On-Road Remote Sensing of Automobile Emissions in the Tulsa Area: Year 1, September 2003

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FOREWORD

This report is a collaborative work between the University of Denver, the Coordinating Research Council, consultant Dr. Robert Slott, and EPA Technical Monitor, Jim Lindner. Along with the work from Tulsa, additional measurements were made in other locations and a final analysis of the combined work was reported on separately. Conclusions stated in this report concerning comparisons with other E-23 sites and data should be considered preliminary and the reader is referred to CRC Final Report No. E-23-8 dated September 2006 in fulfillment of EPA Contract No. 68-C-02-048.

EXECUTIVE SUMMARY

The University of Denver conducted a five-day remote sensing study in the Tulsa, Oklahoma area in September of 2003. The remote sensor used in this study measures the ratios of CO, HC, and NO to CO_2 in motor vehicle exhaust. From these ratios, we calculate the percent concentrations of CO, CO_2, HC and NO 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.

Five days of fieldwork, September 8-12, 2003, were conducted on the uphill interchange ramp from westbound US64 (Broken Arrow Expressway) to southbound US169. A database was compiled containing 20,318 records for which the State of Oklahoma, the Cherokee Nation and the Muscogee (Creek) Nation provided registration information. All of these records contained valid measurements for at least CO and CO_2, and 20,295 records contained valid measurements for HC and NO 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 and NO emissions for the fleet measured in this study was 0.27%, 85ppm and 265ppm, respectively. These levels are much lower than a smaller sample of data collected in 1994 mirroring the national trend of decreasing vehicle emissions seen in other locations. The emissions measurements in this study exhibit a gamma distribution, with the dirtiest 10% of the measurements responsible for 70.8%, 74.5% (59% if not using offset adjusted data), and 60.5% of the CO, HC, and NO emissions, respectively. The HC readings contain a 30ppm offset, which has been used to reduce all of the measured HC values for comparisons.

An analysis of high emitting vehicles showed that there is considerable overlap of CO and HC high emitters, for instance 2.7% of the measurements contribute 31% of the total CO and 28% of the total HC. The noise levels in the CO, HC and NO measurement channels were determined to be within acceptable limits that were minimal when compared to the standard error of the mean of the measurements.

INTRODUCTION

Many cities in the United States are in violation of the air quality standards established by the Environmental Protection Agency (EPA). 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). As of 1998, on-road vehicles were estimated to be the single largest source for the major atmospheric pollutants, contributing 60% of the CO, 44% of the HC, and 31% of the NO_x to the national emission inventory.[1]

For a description of the internal combustion engine and causes of pollutants in the exhaust, see Heywood.[2] 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, many locations still violating the standard may have great difficulty reaching attainment.[3]

The 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.[4,5] The instrument consists of a non-dispersive infrared (NDIR) component for detecting CO, CO_2, and HC, and a dispersive ultraviolet (UV) spectrometer for measuring NO. The source and detector units are positioned on opposite sides of the road in a bi-static arrangement. Colinear beams of IR and UV light are passed across the roadway into the IR detection unit, and are then focused onto 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 off the surface of the beam splitter and is focused into the end of a quartz fiber-optic cable, which transmits the light to a UV spectrometer. The UV unit is then capable of quantifying NO by measuring an absorbance band at 226.5 nm in the UV spectrum and comparing it to a calibration spectrum in the same region.

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, wind, and turbulence behind the vehicle. For these reasons, the remote sensor directly measures only ratios of CO, HC or NO to CO_2. The ratios of CO, HC, or NO to CO_2, termed Q, Q' and Q'' 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 %CO, %HC and %NO in the exhaust gas, corrected for water and excess oxygen not used in combustion. The %HC measurement is a factor of two smaller than an equivalent

measurement by a flame ionization detector (FID).[6] Thus, in order to calculate mass emissions as described below, the %HC values reported will first be multiplied by 2.0 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.

$$\text{gm CO/gallon} = 5506 \bullet \%CO / (15 + 0.285 \bullet \%CO + 2(2.87 \bullet \%HC))$$
$$\text{gm HC/gallon} = 2(8644 \bullet \%HC) / (15 + 0.285 \bullet \%CO + 2(2.87 \bullet \%HC))$$
$$\text{gm NO/gallon} = 5900 \bullet \%NO / (15 + 0.285 \bullet \%CO + 2(2.87 \bullet \%HC))$$

These equations indicate that the relationship between concentrations of emissions to mass of emissions is linear, especially for CO and NO and 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.

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

$$\frac{\text{moles pollutant}}{\text{moles C}} = \frac{\text{pollutant}}{CO + CO_2 + 6HC} = \frac{(\text{pollutant}/CO_2)}{(CO/CO_2) + 1 + 6(HC/CO_2)} = \frac{(Q, 2Q', Q'')}{Q + 1 + 6Q'}$$

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 (as above) because the equation depends upon carbon mass balance and the NDIR HC reading is about half a total carbon FID reading.[6]

$$\text{gm CO/kg} = (28Q / (1 + Q + 6Q')) / 0.014$$
$$\text{gm HC/kg} = (2(44Q') / (1 + Q + 6Q')) / 0.014$$
$$\text{gm NO/kg} = (30Q'' / (1 + Q + 6Q')) / 0.014$$

Quality assurance calibrations are performed twice daily in the field unless observed voltage readings or meteorological changes are judged to warrant additional calibrations. A puff of gas containing certified amounts of CO, CO_2, propane and NO is released into the instrument's path, and the measured ratios from the instrument are then compared to those certified by the cylinder manufacturer (Praxair). These calibrations account for day-to-day variations in instrument sensitivity and variations in ambient CO_2 levels caused by local sources, atmospheric pressure and instrument path length. Since propane is used to calibrate the instrument, all hydrocarbon measurements reported by the remote sensor are 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.[7,8]

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 25ppm for NO, with an error measurement of ±5% of the reading at higher concentrations. Appendix A gives a list of criteria for valid or invalid data.

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 measurements, as well as a time and date stamp, are also recorded on the video image. The images are stored on videotape, 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 generates a pair of infrared beams passing across the road, six feet apart and approximately two feet above the surface. Vehicle speed is calculated from the time that passes between the front of the vehicle blocking the first and the second beams. 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, and reported in mph/s. Appendix B defines the database format used for the data set.

The purpose of this report is to describe the remote sensing measurements made in the Tulsa, Oklahoma area in the fall of 2003, under CRC Contract No. E-23-8. Measurements were made on five consecutive weekdays, from Monday, September 8, to Friday, September 12, between the hours of 7:00 and 19:00 on the uphill interchange ramp from westbound US64 (Broken Arrow Expressway) to southbound US169. A map of the measurement location is shown in Figure 1 and a photograph of the ramp is shown in Figure 2. The uphill grade at the measurement location ranged from 2.9° at the inside of the curve, 2.6° in the middle and 2.5° on the outside of the curve. A value of 2.6° has been used in the VSP calculations. Appendix C gives temperature and humidity data for the study obtained from Tulsa International Airport, approximately ten miles north of the measurement site.

RESULTS AND DISCUSSION

Following the five days of data collection in September of 2003, the videotapes were read for license plate identification. Oklahoma license plates are issued by the state and at least 20 tribal nations. Plates were coded for the State of Oklahoma and 20 tribal nations. A total of 14,016 unique plates were readable and 429 of these were issued by tribal nations. Out of the 429 tribal plates, 387 (90%) were issued by the Cherokee (186) and Muscogee (Creek) (201) Nations. Plates were sent to the State of Oklahoma, the Cherokee Nation and the Muscogee (Creek) Nation to have the vehicle make and model year determined. The resulting database contained 20,318 records with make and model year information and valid measurements for at least CO and CO_2. The database and all previous databases compiled for CRC E-23 campaigns can be found at www.feat.biochem.du.edu. Most of these records also contain valid measurements for

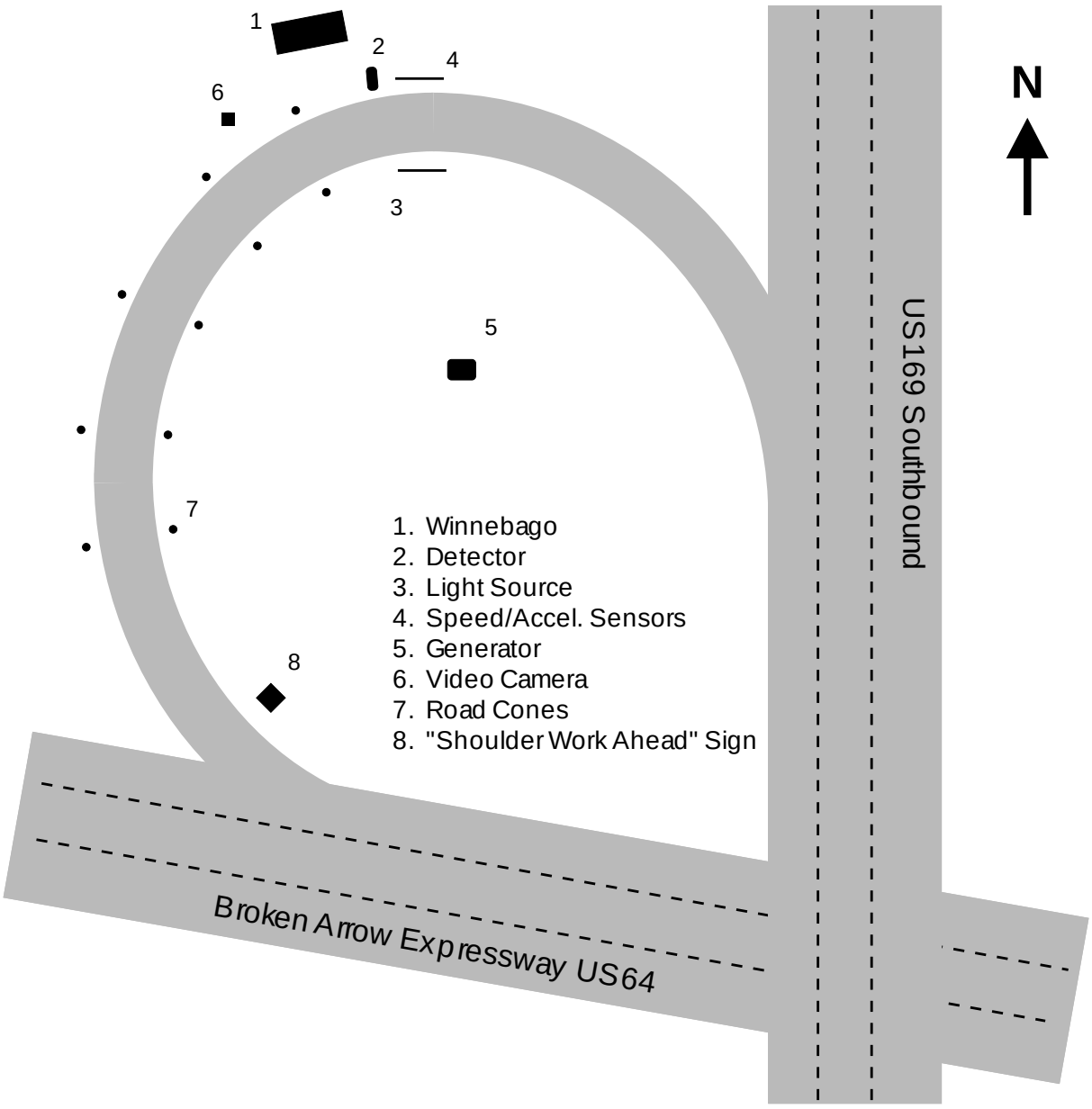

Figure 1. A schematic drawing of the ramp from Westbound US64 (Broken Arrow Expressway) to Southbound US169. The location and safety equipment configuration was for all five days of measurements.

HC and NO as well. 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

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

Table 1. Validity Summary.

	CO	HC	NO
Attempted Measurements		26,131	
Valid Measurements	24,434	24,402	24,428
Percent of Attempts	93.5%	93.4%	93.5%
Submitted Plates	21,137	21,113	21,132
Percent of Attempts	80.9%	80.8%	80.9%
Percent of Valid Measurements	86.5%	86.5%	86.5%
Matched Plates	20,318	20,300	20,313
Percent of Attempts	77.8%	77.7%	77.8%
Percent of Valid Measurements	83.2%	83.2%	83.2%
Percent of Submitted Plates	96.1%	96.1%	96.1%

plume is highly diluted, 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.

Table 2 provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured. Of the 20,318 records used in this fleet analysis, 9,431 (46.4%) were contributed by vehicles measured once, and the remaining 10,887 (53.6%) records were from vehicles measured at least twice. A look at the distribution of measurements for vehicles measured five or more times showed that low or negligible emitters had more normally distributed emission measurements, while higher emitters had more skewed distributions of measurement values.[9] For example, of the 410 vehicles that had five or more valid CO measurements, twenty-one had mean %CO>1. The means varied from 1.02 to 7.35. These twenty-one vehicles' calculated variances were 0.1, 2.3, 0.7, 2.3, 7.6, 0.9, 2.2, 1.4, 1.7, 1.8, 2.7, 2.1, 1.6, 2.5, 0.5, 0.2, 9.9, 9.2, 2.5, 1.5 and 1.0, while the average variance in the measurements of the other 389 vehicles was 0.08. This observation is expected in view of the known large variability in the emissions of high emitting vehicles regardless of the emission testing method.[9]

Table 2. Number of measurements of repeat vehicles.

Number of Times Measured	Number of Vehicles
1	9,431
2	1,869
3	899
4	536
5	265
6	80
7	38
>7	27

Table 3 is the data summary from the current work and some previous data collected at two freeway sites in 1994.[10] The 1994 data contains 5,319 measurements collected at eastbound I-44 to eastbound US64 (this is approximately 5 miles west of the site measured in 2003) and 1,713 measurements collected at Peoria Ave. to southbound US75. The data from this earlier work has not been located and the summary statistics reported here have been taken from the report.

The average HC values for the 2003 data have been adjusted 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. 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

Table 3. Data Summary.

Study Year Location	Tulsa 2003	Tulsa 1994 I-44 to US64	Tulsa 1994 Peoria to US75
Mean CO (%) (g/kg of fuel)	0.27 (34.0)	0.78	1.16
Median CO (%)	0.06	0.27	0.30
Percent of Total CO from Dirtiest 10% of the Fleet	70.8%	56%	50%
Mean HC (ppm) (g/kg of fuel) Offset (ppm)	85* (3.2)* 30	880	610
Median HC (ppm)	40*	580	370
Percent of Total HC from Dirtiest 10% of the Fleet	59.0%	39%	46%
Mean NO (ppm) (g/kg of fuel)	265 (3.7)		
Median NO (ppm)	53		
Percent of Total NO from Dirtiest 10% of the Fleet	60.5%		
Mean Model Year	1997.6		
Mean Speed (mph)	24.1		
Mean Acceleration (mph/s)	0.06		
Mean VSP (kw/tonne) Slope (degrees)	7.8 2.6°	flat	uphill
*Indicates values that have been HC offset adjusted as described in text.			

for the same site. The offset subtraction (30ppm) has been performed where indicated in the analyses in this report, but has not been applied to the archived database.

Figure 3 shows the distribution of CO, HC and NO emissions by percent or ppm category from the data collected in Tulsa in 2003. The black bars show the percentage of the fleet in a given emission category, and the shaded bars show the percentage of the total emissions contributed in that category. This figure illustrates the skewed nature of automobile emissions, showing that the lowest emission category is occupied by no less than 82% of the fleet (for HC) and as much as 94% of the fleet (for CO). The fact that the cleanest 94% of the fleet are responsible for only 41% of the CO emissions further demonstrates how the emissions picture can be dominated by a small number of high-emitting vehicles. The skewed distribution has also been seen at the other E-23 sites and is represented by the consistent high values of percent of total emissions from the dirtiest 10% of the fleet (see Table 3).

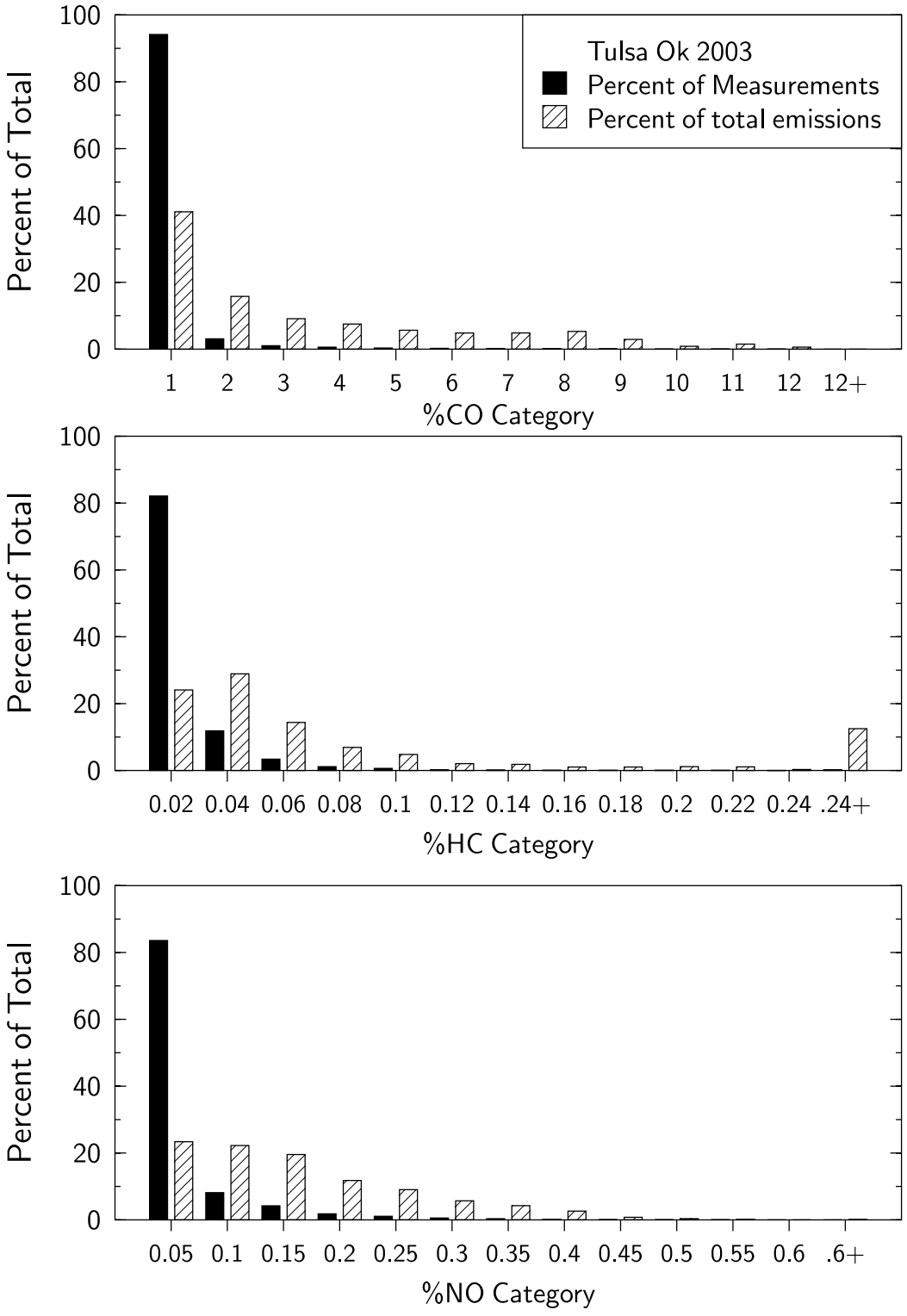

Figure 3. Emissions distribution showing the percentage of the measurements in a given emission category (black bars) and the percentage of the total emissions contributed by the category (shaded bars).

The inverse relationship between vehicle emissions and model year is shown in Figure 4 for data collected in Tulsa. The HC data have been offset adjusted here for comparison. Unlike the CO and HC plots, NO emissions vs. model year rises for about twelve years and then appears to level out in model years prior to 1993. This "leveling out" phenomenon has been observed previously,[5,11] and it has been proposed that the tendency for older vehicles to lose compression and operate under fuel-rich conditions negates the tendency for poor maintenance and catalyst deterioration to result in continually increasing NO emissions with age. Unlike data collected in Chicago from 1997-1999, the Tulsa measurements show increased mean emissions for the newest model year only for the HC data.[12] This is may be the result of the small sample size (79 vehicles) for model year 2004 and not a plate matching artifact.

As originally shown by Ashbaugh et al.,[13] vehicle emissions by model year, with each model year divided into emission quintiles, were plotted for data collected in Tulsa. This resulted in the plots shown in Figure 5. The bars represent the mean emissions for each quintile, and do not account for the number of vehicles in each model year. This figure illustrates that the cleanest 40% of the vehicles, regardless of model year, make an essentially negligible contribution to the total fleet emissions. The large 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, half of the readings will be negative and half will be positive. As the lowest emitting segments of the fleets continue to approach zero emissions, the negative emission readings will continue to grow toward half of the measurements.

Figure 5 can also be used to get a picture of federal compliance standards. The on-road data are measured as mass emissions per kg of fuel. It is not possible to determine mass emissions per mile for each vehicle because the instantaneous gasoline consumption (kg/mile) is not known. An approximate comparison with the fleet-average emissions shown in Figure 5 can, however, be carried out. To make this comparison, we assume a fuel density of 0.75 kg/L and an average gas mileage for all model years of 23mpg. The Tier 1, 100,000 mile standards for light duty gasoline vehicles for CO, HC, and NO are 4.2, 0.31, and 0.6 gm/mi, respectively. With the above assumptions, these correspond to 34, 2.5, and 4.9 gm/kg, respectively. Inspection of Figure 5 shows that significant fractions, especially of the newer vehicles, are measured with on-road emissions well below these standards.

An equation for determining the instantaneous power of an on-road vehicle has been proposed by Jimenez,[14] which takes the form

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

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 this equation, VSP was calculated for all measurements in each of the four years' databases. This

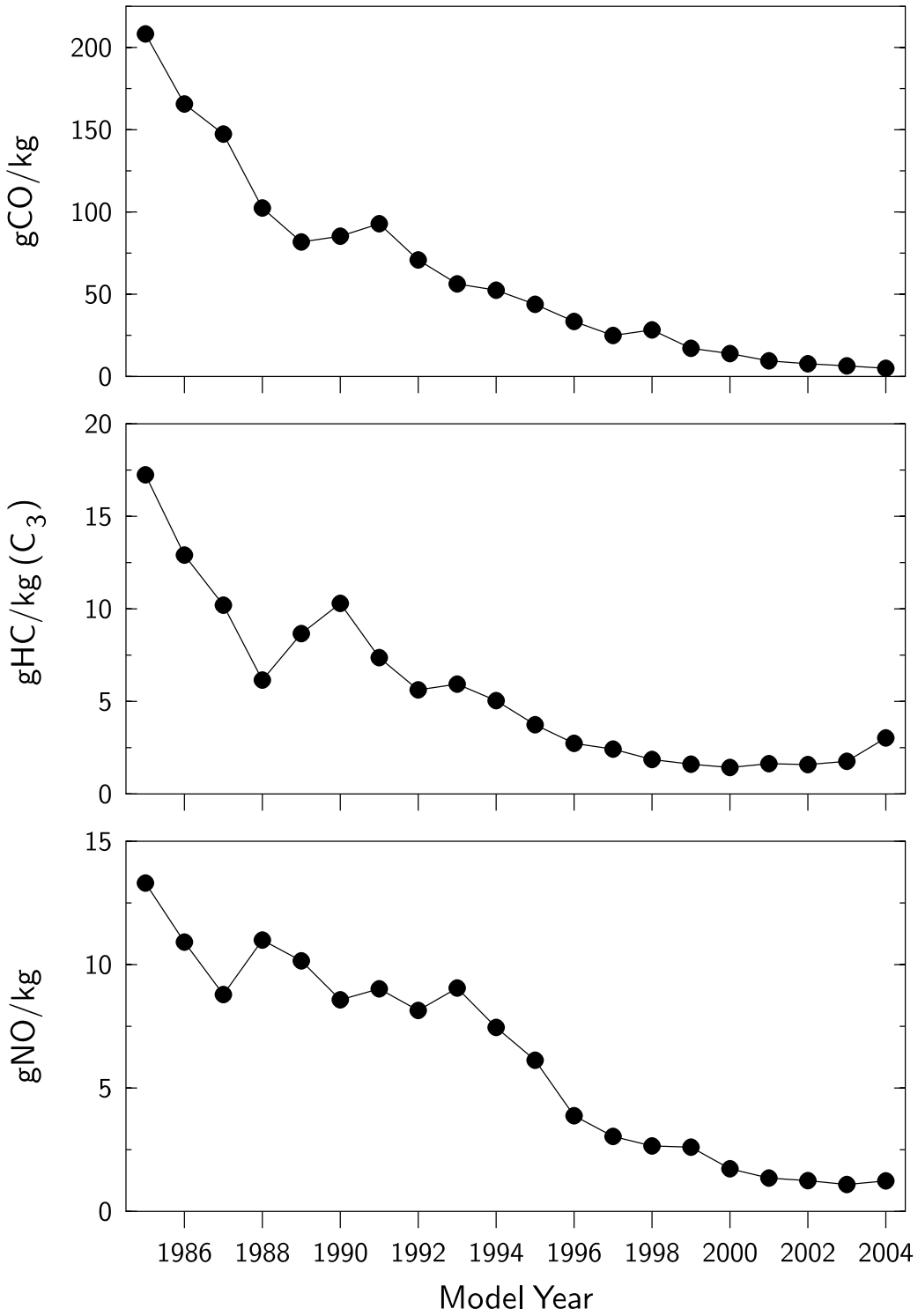

Figure 4. Mean vehicle emissions illustrated as a function of model year for the Tulsa data set. HC data have been offset adjusted as described in the text.

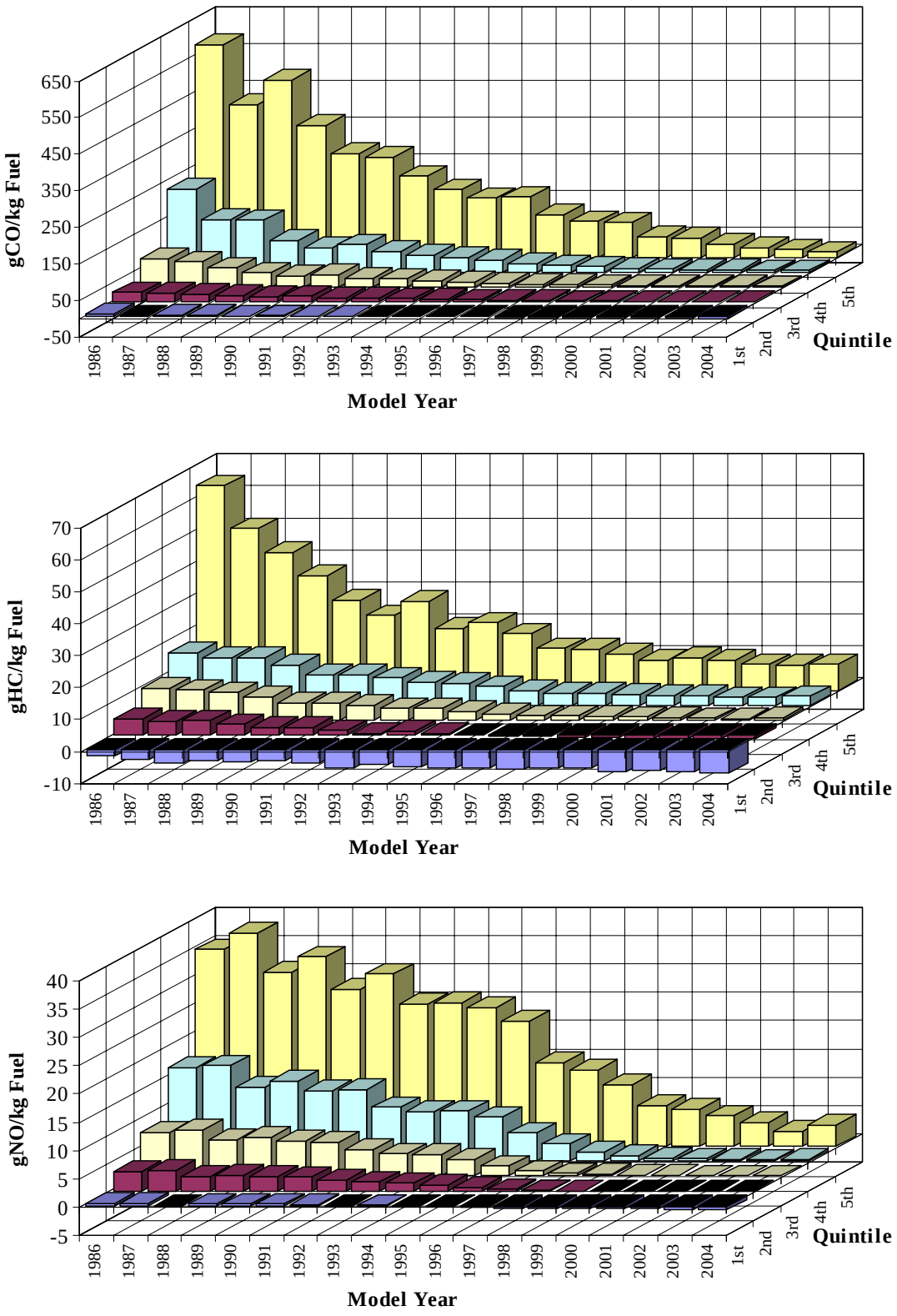

Figure 5. Vehicle emissions by model year for Tulsa, divided into quintiles.

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 6. All of the specific power bins contain at least 147 measurements and the HC data have been offset adjusted for this comparison. The Tulsa data shows similar emissions trends to other E-23 sites with the CO emissions being slightly bowl shaped, HC emissions trending downward at increasing VSP and NO emissions trending upward with increasing VSP. The error bars included in the plot are standard errors of the mean calculated from the daily averages. These uncertainties were generated for these γ-distributed data sets by applying the central limit theorem. Each day's average emission for a given VSP bin was assumed an independent measurement of the emissions at that VSP. Normal statistics were then applied to these daily averages.

Another use of the on-road remote sensing data is to predict the effectiveness with which high emitter identification for one pollutant actually predicts high emissions for another pollutant. One can look at the high CO emitters (as defined as the top emissions decile) and calculate that a percentage of these are also high emitting for HC, for example. This type of analysis would allow a calculation of the maximum HC emission benefits resulting from fixing all high CO emitters. To this extent, we have analyzed our data to determine what percent of the top decile of measurements of one pollutant is also in the top decile for another pollutant. These data are in Table 4; included in the analysis are only those readings that have valid readings for all three pollutants. The column heading is the pollutant whose top decile is being analyzed, and the values indicate the percentage of the fleet that is also in the top decile for the pollutants in the row headings. The values where the column and row headings are the same indicate the percentage that is in the top decile in that pollutant only. The "All" row gives the percentage of the readings that are in the top decile for all three pollutants. Thus, the table shows that 2.7% of the measurements are in the top decile for both HC and CO; 1.0% of the measurements are in the top decile for CO and NO; 5.2% of the measurements are only in the top CO decile.

Table 4. Percent of vehicle overlap in the top decile by exhaust species.

Top 10% Decile	CO	HC	NO
CO	5.2%	2.7%	1.0%
HC	2.7%	5.3%	0.9%
NO	1.0%	0.9%	7.0%
All	1.1%		

The preceding analysis gives the percent of vehicle overlap but does not directly give emissions overlap. In order to assess the overlap, one must convert the Table 4 values to percent of emissions. This number is a maximum because the normal variability of emissions readings, particularly from high emitters,[9] has not been included in this analysis. Table 5 shows that identification of the 5.2% of the measurements that are in the top CO decile only would identify an overall 28.2% of total measured on-road CO. More efficiently, identification of the 2.7%

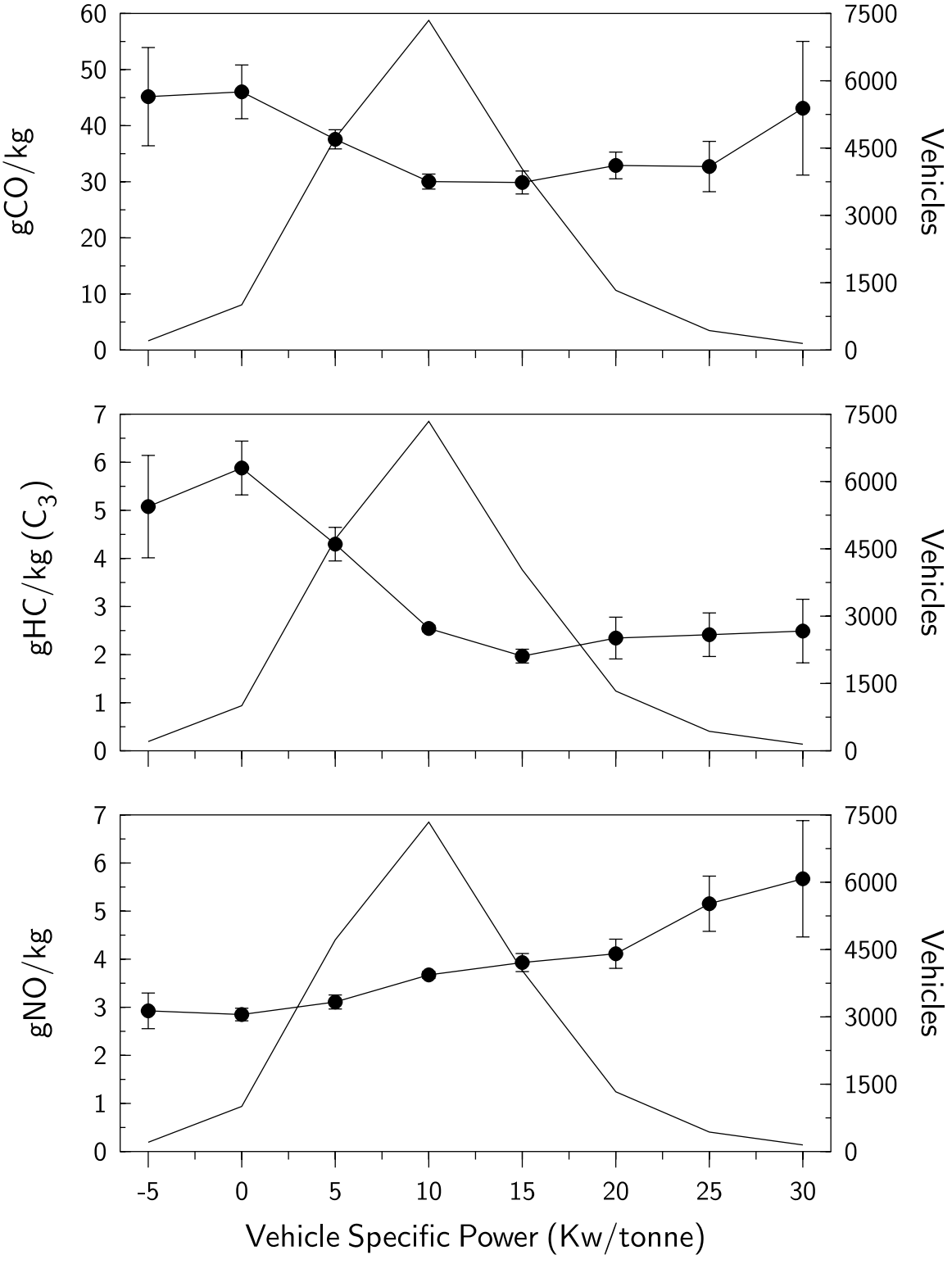

Figure 6. Vehicle emissions as a function of vehicle specific power for the Tulsa data. Error bars are standard errors of the mean calculated from the daily samples. The solid line without markers is the vehicle count profile.

vehicles in the top decile for both CO and HC account for 30.8% of the total CO and 27.5% of the total HC from these data.

Table 5. Percent of total g/kg emissions from the top decile vehicles.

Top 10% Decile	CO Emissions	HC[a] Emissions	NO Emissions
CO	28.2%	27.5%	6.9%
HC	30.8%	32.9%	5.9%
NO	4.6%	6.4%	41.1%
All	5.5%	7.7%	6.5%

[a]HC data used has been offset adjusted.

Most vehicles are low emitting and show little emissions variability when measured more than once. Vehicles that have one high reading often have other readings that vary widely.[9] This effect has also been observed from multiple FTP and IM240 tests. The evidence from pullover studies in California is that even one high reading identifies vehicles that have a >90% probability of failing an alternative I/M test if performed immediately. These vehicles also have a high probability of showing evidence of tampered or defective emission control equipment.[7,15] Because of this variability in the emissions of broken cars, the emissions distribution obtained from any snapshot of fleet emissions (remote sensing or annual I/M testing) is bound to be more skewed than were one able to monitor the emissions of all vehicles at all times. This phenomenon does not affect the means measured by these snapshots, but it does imply that the overlap and high emitter fractions in the tables above would show less skewness were one able to fully characterize all vehicles and their variability.

In the manner described in the Phoenix, Year 2 report,[16] 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. 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 5.2, 3.9, and 0.4 for CO, HC and NO, respectively. These values indicate standard deviations of 7.3 g/kg (0.06%), 5.5 g/kg (132ppm) and 0.6 g/kg (47ppm) for individual measurements of CO, HC and NO, respectively. These levels are consistent with the low noise level as discussed in a previous Phoenix report.[16] 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, which is the low limit for number of measurements per bin, the uncertainty reduces by a factor of 10. Thus, the uncertainties in the averages of 100 measurements reduce to 0.7 g/kg, 0.6 g/kg, and 0.06 g/kg, respectively.

CONCLUSIONS

The University of Denver has completed a week of measurements in the Tulsa, OK area. A database was compiled containing 20,318 records for which the State of Oklahoma, the Cherokee Nation and the Muscogee (Creek) Nation provided registration information. All of these records contained valid measurements for at least CO and CO_2, and 20,295 records contained valid measurements for HC and NO as well.

The mean CO, HC and NO emissions for the fleet measured in this study was 0.27%, 85ppm and 265ppm, respectively. These levels are much lower that a smaller sample of data collected in 1994 mirroring the national trend of decreasing vehicle emissions seen in other locations. The fleet emissions observed at the site exhibited a skewed distribution, with most of the total emissions contributed by a relatively small percentage of the measurements. Data are available at www.feat.biochem.du.edu for the Tulsa measurements and all of the other measurement campaigns undertaken by the University of Denver.

An analysis of high emitting vehicles showed that there is considerable overlap of CO and HC high emitters, for instance 2.7% of the measurements contribute 31% of the total CO and 28% of the total HC. The noise levels in the CO, HC and NO measurement channels were determined to be within acceptable limits that were minimal when compared to the standard error of the mean of the measurements.

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ACRONYMS

CO – Carbon monoxide
CO_2 – Carbon dioxide
CRC – Coordinating Research Council
EPA – Environmental Protection Agency
FID – Flame Ionization Detector
HC – Hydrocarbons
I/M – Inspection and Maintenance
IR – Infrared
MY– Model Year
NDIR – Non-Dispersive Infrared
NO – Nitric Oxide
PPM – Parts per million
UV – Ultraviolet
VSP – Vehicle Specific Power

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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".

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_03.dbf database.

The Tulsa_03.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 CD-ROM or FTP. The following is an explanation of the data fields found in this database:

License	Oklahoma, Cherokee or Muscogee nation 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”.
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.
Ref_factor	Measurements background reference voltage value.
CO2_factor	Measurements background CO_2 voltage value.
Vin	Vehicle identification number.
Make	Manufacturer of the vehicle.
Year	Model year.

Model	Oklahoma model designation.
Body_style	Oklahoma designated body style
GVW	Gross vehicle weight.
City	Registrant’s mailing city.
State	Registrant’s mailing State.
County	County of registration.
Zip	Registrant's mailing zip code.
Exp_year	Tag expiration year.
Exp_month	Tag expiration month.
Nation	Nation of registrations.

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

APPENDIX D: Example Calculation of Vehicle Specific Power Adjusted Vehicle Emissions

1997 (Measured)	VSP Bin	Mean NO (ppm)	No. of Measurements	Total Emissions
	-5	236	225	53200
	0	224	1609	360090
	5	307	4985	1531000
	10	431	6146	2648020
	15	548	2624	1438060
	20	590	456	269180
			16045	6299550
			Mean NO (ppm)	**393**
1998 (Measured)	VSP Bin	Mean NO (ppm)	No. of Measurements	Total Emissions
	-5	233	137	31951
	0	239	784	187394
	5	265	3613	956613
	10	385	6685	2576433
	15	475	6012	2856195
	20	483	2392	1156320
			19623	7764906
			Mean NO (ppm)	**396**
1998 (Adjusted)	VSP Bin	'98 Mean NO (ppm)	'97 No. of Meas.	Total Emissions
	-5	233	225	52474
	0	239	1609	384588
	5	265	4985	1319877
	10	385	6146	2368700
	15	475	2624	1246616
	20	483	456	220436
			16045	5592691
			Mean NO (ppm)	**349**

Note that the Mean NO readings listed here have been rounded to the nearest ppm values which results in the Total Emissions column appearing to not be a direct multiplication product. The -5 to 20 kw/tonne bins are chosen to preclude any "off-cycle" emissions.

The object of this adjustment is to have the 1998 fleet's emissions calculated as if they drove (VSP wise) like the 1997 fleet. This is accomplished by first binning and averaging the 1997 and 1998 data (the top two tables). We then combine the mean NO values from the 1998 fleet with the numerical VSP bin distribution from the 1997 fleet in the bottom table. The product of these two columns is summed and the sum total emissions are divided by the number of 1997 vehicles to produce the 1998 adjusted mean NO average. For this example, it shows that the 1998 fleet when driven like the 1997 fleet has lower NO emissions than the 1997 fleet.

APPENDIX E: Example Calculation of Model Year Adjusted Fleet Emissions

1997 (Measured)	Model Year	Mean NO (ppm)	No. of Measurements	Total Emissions
	83	690	398	274620
	84	720	223	160560
	85	680	340	231200
	86	670	513	343710
	87	690	588	405720
	88	650	734	477100
	89	610	963	587430
	90	540	962	519480
	91	500	1133	566500
	92	450	1294	582300
	93	460	1533	705180
	94	370	1883	696710
	95	340	2400	816000
	96	230	2275	523250
	97	150	2509	376350
			17748	7266110
			Mean NO (ppm)	**409**
1998 (Measured)	Model Year	Mean NO (ppm)	No. of Measurements	Total Emissions
	83	740	371	274540
	84	741	191	141531
	85	746	331	246926
	86	724	472	341728
	87	775	557	431675
	88	754	835	629590
	89	687	1036	711732
	90	687	1136	780432
	91	611	1266	773526
	92	538	1541	829058
	93	543	1816	986088
	94	418	2154	900372
	95	343	2679	918897
	96	220	2620	576400
	97	177	3166	560382
			20171	9102877
			Mean NO (ppm)	**451**
1998 (Adjusted)	Model Year	'98 Mean NO (ppm)	'97 No. of Meas.	Total Emissions
	83	740	398	294520
	84	741	223	165243
	85	746	340	253640
	86	724	513	371412
	87	775	588	455700
	88	754	734	553436
	89	687	963	661581
	90	687	962	660894
	91	611	1133	692263
	92	538	1294	696172
	93	543	1533	832419
	94	418	1883	787094
	95	343	2400	823200
	96	220	2275	500500
	97	177	2509	444093
			17748	8192167
			Mean NO (ppm)	**462**

APPENDIX F: Field Calibration Record.

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