emission differences in grams per kilogram for NO (top) and NH_3 (bottom) as a function of model year. A positive value indicates the presence of emissions that likely would have been eliminated if fleet turnover rates had not been slowed by the recession. The sum total of the difference in g/kg is listed in the upper right hand corner of each graph.

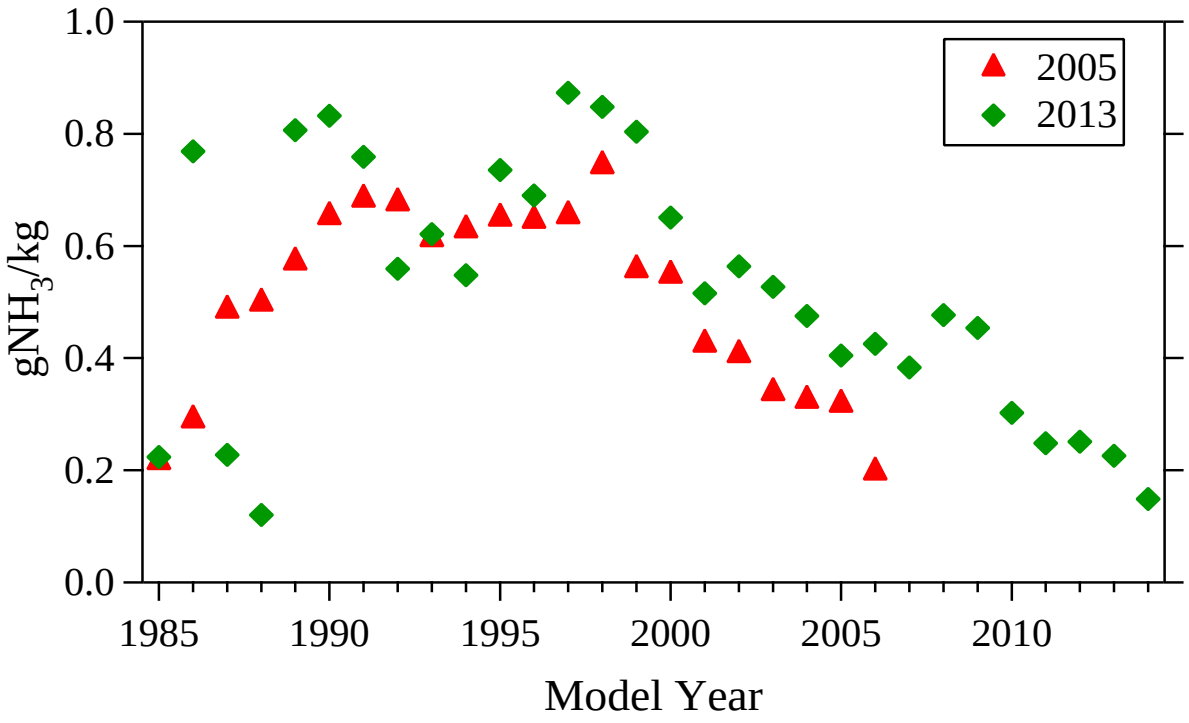

Figure 11. Mean gNH_3/kg emissions plotted against vehicle model year for the 2013 and 2005 measurements at the Tulsa site.

data sets were collected eight years apart, it is difficult to see if any differences exist between the two data sets graphed in this manner. Figure 12 compares the same two data sets but plots them against vehicle age, so year 0 is 2014 models for the most recent data set and 2006 models in the older data set. The errors plotted are standard errors of the mean calculated from distributing the daily means for each year's data.

In Figure 12 the differences between the two data sets are more obvious. In 2013, the rate of increase in NH_3 emissions as a function of vehicle age appears to be at a slightly lower rate than that observed in 2005. The other striking feature is the differences between the two datasets with respect to the average vehicle age at which NH_3 emissions peak and then begin to decrease. The unique shape of the NH_3 emissions trend, rising for a number of years and then retreating, has been linked with the path that the reducing capability of the three-way catalytic converter follows. The period of increasing NH_3 emissions has grown since 2005, though it is debatable as to the exact point in the 2005 data that the emissions peak. The 2005 data set rises for 10 years (1996 models) and starts to decline at 15 years (1991 models). The 2013 data set rises for 17 years (1997 models) and then declines which is more consistent with several other data sets collected since 2008.[27] 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.

The NH_3 mean emissions observed in 2005 and 2013 were 0.5 ± 0.01 g/kg and 0.43 ± 0.01 g/kg respectively, which is a 14% reduction in emissions over eight years. This difference has likely been negatively impacted by the aging of the light-duty fleet due to the 2008-2010 recession as previously discussed. We can estimate the recession's impact by applying the age distribution from the 2005 measurements to the 2013 data which lowers the 2013 measured mean gNH_3/kg to

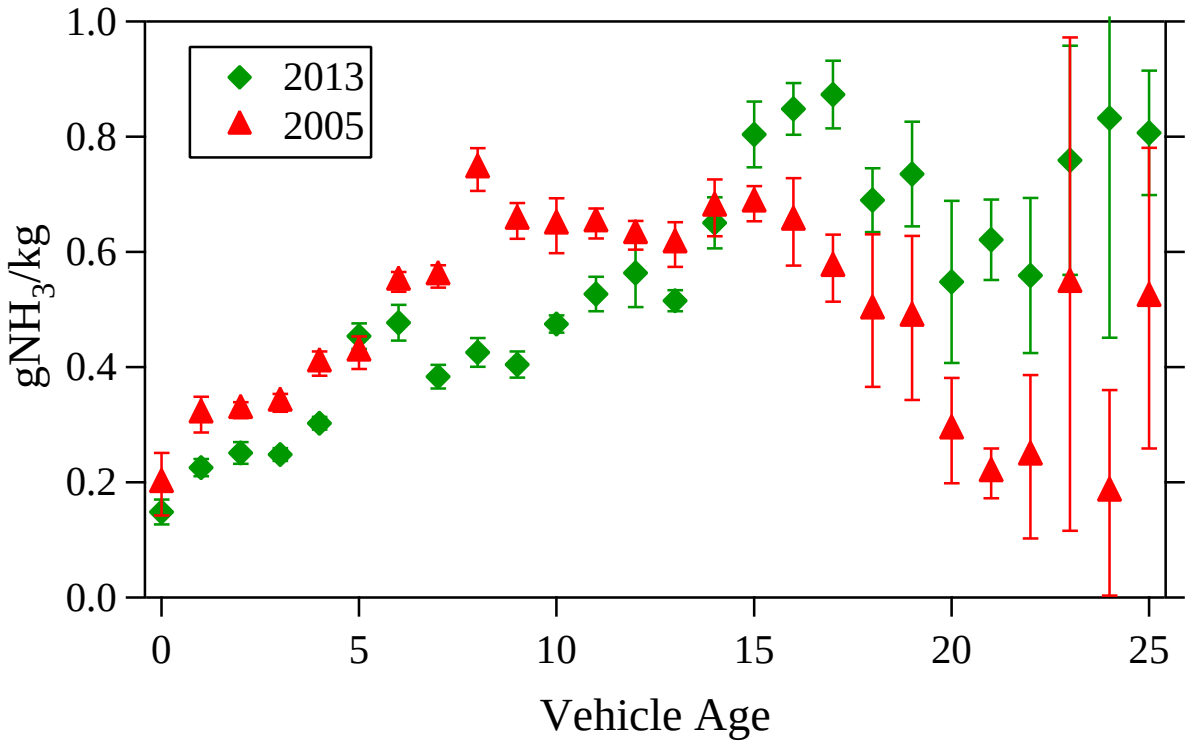

Figure 12. Mean gNH_3/kg emissions plotted against vehicle age for the 2013 and 2005 measurements at the Tulsa site. The uncertainty bars plotted are the standard error of the mean determined from the daily samples.

0.4, a 20% reduction when compared with the 2005 mean. The rate of reduction measured in Tulsa in 2013 is much smaller than reduction rates previously reported by Kean et al. in the Caldecott tunnel in California between 1999 and 2006 of 38% ± 6%.[23] In addition NO emissions at this Tulsa site have decreased by 46% (2.9 gNO/kg in 2005 to 1.5 gNO/kg in 2013) over the same time period. This raises the question why if NO emissions have decreased so dramatically during the eight year period has NH_3 not followed suit 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.[21, 29] 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.[22, 29]

An equation for determining the instantaneous power of an on-road vehicle has been proposed by Jimenez,[30] 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 13. 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 2013 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 2013 data showing significant overall 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 2013 dataset sorted by specific power bin.

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 7.8, 6.5, 0.2, 0.03 and 0.4 for CO, HC, NO, NH_3 and NO_2, respectively. These values indicate standard deviations of 11 g/kg (0.09%), 9.3 g/kg (223ppm), 0.3 g/kg (22ppm), 0.04 g/kg (7ppm) and 0.6 g/kg (26ppm) for individual measurements of CO, HC, NO, NH_3 and NO_2, respectively. These levels were higher than the low noise level as discussed in the Phoenix report.[31] This may be a result of the high winds that buffeted the site for the entire week of 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, 0.9 g/kg, 0.03 g/kg, 0.004 g/kg and 0.06 g/kg, respectively.

ACKNOWLEDGEMENTS

The successful outcome of this project would not be possible without the assistance of J. Bruce Arnold and Stan Westfall of the Oklahoma Department of Transportation, Brandon Welborn of the Oklahoma Tax Commission and Mrs. Annette Bishop whose plate reading skills were severely tested with this plate set. Comments from the various reviewers of this report were also invaluable.

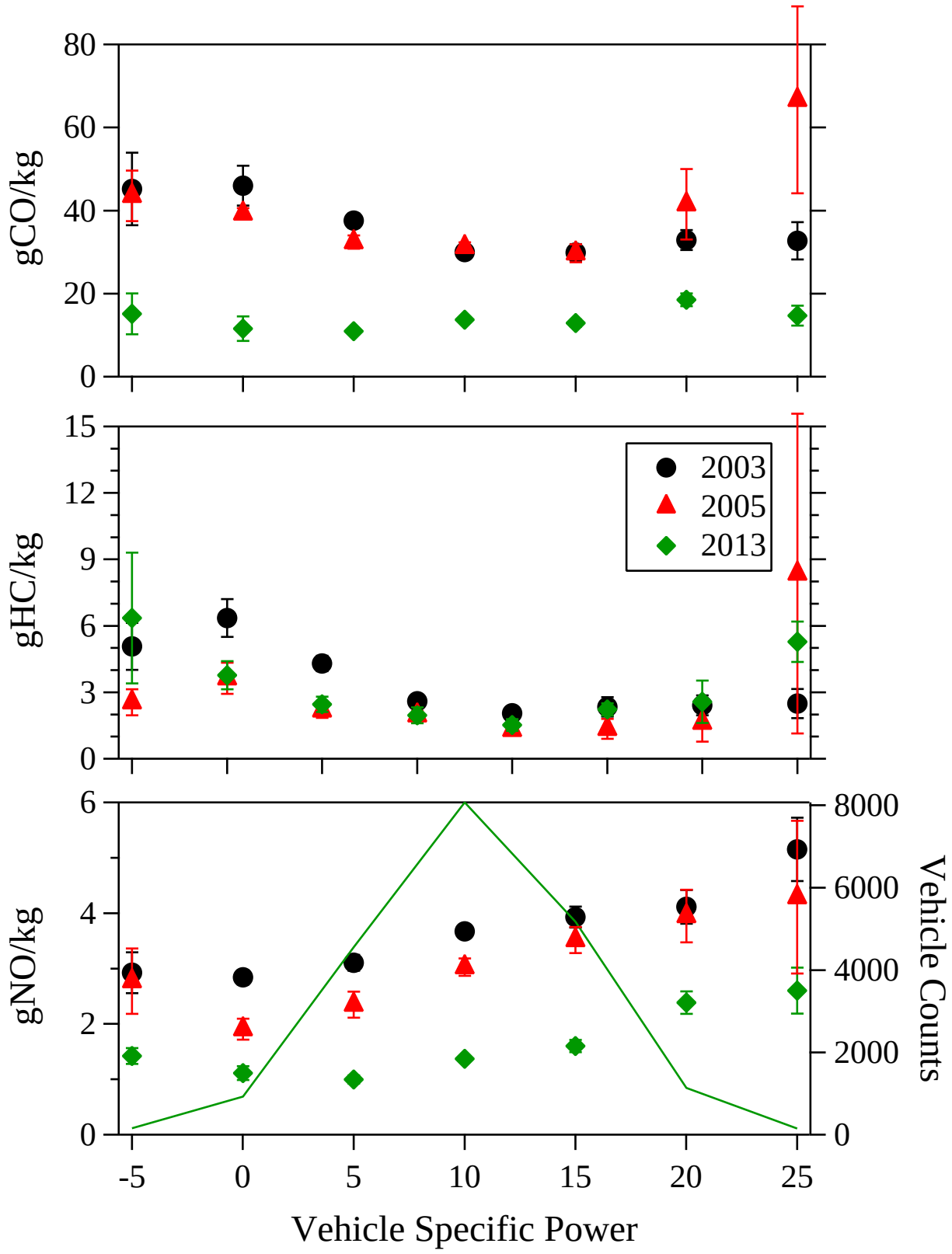

Figure 13. Vehicle emissions as a function of vehicle specific power for all of the Tulsa data sets. Error bars are standard errors of the mean calculated from the daily samples. The solid line without markers is the vehicle count profile for the 2013 data.

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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_13.dbf database.

The Tulsa_13.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	Oklahoma license plate.
Date	Date of measurement, in standard format.
Time	Time of measurement, in standard format.
Percent_CO	Carbon monoxide concentration, in percent.
CO_err	Standard error of the carbon monoxide measurement.
Percent_HC	Hydrocarbon concentration (propane equivalents), in percent.
HC_err	Standard error of the hydrocarbon measurement.
Percent_NO	Nitric oxide concentration, in percent.
NO_err	Standard error of the nitric oxide measurement.
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
GVW	Gross vehicle weight.
City	Registrant's mailing city.
State	Registrant's mailing State.
V_model	Vin decoded model information
V_body	Vin decoded body type (4D, PK, SP etc.)
V_type	Vin decoded Passenger (P) or Truck (T) type
V_engine	Vin decoded engine size in liters
V_wtclass	Vin decoded weight class
V_gvw	Vin decoded gross vehicle weight
V_fuel	Vin decoded fuel (G, D, F (flex), B (hybrid), C, N)
V_trans	Vin decoded transmission type
V_xdrive	Vin decoded all-wheel drive capability

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

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