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On-Road Remote Sensing of Automobile Emissions in the Phoenix Area: Year 3

Sajal S. Pokharel

Gary A. Bishop

Donald H. Stedman

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Sajal S. Pokharel, Gary A. Bishop and Donald H. Stedman

Department of Chemistry and Biochemistry
University of Denver
Denver, CO 80208

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EXECUTIVE SUMMARY

The University of Denver conducted a five-day remote sensing study in the Phoenix, AZ area in the fall of 2000. The remote sensor used in this study is capable of measuring the ratios of CO, HC, and NO to CO_2 in motor vehicle exhaust. From these ratios, we calculate mass emissions per kg (or gallon) of fuel and the percent concentrations of CO, CO_2, HC and NO in motor vehicle exhaust which would be observed by a tailpipe probe, corrected for water and any excess oxygen not involved in combustion. The system used in this study was also 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. Furthermore, a second FEAT unit was set up and measured vehicles at two other location on the ramp.

Five days of fieldwork (November 13-17, 2000) were conducted on the uphill exit ramp from Hwy 202 / Sky Harbor Blvd. Westbound to Hwy 143 Southbound in Phoenix, AZ. A database was compiled containing 20,801 records for which the State of Arizona provided make and model year information. All of these records contained valid measurements for at least CO and CO_2, and 20,700 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 percent CO, HC, and NO were determined to be 0.37%, 0.0099%, and 0.045%, respectively. The fleet emissions measured in this study exhibit a gamma distribution, with the dirtiest 10% of the fleet responsible for 75%, 71%, and 53% of the CO, HC, and NO emissions, respectively. This year's HC readings seem to contain a negative offset such that the average HC of the cleanest make and model years are negative. Comparisons include removal of this negative offset.

This was the third year of a multi-year continuing study to characterize motor vehicle emissions and deterioration in the Phoenix area. However, because of the non-ideal driving mode at the site in the first year (1998), a new ramp similar to the Denver, Chicago and L.A. Basin sites had been used in 1999 and was again used this year. In 1999 measurements were made at two locations on the same ramp. Thus, this year a second instrument was used to measure at one of the locations while the main measurements were made throughout the week at the other more suitable location. Measurements were also made with the second instrument and a RSD3000 from ESP just upstream of the first instrument.

A comparison of measurements made at three locations on the ramp used this year showed that correctly measured VSP can account for many of the emissions differences observed at the two locations in 1999. An intercomparison of three on-road remote sensing instruments indicated that the devices measured pollutants equivalently and that data from the instruments can be compared when binned by model year.

Vehicle emissions as a function of vehicle specific power revealed that NO emissions show a positive dependence on specific power when speed and acceleration are measured before emissions. HC emissions show a negative dependence on specific power – the expected trends. Carbon monoxide emissions show a slight negative dependence on

specific power in the range from –5 to 25 kW/tonne.

Using vehicle specific power, it was possible to adjust the emissions of the vehicle fleet measured in 2000 to match the vehicle driving patterns of the fleet measured in 1999 (at the two locations) and 1998. After doing so, it was seen that the emissions measured in the current year are not significantly different from those measured during the previous two years. Model year adjustments gave similar results.

Tracking of model year fleets through three measurements indicated that the rate of emissions deterioration increases significantly after the vehicle has aged several years, though the analysis was somewhat confounded by alterations in measurement site. An analysis of high emitting vehicles showed that there is considerable overlap of CO and HC high emitters, for instance 2.7% of the fleet emit 20% of the total CO and 19% of the total HC. The noise levels in the CO, HC and NO measurement channels were determined to be minimal.

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]

According to Heywood[2], carbon monoxide emissions from automobiles are at a maximum when the air/fuel ratio is rich of stoichiometric, and are caused solely by a lack of adequate air for complete combustion. Hydrocarbon emissions are also maximized with a rich air/fuel mixture, but are slightly more complex. When ignition occurs in the combustion chamber, the flame front cannot propagate within approximately one millimeter of the relatively cold cylinder wall. This results in a quench layer of unburned fuel mixture on the cylinder wall, which is scraped off by the rising piston and sent out the exhaust manifold. With a rich air/fuel mixture, this quench layer simply becomes more concentrated in HC, and thus more HC is sent out the exhaust manifold by the rising pistons. There is also the possibility of increased HC emissions with an extremely lean air/fuel mixture when a misfire can occur and an entire cylinder of unburned fuel mixture is emitted into the exhaust manifold. Nitric oxide (NO) emissions are maximized at high temperatures when the air/fuel mixture is slightly lean of stoichiometric, and are limited during rich combustion by a lack of excess oxygen and during extremely lean combustion by low flame temperatures. In most vehicles, practically all of the on-road NO_x is emitted in the form of NO.[2] Properly operating modern vehicles with three-way catalysts are capable of partially (or completely) converting engine-out CO, HC and NO emissions to CO_2, H_2O and N_2.[2]

Control measures to decrease mobile source emissions in non-attainment areas include inspection and maintenance (I/M) programs, oxygenated fuel mandates, and transportation control measures, but the effectiveness of these measures remains questionable. 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 (IR) component for detecting carbon monoxide, carbon dioxide (CO_2), and hydrocarbons, and a dispersive ultraviolet (UV) spectrometer for measuring nitric oxide. The source and detector units are positioned on opposite sides of the road in a bi-static arrangement. Collinear beams of 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 distributes 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 an ultraviolet spectrometer. The UV unit is then capable of quantifying nitric oxide by measuring an absorbance band at 226.5 nm in the ultraviolet spectrum and comparing it to a calibration spectrum at the same wavelength.

The exhaust plume path length and the 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 can only directly measure 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. The remote sensor used in this study reports the %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 an FID instrument.[6] Thus, in order to calculate mass emissions the %HC values in the equations below would be RSD measured values multiplied by 2. These percent emissions can be directly converted into mass emissions per gallon by the equations shown below.

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

These equations indicate that the relationship between concentrations of emissions to mass of emissions is almost linear, especially for CO and NO and at the typical low concentrations for HC. Thus, the percent differences in emissions calculated from the concentrations of pollutants reported here are equivalent to differences calculated from the fuel-based mass emissions of the pollutants.

Another useful conversion is directly from the measured ratios to g pollutant per kg of fuel. This conversion is achieved directly by first converting the pollutant ratio readings to the moles of pollutant per mole of carbon in the exhaust from the following equation:

$$\frac{\text{moles pollutant}}{\text{moles C}} = \frac{\text{pollutant}}{CO + CO_2 + 3HC} = \frac{(\text{pollutant}/CO_2)}{(CO/CO_2) + 1 + 6(HC/CO_2)} = \frac{(Q, 2Q', Q'')}{Q + 1 + 6Q'}$$

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]

Quality assurance calibrations are performed as dictated in the field by the atmospheric conditions and traffic volumes. 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 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. Tests involving a late-model low-emitting vehicle indicate a detection limit (±3•) of 25 ppm for NO, with an error measurement of ±5% of the reading at higher concentrations. Appendix A gives a list of the criteria for valid/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 information for the vehicle, as well as a time and date stamp, is 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 generate a pair of infrared beams passing across the road, 6 feet apart and approximately 2 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 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 and reported in mph/s.

The purpose of this report is to describe the remote sensing measurements made in the Phoenix, AZ area in November 2000, under CRC contract no. E-23-4. Measurements were made for 5 consecutive weekdays, from Monday, Nov. 13 to Friday, Nov. 17, conducted on the uphill exit ramp from Hwy 202 / Sky Harbor Blvd. Westbound to Hwy 143 Southbound in Phoenix, AZ.   This intersection is just east of Sky Harbor Airport, and the ramp consists of a rather large loop approximately a mile long. The main instrument was located as far up the ramp as possible (location A) – same location as was used during the last three days of measurement in 1999. Measurements were also made with a second instrument 9 yards upstream (location B) of the main instrument and approximately 200 yards upstream (location C) – at the location used during the first two days of measurement in 1999. The uphill road grades at the three measurement locations are as follows: A – 2.2%, B – 1.9%, C – 2.4%. The analyses presented herein refer to the data from location A unless stated otherwise. Measurements were generally made between the hours of 6:00 and 17:00. This was the third year of a multi-year study to characterize motor vehicle emissions and deterioration in the Phoenix area.

RESULTS AND DISCUSSION

Following the five days of data collection in November of 2000, the videotapes were read for license plate identification. Plates which appeared to be in-state and readable were sent to the State of Arizona to be matched against registration records. The resulting database contained 20,801 records with registration information and valid measurements for at least CO and CO_2. Most of these records also contained valid measurements for HC and NO (see Table I). The complete structure of the database and the definition of terms are included in Appendix B. The temperature and humidity record from nearby Sky Harbor Airport is included in Appendix C.

Table 1: Validity summary.

	CO	HC	NO
Attempted Measurements		28,800	
Valid Measurements	26,458	26,331	26,431
Percent of Attempts	91.9%	91.4%	91.8%
Submitted Plates	21,086	21,006	21,062
Percent of Attempts	73.2%	73.1%	73.1%
Percent of Valid Measurements	79.7%	80.0%	79.7%
Matched Plates	20,801	20,723	20,777
Percent of Attempts	72.2%	72.0%	72.1%
Percent of Valid Measurements	78.6%	78.7%	78.6%
Percent of Submitted Plates	98.6%	98.7%	98.6%

The percent validity this year (92%) is higher than the validity at other E-23 sites due to vehicles being under higher load at this location than at location C (used during the first two days in 1999) and at the site in 1998. Furthermore, the greatest loss occurs during the license plate reading process where hitches, trailers, etc. obstruct the view of the license plate.

Table 2. Number of measurements of repeat vehicles.

Number of Times Measured	Number of Vehicles
1	9,047
2	2,065
3	1246
4	677
5	176
6	29
7	9
>7	7

Table 2 provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured. Of the 20,081 records used in this fleet

analysis, 9,047 (45%) were contributed by vehicles measured once, and the remaining 11,034 (55%) 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, as shown previously by Bishop *et al.*[9] Figure 2 illustrates this phenomenon. The high emitters (vehicles which registered at least one measurement above 1% CO) have most measurements clustered near zero even though occasionally they emit >1% CO.

Table 3: Overall Fleet Data Summary

	2000*	1999*	1998*
Mean CO (%) (g/kg of fuel)	0.27 (34.2)	0.31 (38.3)	0.28 (35)
Median CO (%)	0.05	0.06	0.07
Percent of Total CO from Dirtiest 10% of the Fleet	75.5	77.8	70.7
Mean HC (ppm)[†] (g/kg of fuel)[†]	99 (2.0)	85 (1.7)	110 (2.2)
Median HC (ppm)[†]	70	40	10
Percent of Total HC from Dirtiest 10% of the Fleet[†]	71.1	79.0	65.5
Mean NO (ppm) (g/kg of fuel)	448 (6.4)	572 (8.1)	360 (5.1)
Median NO (ppm)	99	167	120
Percent of Total NO from Dirtiest 10% of the Fleet	52.6	49.1	56.0
Mean Model Year	1995.3	1994.0	1993.3
Mean Speed (mph)	35.0	34.6	37.2
Mean Acceleration (mph/s)	1.1	1.22	-0.7

* 1998 data from previous site, 1999 data from current site at both locations A and C, 2000 data from location A only (see below). [†]HC offset corrected.

Table 3 is the data summary; included is the summary of the previous remote sensing database collected by the University of Denver at the older site in the Phoenix area in the Fall of 1998 and the 1999 data from the current site. Since the site of measurement during the three years was not the same, it is difficult to compare these fleet averages because influential factors such as load are not constant. More realistically comparable numbers are given below.

The fleet measured in 2000 seems to have approximately the same average CO and HC emissions as in the previous two years of measurement. The NO emissions, however, are

somewhat lower than 1999 and higher than 1998. These differences may be due to load variability among the year 1 site, location C (used during two days of measurement in 1999) and the current location. The influence of load is discussed below. The mean age (Year of measurement – Model year) of the fleets also fluctuates during the three years. The 1999 fleet was 0.3 years older than the fleet measured during the other two years. This may also account for the higher NO in 1999.

The average HC values here have been adjusted so as 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, but diagnosis has proved difficult. In the absence of a true diagnosis of the problem, we proposed a remedy to remove the offset and obtain data that can be compared from the several years of study. This adjustment was to subtract a predetermined offset from the averaged data. The offset was determined as the average emissions of the cleanest model year and make of vehicles from each data set. Since we assume the cleanest vehicles to emit next to nothing, such an approximation will only err slightly towards clean because the true offset will be a value somewhat less than the average of the cleanest model year and make. However, this procedure adjusts the data so that measurements from different years can be compared.

The make/model year groups chosen are restricted to those containing at least 200 measurements. The groups with the lowest average emissions are not always the same during the different years of measurement. Instead, the groups tend to be up to three-year old model years from one or more of the following makes: Ford, Chevrolet, Toyota and Honda. For example, in this year's data set the 2000 Honda and Toyota groups had the lowest average HC emissions (in fact, they were negative) so were chosen as the offset standards and gave an average offset of –60 ppm. For the Phoenix data sets, offsets were determined to be 80, 50, and -60 ppm for yearly measurements conducted between 1998 and 2000, respectively. The offset subtraction (actually addition in 2000) has been performed here and later in the analysis unless otherwise indicated.

Figure 3 shows the distribution of CO, HC, and NO emissions by percent category from the data collected in this study. The solid bars show the percentage of the fleet in a given emissions category, and the gray bars show the percentage of the total emissions contributed by the given category. This figure illustrates the skewed nature of automobile emissions, showing that the lowest emission category for each of three pollutants is occupied by no less than 73% of the fleet (for NO), and as much as 93% of the fleet (for CO and HC). The fact that the cleanest 93% of the vehicles are responsible for only 39% of the CO emissions further demonstrates how the emissions picture can be dominated by a small number of high emitting vehicles. This skewed distribution was also seen in 1998 and 1999 and is represented by the consistent high values of percent of total emissions from the dirtiest 10% of the fleet (see Table 3).

Figure 4 illustrates the data in a different manner. The fleet is divided into deciles, showing the mean measurement for each decile. The ten bars illustrate the emissions that a fleet of ten vehicles would have if it were statistically identical to the observed fleet. Again, the skewed nature of the data distribution is evident, as the average emissions for each bin increases non-linearly from decile to decile.

The inverse relationship between vehicle emissions and model year has been observed at a number of locations around the world, and Figure 5 shows that the fleet in the Phoenix area, during all three years of measurement, is not an exception.[4] The plot of % NO vs. model year rises rather sharply, at least compared to the plots for CO and HC, and then appears to level out in model years prior to 1987. This has been observed previously,[5, 10] and is likely due to the tendency for older vehicles to lose compression and operate under fuel-rich conditions, both factors resulting in lower NO emissions. Unlike data collected in Chicago from 1997-1999, the Phoenix measurements do not show a tendency for the mean and median emissions to increase significantly for the newest model year.[11] The absence is most likely due to license plates remaining with the vehicle in Arizona, as opposed to license plates moving with the owner, as is the case in Illinois.

Plotting vehicle emissions by model year, with each model year divided into emission quintiles results in the plots shown in Figure 6. Very revealing is the fact that, for all three major pollutants, the cleanest 40% of the vehicles, regardless of model year, make an essentially negligible contribution to the total emissions. This observation was first reported by Ashbaugh and Lawson in 1990.[12] The results shown here continue to demonstrate that broken emissions control equipment has a greater impact on fleet emissions than vehicle age.

An equation for determining the instantaneous power of an on-road vehicle has been proposed by Jimenez[13], which takes the form

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

where SP 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. Using this equation, vehicle specific power was calculated for all measurements in the database. The emissions data were binned according to vehicle specific power, and illustrated in Figure 7. The solid line in the figure provides the number of measurements in each bin. As expected, CO and HC emissions show a negative dependence on specific power in the VSP range of –10 to 20 kW/tonne. At values above 20 kW/tonne, CO emissions increase again, especially in the 2000 measurements, while HC values level off. The general VSP profiles of CO and HC emissions are consistent during the three years of measurement. The NO profile is somewhat shifted to higher ppm during 1999, however.

NO emissions in 2000 and 1999 also have less of a dependence on VSP than 1998 measurements. There has recently been significant analysis of the data to determine the cause of this discrepancy.[14] One possibility is that changing car/truck ratios with VSP cause the VSP plots to flatten out since cars and trucks have differing emissions. This possibility is discussed in Appendix G of the E-23 Phoenix, Year 2 report.[15]

Using vehicle specific power, it is possible to eliminate some of the influence of load and of driving behavior from the mean vehicle emissions for the 1998, 1999 and 2000 databases. Table 4 shows the mean emissions from vehicles in the 1998 database, from vehicles measured at the two locations in 1999 and from vehicles in 2000 with specific powers between -5 and 20 kW/tonne. Note that these emissions do not vary considerably

from the mean emissions for the entire databases, as shown in Table 2. Also shown in Table 4 are the mean emissions for the two 1999 locations and the 2000 fleet adjusted for specific power. This correction is accomplished by applying the mean vehicle emissions for each specific power bin in Figure 7, for each of the two locations in 1999 and the 2000 measurements, to the vehicle distribution, by specific power, for each bin from 1998. A sample calculation, for the specific power adjusted mean NO emissions in Chicago in 1998, is shown in Appendix D. The uncertainty values in the table are 95% confidence interval of the mean of daily averages. It can be seen from Table 4 that the mean VSP adjusted emissions during the three years and four locations of measurement are not significantly different from one another. The average NO measurement, and to some extent CO, at the second location in 1999 is somewhat higher than in 1998 and 2000 and even at the first location in 1999. These results indicate that the second location, or alternatively the last three days of measurements in 1999, contains a higher emitting fleet.

Table 4. Specific power adjusted fleet emissions (-5 to 20 kW/tonne only).

	1998	1999 Site C (measured)	1999 Site C (adjusted)	1999 Site A (measured)	1999 Site A (adjusted)	2000 Site A (measured)	2000 Site A (adjusted)
Mean CO (%)	**0.26 ±.04**	0.27 ±.02	**0.27 ±.02**	0.30 ±.02	**0.34 ±.03**	0.26 ±.02	**0.30 ±.02**
Mean HC (ppm)	**89 ±45**	84 ±22	**90 ±23**	90 ±23	**115 ±30**	100 ±25	**116 ±29**
Mean NO (ppm)	**365 ±62**	331 ±123	**311 ±119**	576 ±94	**551 ±90**	421 ±47	**408 ±46**

A correction similar to the VSP adjustment can be applied to a fleet of specific model year vehicles to look at model year deterioration, provided we use as a baseline only model years measured in the 1998 study. Table 5 shows the mean emissions for all vehicles from model years 1984 to 1999, as measured in 1998, 1999 and 2000. Applying the vehicle distribution by model year from 1998 to the mean emissions by model year from each of the other two years of measurement yields the model year adjusted fleet emissions. A sample calculation, for the model year adjusted mean NO emissions in Chicago in 1998, is shown in Appendix E. The emissions do not show a statistically significant deterioration effect, presumably due to site inconsistency. A better understanding of deterioration in the Phoenix fleet will be attained with continual measurements at the current site.

Table 5. Model year adjusted fleet missions (MY 1984-1999 only).

	1998	1999 (measured)	**1999 (adjusted)**	2000 (measured)	**2000 (adjusted)**
Mean CO (%)	**0.24±.04**	0.27±.02	**0.30±.02**	0.27±.02	**0.32±.02**
Mean HC (ppm)	**85±43**	71±18	**76±19**	94±24	**103±26**
Mean NO (ppm)	**335±57**	546±89	**584±95**	487±54	**540±60**

Vehicle deterioration can also be illustrated by Figure 8, which shows the mean emissions of the 1982 to 2001 model year fleet as a function of vehicle age. The first point for each model year was measured in 1998, the second in 1999 and the third in 2000. Vehicle age was determined by the difference between the year of measurement and the vehicle model year. The analysis is somewhat confounded by differences in measurement location during the three years of measurement. This is especially noticeable in the highly load dependent pollutant - NO - which measured high in 1999. Nevertheless, one may still observe that the most recent model years (up to 5 years old) show a small deterioration from one year to the next for CO and HC as seen at other E-23 sites.

Another use of the on-road remote sensing data is to predict the abundance of vehicles that are high emitting for more than one pollutant measured. One can look at the high CO emitters and calculate what percent of these are also high HC emitters, for example. This type of analysis would allow a calculation of 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 emitters of one pollutant are also in the top decile for another pollutant. These data are in Table 6; included in the analysis are only those vehicles that have valid readings for all three pollutants. The column heading is the pollutant whose top decile is being analyzed, and the values indicate what percentage of the fleet are high emitters only for the pollutants in the column and row headings. The values where the column and row headings are the same indicate the percentage that are high emitting in the one pollutant only. The "All" row gives the percentage of the fleet that is high emitting in all three pollutants.

Table 6: Percent of all vehicles that are high emitting.

Top 10% Decile	CO	HC	NO
CO	6.2%	2.7%	0.6%
HC	2.7%	5.6%	1.3%
NO	0.6%	1.3%	7.6%
All	0.5%	0.5%	0.5%

Thus, the table shows that 2.7% of the fleet are in the top decile for both HC and CO but not NO; 0.6% of the of the fleet is high emitting for CO and NO but not HC; 6.2% of the fleet are high CO emitters only.

Table 7: Percent of total emissions from high emitting vehicles.

Top 10% Decile	CO	HC	NO
CO	46.8%	19.0%	3.2%
HC	20.4%	39.5%	6.8%
NO	4.5%	9.2 %	39.9%
All	3.8%	3.5%	2.6%

The preceding analysis gives the percent of vehicle overlap but does not directly give emissions overlap. In order to assess the overall emissions benefit of fixing all high emitting vehicles of one or more pollutant, one must convert the Table 6 values to percent of emissions. Table 7 shows that identification of all vehicles that are high emitting for CO would identify an overall 19.0% of HC and 3.2% of NO reduction. More efficiently, identification of the 2.7% high CO and HC vehicles accounts for 20.4% of the total CO and 19% of the total on-road HC.

In the manner described in the Phoenix, Year 2 report[15], instrument noise was measured by looking at the slope of the negative portion of the log plots. 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 found to be 0.067, 0.020 and 0.0059 for CO, HC and NO, respectively. These values indicate standard deviations of 0.095%, 280 ppm and 83 ppm for individual measurements of CO, HC and NO, respectively. 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 reduce to 0.0095%, 28 ppm and 8.3 ppm, respectively. This HC noise puts these HC measurements in the lower of the two HC noise groups reported earlier.[15]

Laplace factors were also derived for the other two instruments whose measurements are analyzed below. For the FEAT 3005 unit these factors were 0.045, 0.019 and 0.010 for CO, HC and NO, respectively. The corresponding uncertainties in a bin of 100 measurements are 0.006% CO, 27 ppm HC and 14 ppm NO. The RSD3000 instrument (from ESP) had Laplace factors of 0.036, 0.005 and 0.006 for CO, HC and NO, respectively. Thus, the uncertainties for bins of 100 were 0.005% CO, 7 ppm HC and 8 ppm NO.

Table 8. Calculated standard deviations in averages of 100 measurements due to noise in three instruments for three pollutants.

	CO	HC	NO
FEAT 3002	0.0095%	28 ppm	8.3 ppm
FEAT 3005	0.006%	27 ppm	14 ppm
RSD3000	0.005%	7 ppm	8 ppm

Site Comparison

In the Phoenix area, we have measured vehicles at four locations for the current project. In the first year, FEAT was set up on an uphill exit ramp from I-10W to US 143N in Tempe, AZ. In the second year, the instrument measured vehicles at two locations on the exit ramp from Hwy 202 / Sky Harbor Blvd. Westbound to Hwy 143 Southbound in

Phoenix, AZ. The location during the first two days of measurements (location C) was approximately a quarter of the way down the ramp (270 yards) compared to the location during the last three days (location A), which was as far up the ramp as possible. During the current year's measurements, a whole set of measurements (5 days) was made at location A. A second FEAT instrument was used to make measurements at location C for two days and at location B, which is 10 yards upstream of location A (basically as close to location A as possible), for three days. These additional measurements at locations B and C were made in hopes that they would help enlighten some issues that arose during the 1999 measurements and analysis.[14-16] Furthermore, ESP measured emissions using a RSD3000 unit at location B during the two days in 2000 when the second FEAT unit was at location C. The instruments used at each location during the five days in 2000 are organized in Table 9. The number of measurements reported in the database for each day is also included in the table. The University of Denver made more than 32,000 measurements with FEAT instruments, while ESP contributed 4354 measurements.

Among the measurement locations on the same ramp in 1999 and 2000, fleet composition should be relatively constant. Age distribution, fraction of trucks and fraction of diesel vehicles are similar between the two years. This is especially true since measurements were made during the same week of the calendar year. Furthermore, when two instruments were used in 2000 they measured the same vehicles. Thus, differences in measured emissions among locations must arise from vehicle load or other external variables that were different among the days of measurement. Load, or vehicle specific power, is a variable that can be measured so it is analyzed as a possible cause of the differences in emissions, most notably for the discrepancies in average NO and NO vs. VSP profile between locations A and C in 1999.

Table 9. Summary of various instruments operating at three locations during 5 days.

Instrument	Day				
Measurements	1	2	3	4	5
Site A	FEAT 3002	FEAT 3002	FEAT 3002	FEAT 3002	FEAT 3002
	3393	2970	5053	5109	4276
Site B	FEAT 3005	ESP RSD3000	ESP RSD3000	FEAT 3005	FEAT 3005
	2182	2350	2004	3485	3047
Site C		FEAT 3005	FEAT 3005		
		866	1765		

Figure 9 gives the VSP distribution for the three locations on the ramp during the two years of measurement. Location C has a very narrow VSP distribution and is also centered at lower values compared to locations A and B. The distribution at location C is also shifted to somewhat lower VSP in 2000. The curves for location A during 1999 and 2000 are very similar, while location B is shifted slightly to higher VSP indicating that vehicle are at higher load before reaching measurement location A. These differences in VSP could cause differences in emissions. To normalize the effect of load, we look at emissions as functions of VSP.

These data are given in Figure 10. The CO and HC emissions from the various locations appear to generally overlap when grouped by VSP. There is only slight deviation with CO at low and high VSP ends. Surprisingly similar profiles occur within each measurement location (A or C). This is even true in terms of NO for location C. Furthermore, NO emissions at location C are dependent on VSP and follow a profile similar to that at other E-23 sites. Location B also shows an increase in NO with increasing VSP.

The NO plots continue to be unusual at location A. The 2000 curve follows a profile very similar to that in 1999 at location A. Although there is not a continual trend of NO with VSP, there is a hump between 0 and 30 kw/tonne VSP. The 2000 curve is, however, shifted down to lower ppm NO values more typical of automobile emissions measured at other sites. Reasons for the rather flat and high NO profile at location A in 1999 are discussed in a recently published paper.[16]

The high NO at low VSP may arise from trucks and older vehicles (which have higher NO) clustering at lower loads, raising the average NO at low VSP. Another possibility that was addressed as the cause for the high NO at low VSP was the simultaneous measurement of speed, acceleration and emissions. More specifically, there is a time lag between when combustion products are produced in the engine and when they are released out of the tailpipe and measured. If one assumes the vehicle responds (in terms of its motion) at the time when the combustion occurs, then speed and acceleration should be measured on a roadway somewhere before where emissions are measured. As is discussed in Jose Jimenez's doctoral thesis to the MIT Department of Mechanical Engineering[17], the time, and thus distance, between when emissions are produced in the engine and when they are emitted from the exhaust pipe is a function of VSP. At moderate and high loads, the time and distance is short, while at low VSP they are relatively long, reaching up to 30 meters at 0 kw/tonne of VSP. Thus, our measurements of speed and acceleration when vehicles are at low loads may be imprecise. If load is decreasing as vehicles are being measured (as may be assumed since VSP at location B is higher than at location A), then measurement of speed and acceleration at the same time as emissions measurement would underestimate the actual VSP which caused the measured emissions. This would result in apparent high NO at low VSP.

One remedy with the current data is to use speed and acceleration measured at location B to match with NO emissions when the vehicles are at location A. The speed bars from the instrument at location B were approximately 5 meters upstream of emission measurements at location A. Jimenez has derived an equation for predicting distance traveled by a Jeep Cherokee while the exhaust gases move from the engine and out of the tailpipe.[17] Using this equation, the distance traveled by a vehicle with average VSP is 6 meters. The VSP measured at B should be a good approximation of the VSP experienced by the vehicle during the instant when the exhaust being measured was produced. Thus, the first potential cause of VSP underestimation discussed above can be evaluated.

Figure 11 illustrates the result of using speed and acceleration measured 5 meters before emissions measurement. NO emissions at location A were binned and averaged according to VSP measurements at location B. The speed bars from location B were actually 5 meters upstream of the light beams used to measure emissions. The

dependence of NO on VSP is significantly more evident here. Notice that at low VSP bins, ppm NO is lowered compared to Figure 10 (2000A), and at high VSP bins the NO emissions are slightly increased resulting in a sloped plot. This analysis suggests that at this particular location in Phoenix, emissions are released from the tailpipe some time after they are produced in the engine. The Phoenix E-23 location has lower traffic flow than some other E-23 sites. At congested sites, large changes in vehicle load with distance around the ramp are essentially impossible because the speed/load is fixed by the closely spaced vehicles driving as a "platoon".

Instrument Intercomparison

As remote sensing devices for on-road vehicle emissions are being developed, a useful study is to compare the devices to each other. Such an intercomparison can be accomplished by operating the devices simultaneously at the same on-road site so that outside factors affecting the emissions are minimized. During the weeklong measurements in 2000 in the Phoenix area, an ESP instrument (RSD3000) was kindly set up for two days at location B and operated by Mary Salgado from ESP. There were thus three instruments on this particular ramp during this year's measurements. The emission measurements of these instruments are compared below.

Since location A and B are spaced very close together, a useful analysis would be to directly compare individual vehicle measurements. This is done with the two FEAT instruments (Figure 12) and between FEAT 3002 and the RSD3000 unit (Figure 13) for all three pollutants. Data between two FEAT units were matched using VINs and measurement times. RSD3000 data were correlated with FEAT data using license plate numbers and time of measurement. RSD3000 measurements with "V" and "E" validity flags were used. Such matching resulted in 8603 simultaneous measurements with the FEAT units and 1857 measurements by RSD3000 and FEAT.

In the FEAT to FEAT comparisons, very high emitters of CO and HC are similarly measured by both instruments. With NO, however, there is more scatter. This may be a result of the two instruments measuring at different loads. Since NO is very load dependent and drops dramatically upon the onset of commanded fuel enrichment, the two instruments may measure different NO values depending on the load on the vehicle during measurement.

Comparison of a FEAT unit with a RSD3000 instrument gives similar results for CO and NO. The HC plot looks markedly different. Most noticeable is the limited range of measurement with the RSD3000 data compared to FEAT. The causes of this disparity is mostly that RSD3000 reports HC in hexane equivalents while FEAT reports in propane equivalents. Thus, FEAT reports HC a factor of two higher than RSD3000.

Because of the variability in automobile emissions, exemplified by the scatter in Figures 12 and 13, instrument comparisons may be more easily understood using averaged data. Model year binned correlation plots were constructed for the three measured pollutants. Figure 14 shows that the model year averaged correlations between the two FEAT units and between the FEAT and RSD3000 units is quite good with all R^2 values greater than 0.80 and some as high as 0.98. The small amount of scatter present is due to the small

sample size. The FEAT units at locations A and B overlapped slightly more than 8000 measurements, while RSD3000 and FEAT at C measured only 1200 of the same vehicles. These relatively small sample sizes resulted in some model year bins containing less than 30 measurements. Again, due to the skewed nature of automobile emissions, small sample size introduces a significant amount of uncertainty. Thus, the r^2 values are not as good as in FEAT versus IM240 correlations reported elsewhere.[18]

The CO correlations all have slopes approximating unity, indicating that the three instruments measure carbon monoxide similarly and accurately. The HC slopes, on the other hand, differ. Both correlations between the two FEAT units yielded slopes greater than 1. Thus, FEAT 3005 at locations B and C was measuring higher HC than the 3002 instrument at location A. This effect may be due to the differing load conditions at the three sites. The HC correlations between FEAT and RSD3000 are also not 1 to 1. RSD3000 measures considerably lower levels of HC compared to FEAT. Much of this discrepancy is due to difference in reporting units used by the two instruments.

The NO correlations between instruments at location A and B are very close to one to one. Vehicles at these two locations are under similar loads. Correlations between locations C and A or B, however, do not have slopes of unity. This is because location C measurements contain vehicles at lower loads. Thus, the NO measured there is significantly less than at A or B. Notice that in the plot with slope significantly less than one, the high load site is on the x-axis, while the slope greater than unity has the high load site on the y-axis. These analyses indicate that the three instruments studied here measure emissions relatively equivalently, and data from the instruments can be compared especially on a fleet averaged basis.

CONCLUSION

The University of Denver successfully completed the third year of a multi-year remote sensing study in Phoenix. Five days of fieldwork (November 13-17, 1999) were conducted on the uphill exit ramp from Hwy 202 / Sky Harbor Blvd. Westbound to Hwy 143 Southbound in Phoenix, AZ. A database was compiled containing 20,801 records for which the State of Arizona provided make and model year information. All of these records contained valid measurements for at least CO and CO_2, and 20,700 contained measurements for HC and NO. Of these measurements, 9047 (43%) were of vehicles measured only once. The rest were of vehicle measured two or more times. Analysis of these repeat vehicles showed that high emitters have skewed emissions distributions while low emitters have more normally distributed emissions.

The mean measurements for CO, HC, and NO were determined to be 0.27%, 99 ppm and 450 ppm, respectively with an average model year of 1994.3. As expected, the fleet emissions observed in this study exhibited a typical skewed distribution, with the dirtiest 10% of the fleet contributing 75%, 71%, and 53% of the CO, HC, and NO emissions, respectively. An analysis of emissions as a function of model year showed a typical inverse relationship.

Measured emissions as a function of vehicle specific power revealed that HC and CO show a slight negative correlation in the range of –5 to 25 kW/tonne normally experienced by on-road vehicles. More revealing was the relationship between NO emissions and vehicle specific power, showing a strong positive correlation with some of the measurements and no correlation with others. Further analysis revealed that the lack of correlation was at least in part due to delay in the measurement of speed and acceleration. VSP and model year normalizations resulted in emissions that were statistically indistinguishable during the three years of measurement.

A comparison of measurements made at three locations on the ramp used this year showed that correctly measured VSP can account for many of the emissions differences observed at the two locations in 1999. Finally, an intercomparison of three on-road remote sensing instruments indicated that the devices measured pollutants equivalently and that data from the instruments can be compared when binned by model year.
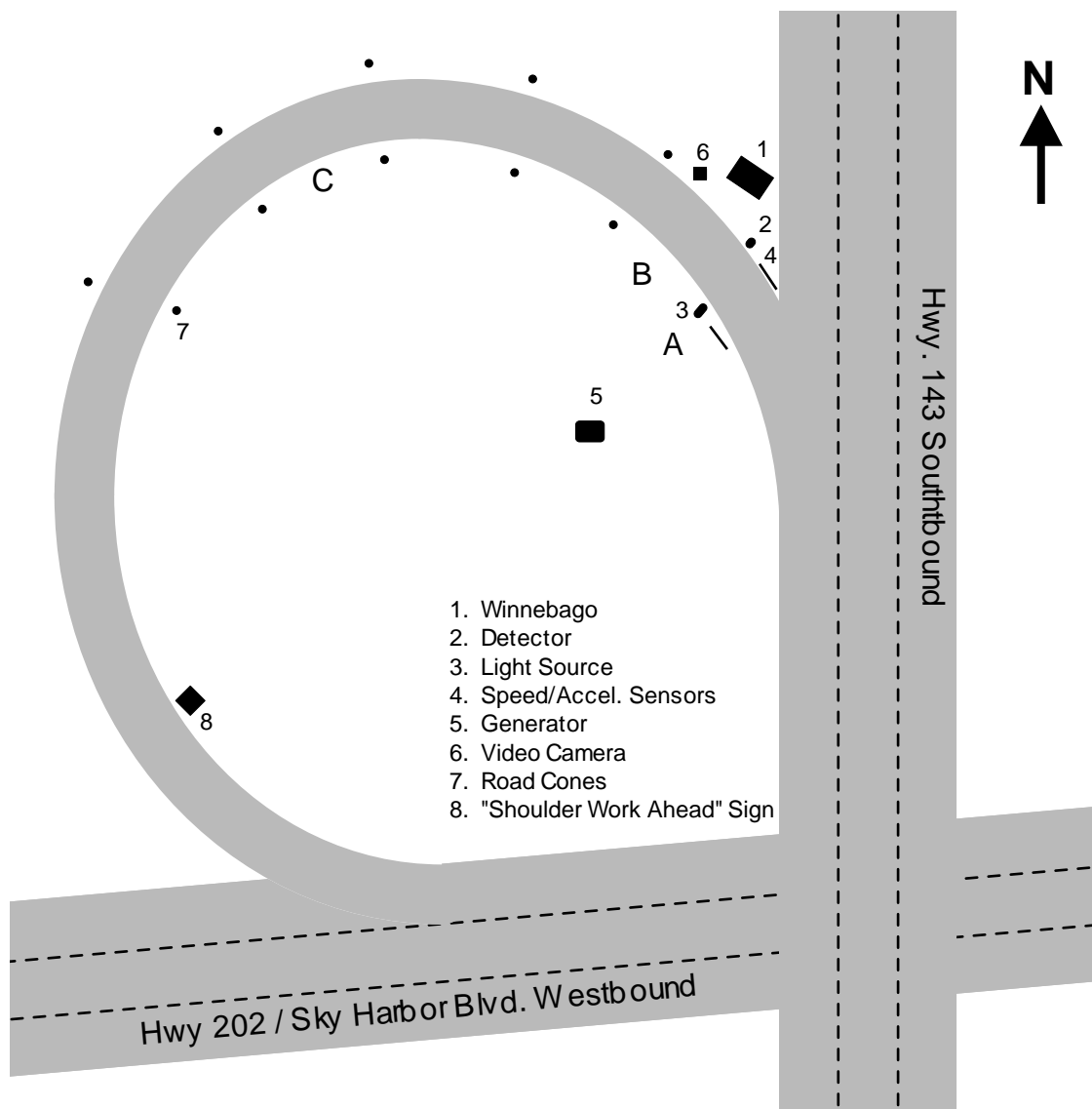
1. Winnebago
2. Detector
3. Light Source
4. Speed/Accel. Sensors
5. Generator
6. Video Camera
7. Road Cones
8. "Shoulder Work Ahead" Sign

Figure 1: Area map of the on-ramp from Hwy 202 to Hwy 143 in the Phoenix area. The location A remote sensor and safety equipment configuration was for all five days of measurements.
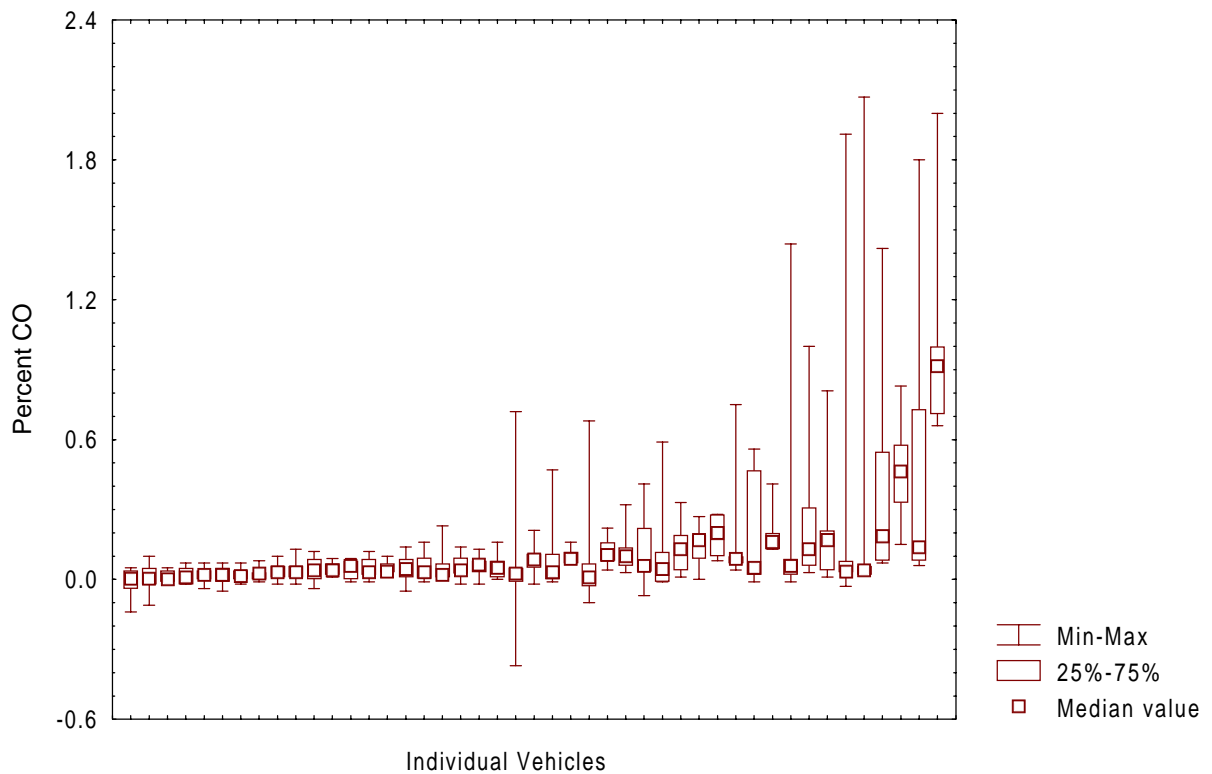
Figure 2. Plot illustrating clustering of CO measurements of vehicles measured five or more times, sorted according to average percent CO. Vehicles which have at least one measurement above 1% (high emitters) tend to have most other measurements clustered near zero. There is one notable exception, which repeatedly measures above 0.6% CO. Even this vehicle, however, exhibits a skewed distribution of CO measurements.
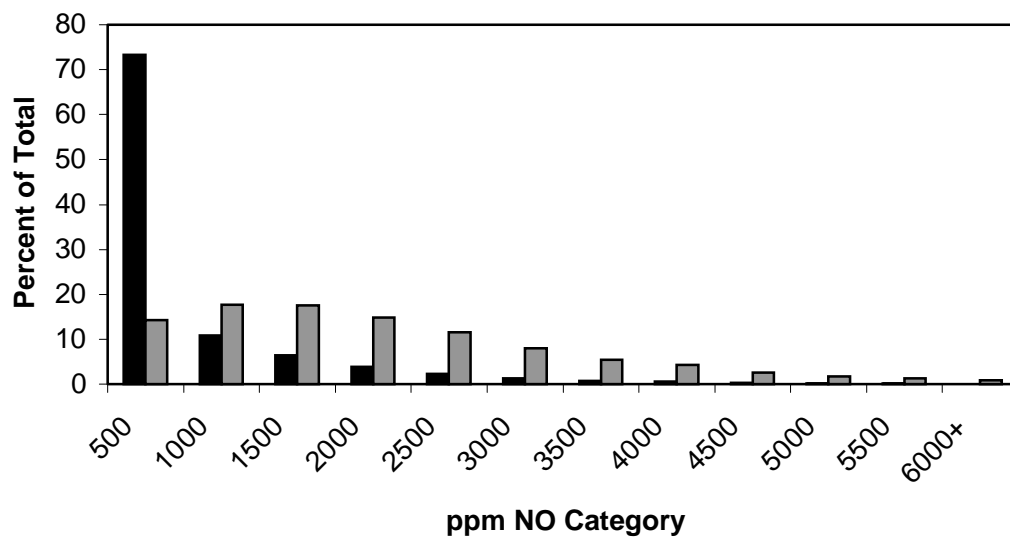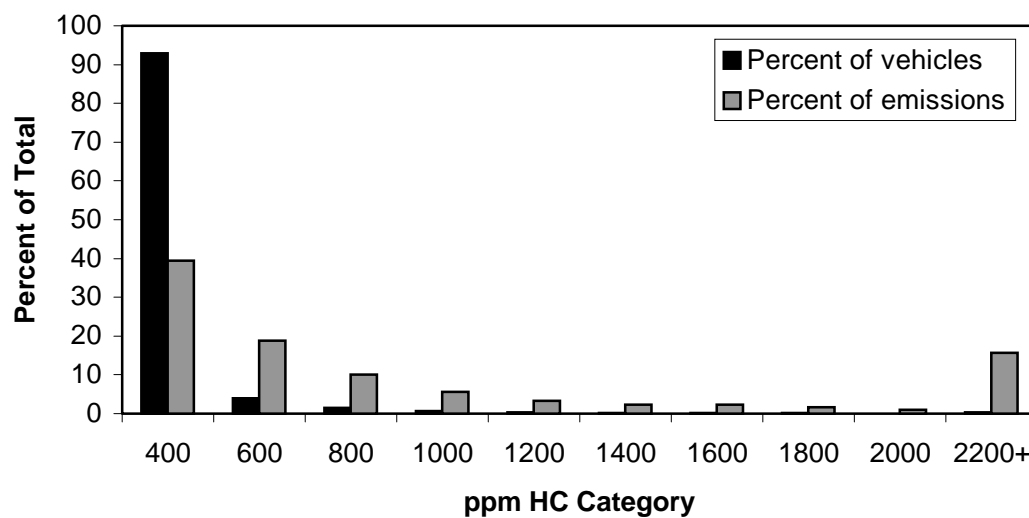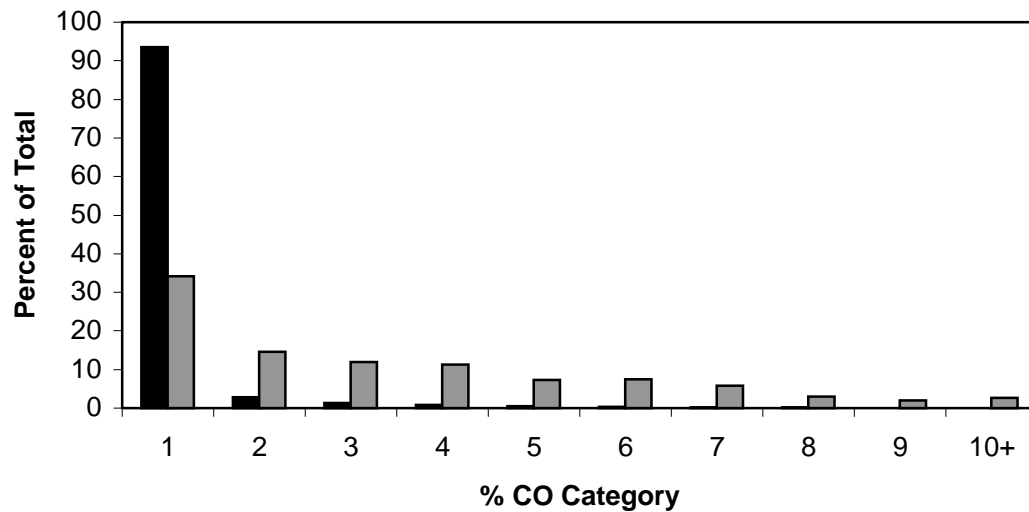
Figure 3. Emissions distribution showing the percentage of the fleet in a given emissions category (black bars) and the percentage of the total emissions contributed by the given category (gray bars).
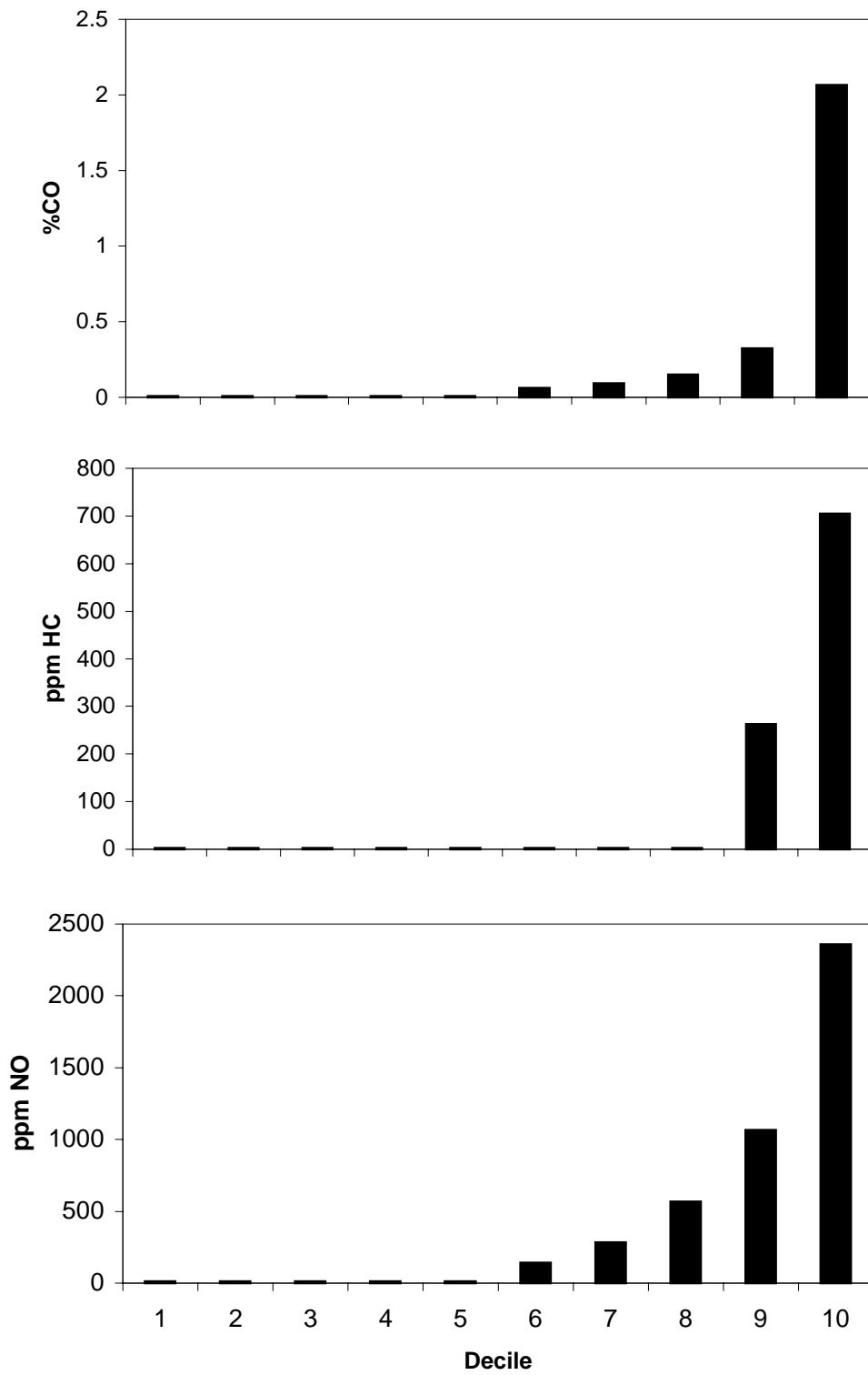
Figure 4. Fleet emissions organized into decile bins.
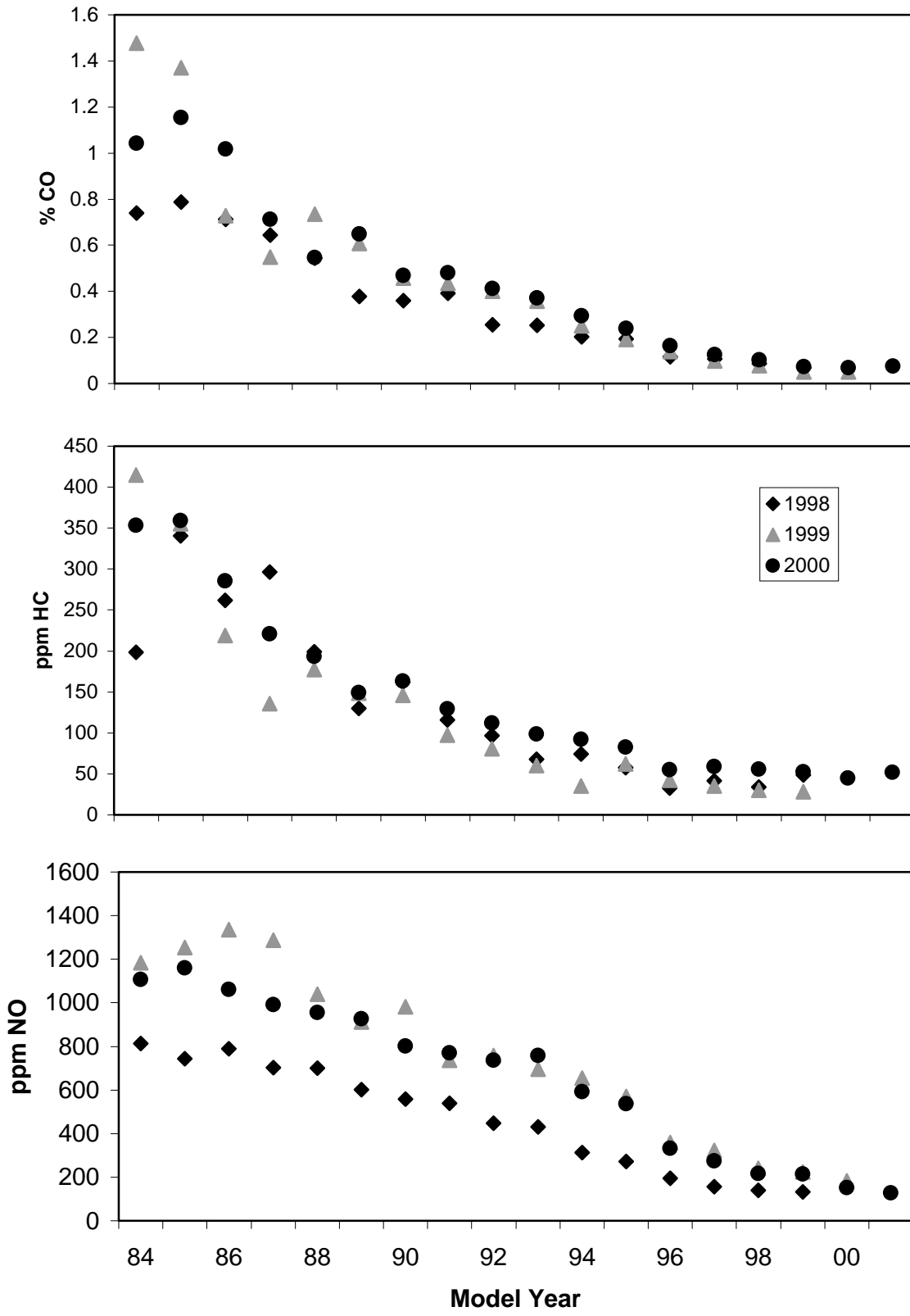
Figure 5. Mean vehicle emissions illustrated as a function of model year. All three years of measurement are included.
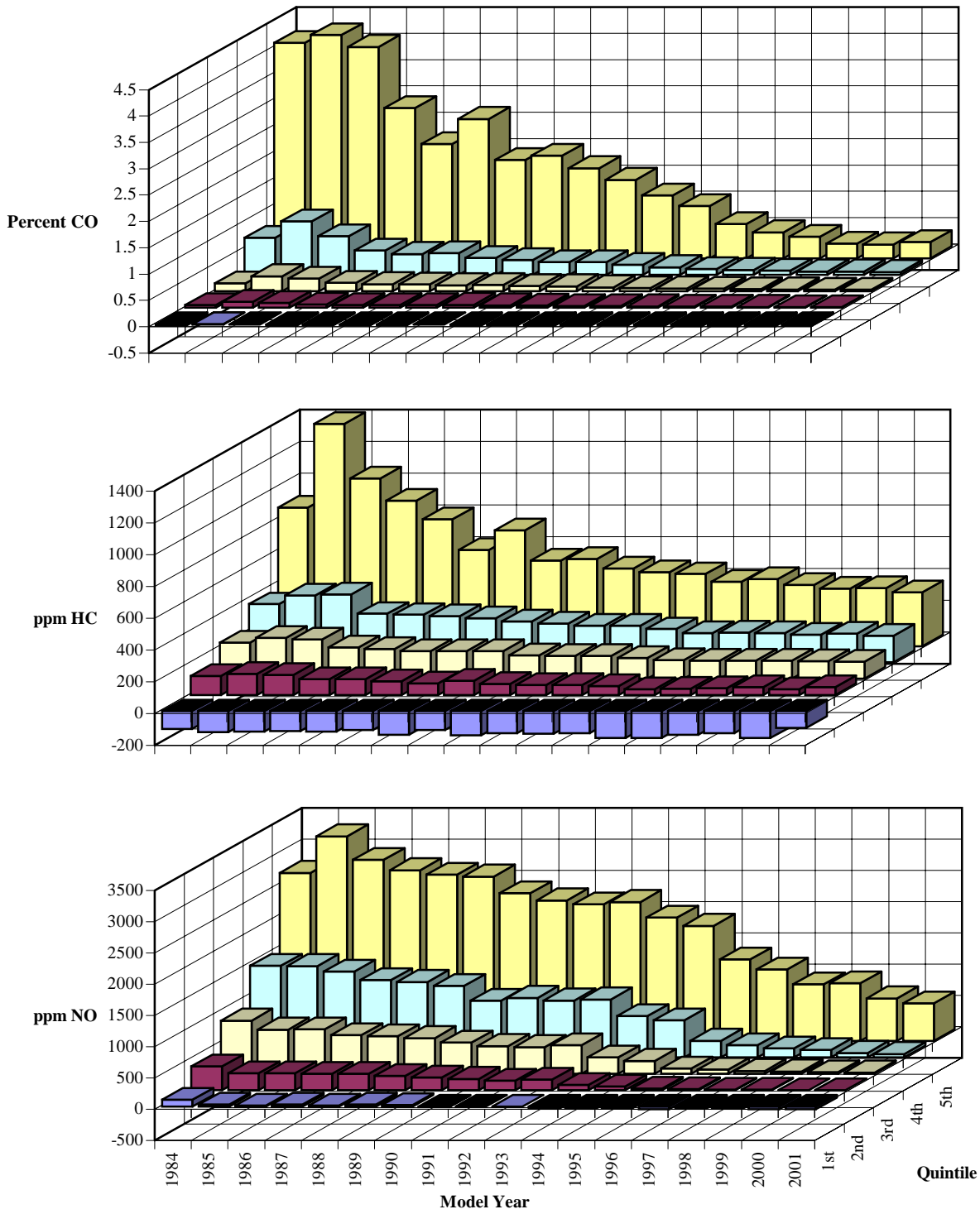
Figure 6. Vehicle emissions by model year, divided into quintiles.
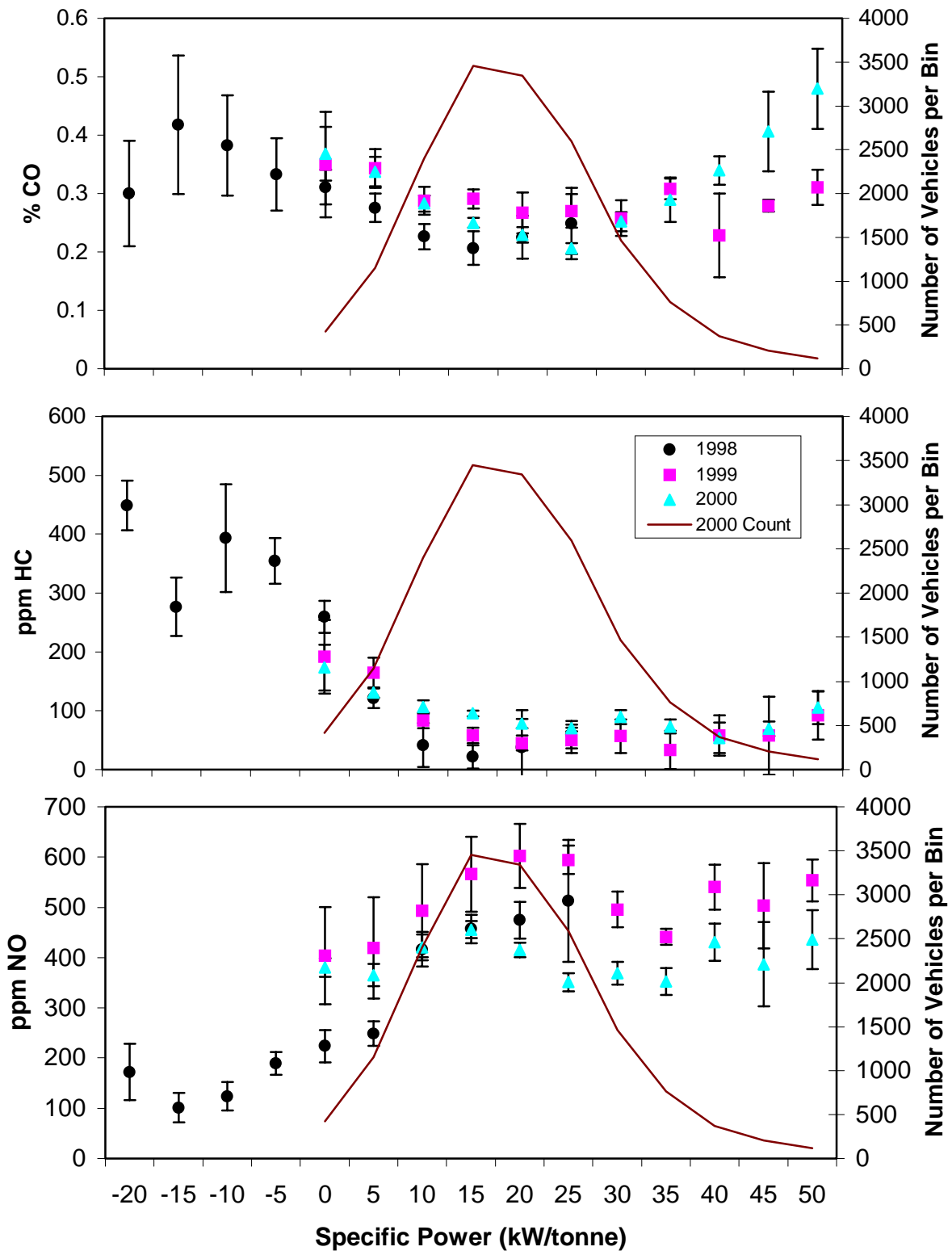
Figure 7. Vehicle emissions as a function of vehicle specific power. Data from all three years of measurement are included. The error bars are standard errors of the mean of daily averages.
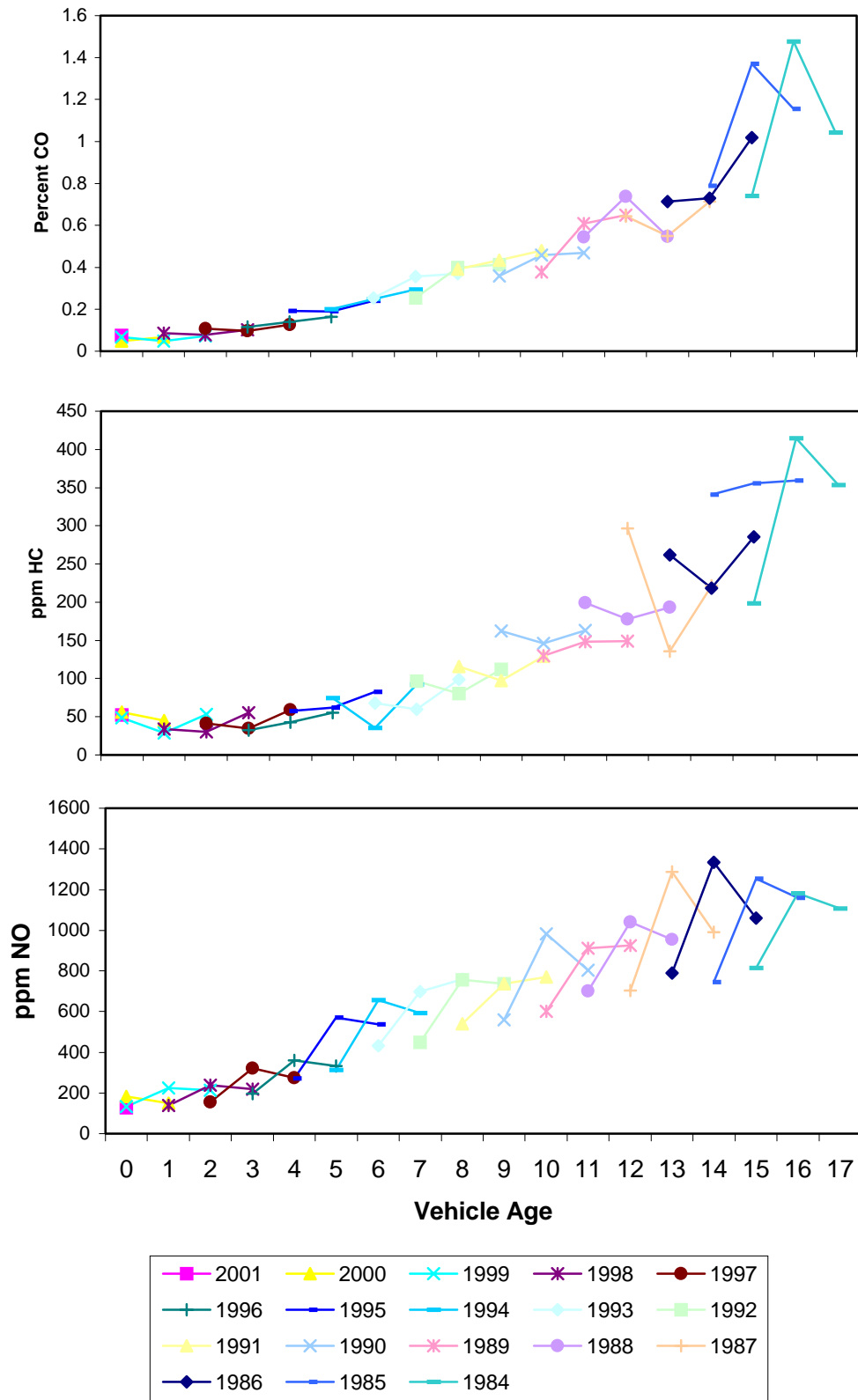
Figure 8. Mean vehicle emissions as a function of age, shown by model year. Included are data from the site in 1998 (first point) and the site in 1999 (second point) and 2000 (third point).
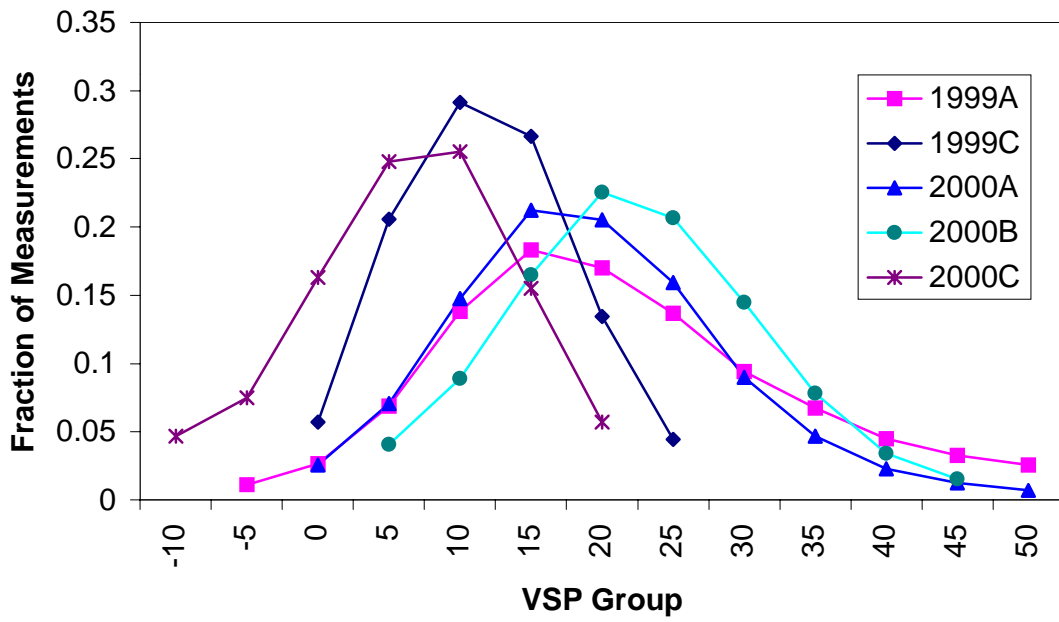
Figure 9: VSP distribution of vehicles at three measurement locations during two years of measurement in Phoenix.
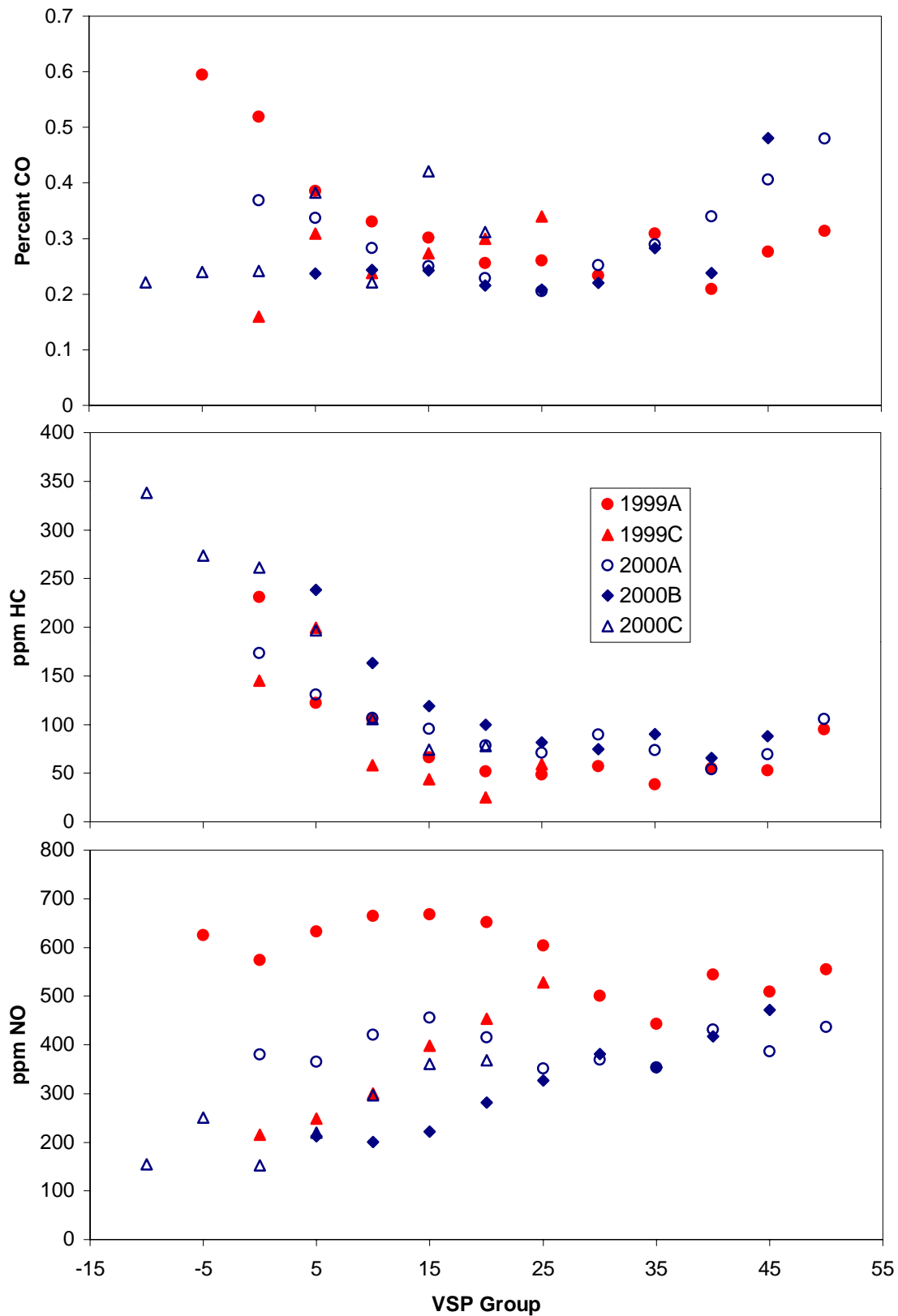
Figure 10: Emissions by VSP bin. Data from two measurement locations in 1999 and three locations in 2000 are included.
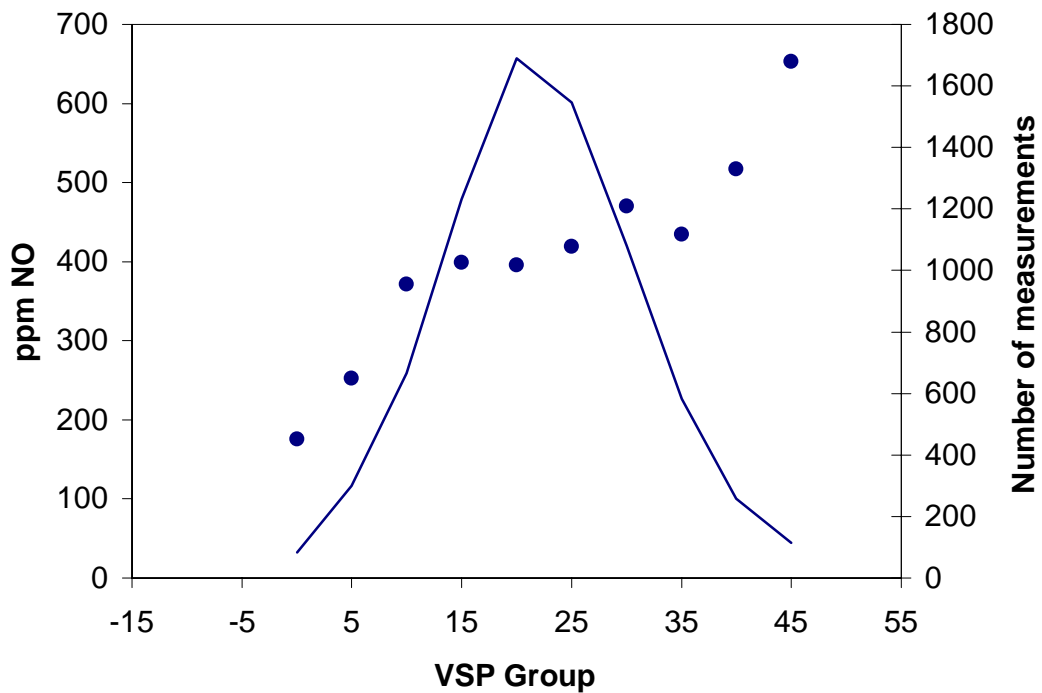
Figure 11. The NO profile as a function of VSP when VSP is calculated using speed and acceleration measured 5 meters before emissions measurement. Phoenix 2000 location A NO data plotted against location B VSP. Included is the measurement distribution.
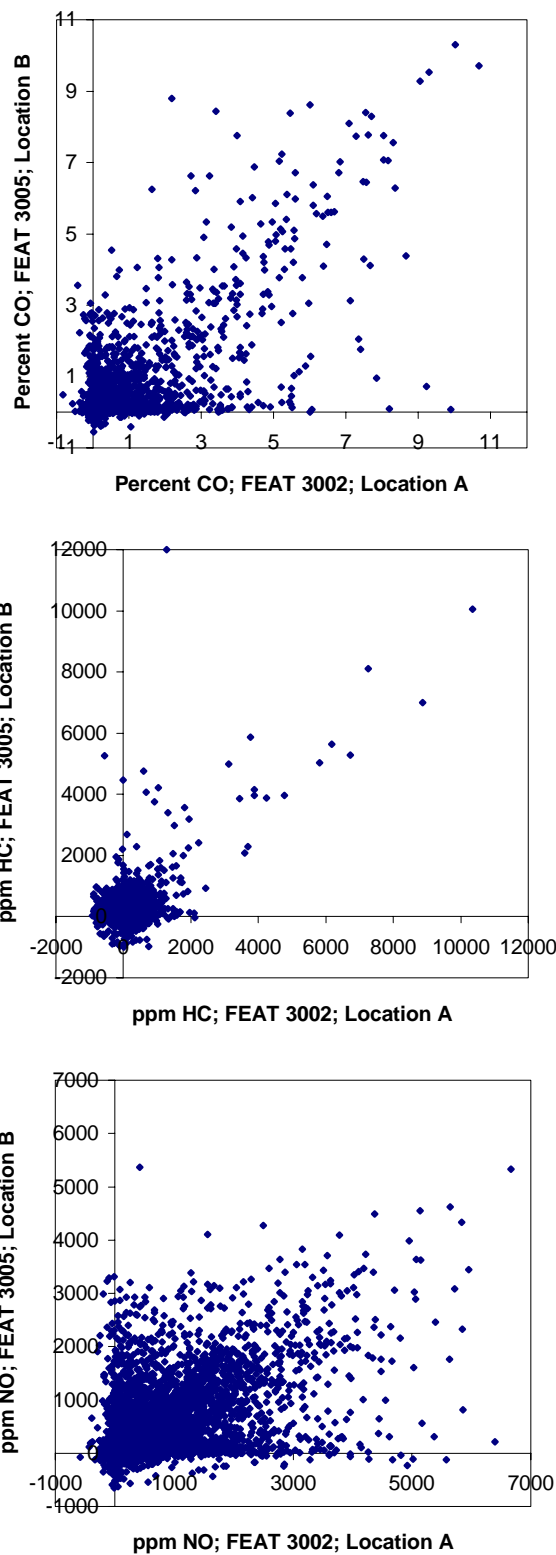
Figure 12. Individual emission measurements from a FEAT unit (3005) at location B plotted against measurements for the same vehicles measured by another FEAT unit (3002) at location A. Each plot contains approximately 8600 sets of simultaneous measurements.
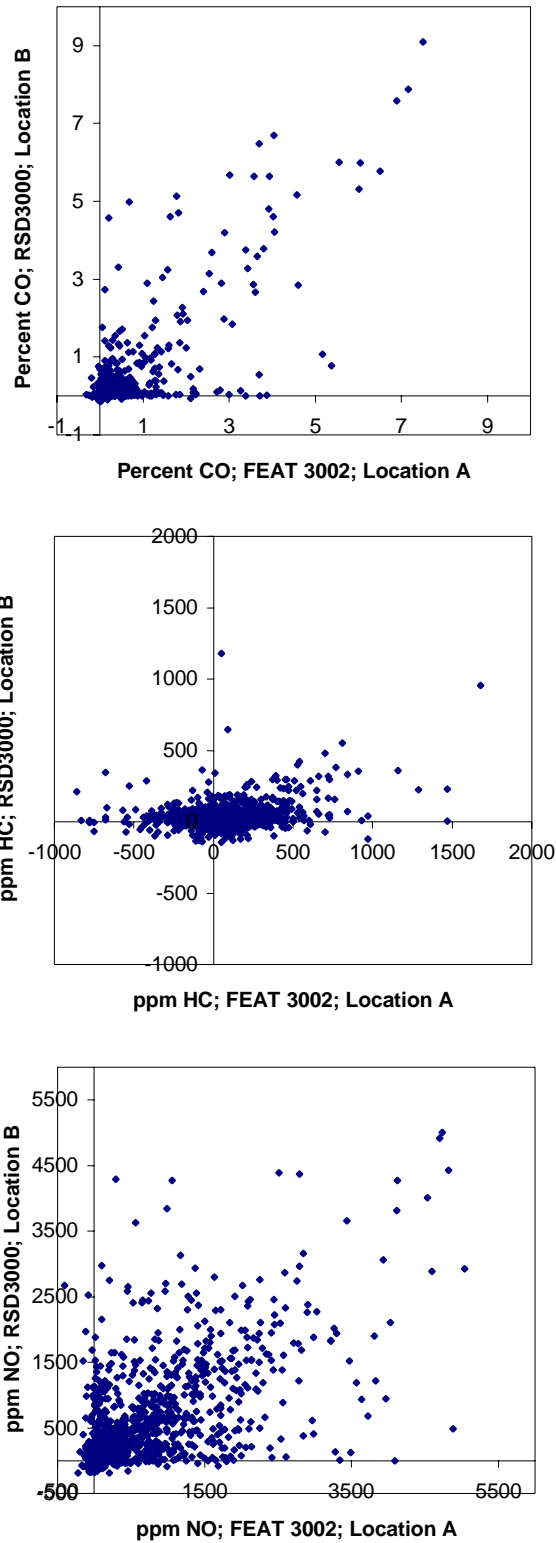
Figure 13. Individual emission measurements from a RSD3000 RSD at location B plotted against measurements for the same vehicles measured by a FEAT unit (3002) at location A. Each plot contains approximately 1850 sets of simultaneous measurements.
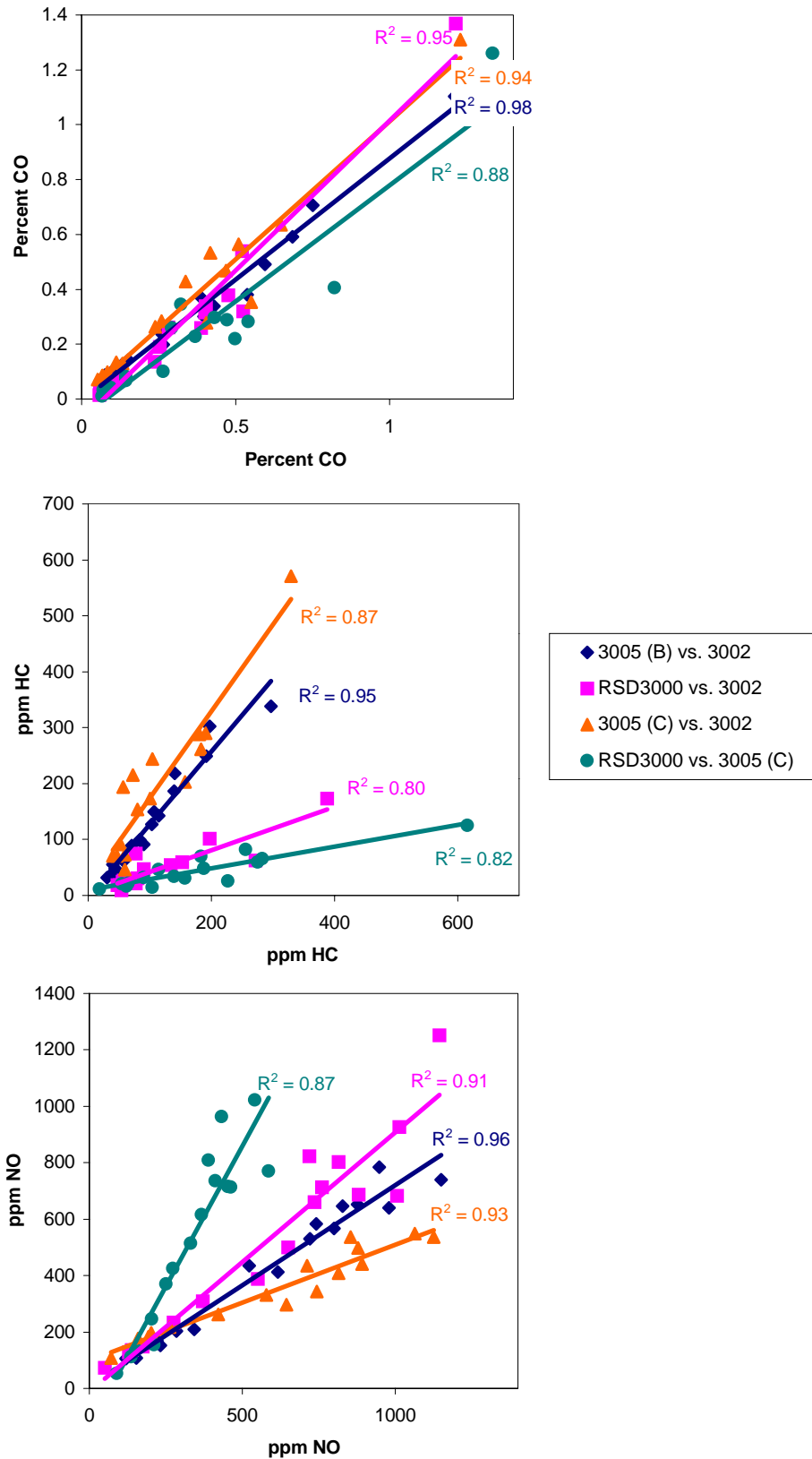
Figure 14. Correlation between two FEAT units and an RSD3000 (always at site B) emission measurements. Data points are model year bins. Best-fit linear regression lines are shown as are R^2 values.

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

Not measured:

1) vehicle 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 data base.

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 >160ppmm CO_2 or >400 ppmm CO. (0.2 %CO_2 or 0.5% CO in an 8 cm cell. This is equivalent to the units used for CO_2 max.) Often HD diesel trucks, bicycles.

2) too much error on CO/CO_2 slope, equivalent to $\pm20\%$ 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 $\pm20\%$ 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 $\pm20\%$ 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.

A restart is an occurrence of a beam block within the 0.5 s exhaust data acquisition time. Data analysis is restarted using the clean air data collected in advance of the first blocking event. High clearance pickups typically generate one restart.

APPENDIX B: Explanation of the phnx_00.dbf database.

The phnx_00.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	Arizona 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	Reference factor.
CO2_factor	CO2 factor.
Plate_key	Coded plate type.
Vin	Vehicle identification number.
Category	Coded vehicle category.

Make   Manufacturer of the vehicle.

Year   Model year.

Fuel   Fuel type G (gasoline), D (diesel) and N (natural gas).

Weight   Gross vehicle weight.

County   Arizona county vehicle is registered in.

City   Registrant's mailing city.

Zip   Registrant's mailing zip code.

Reg_state   Registrant's mailing state abbreviation.

Emis_type   Code for tested vehicle emissions type.

Init_test   8 digit date of initial emissions test.

Pass_date   8 digit date of passing emissions test.

Result_cd   Coded result of emissions test.

Waiver   Flag if emissions waiver was granted.

Exp_date   License expiration date.

AR   Unknown.

Instrument Serial number of FEAT instrument used to make measurement.

Location   Location of measurement on ramp (A,B,C).

APPENDIX C: Temperature and Humidity Data.

				Phoenix 1998 Temperature and Humidity Data				
Time	11/16 °F	11/16 %RH	11/17 °F	11/17 %RH	11/18 °F	11/18 %RH	11/19 °F	11/19 %RH
7:56	55	57	56	49	53	49	50	61
8:56	61	46	60	41	58	41	55	45
9:56	65	40	66	33	63	35	60	38
10:56	70	35	69	31	66	34	64	33
11:56	74	28	72	26	70	30	67	30
12:56	77	26	75	23	73	29	69	25
13:56	79	24	77	21	75	26	71	24
14:56	80	23	79	19	75	25	71	24
15:56	81	22	78	19	74	24	72	24
16:56	79	24	77	21	72	24	70	26

					Phoenix 1999 Temperature and Humidity Data					
Time	11/15 °F	11/15 %RH	11/16 °F	11/16 %RH	11/17 °F	11/17 %RH	11/18 °F	11/18 %RH	11/19 °F	11/19 %RH
6:56	61	44	63	37	59	42	57	51	55	49
7:56	64	41	63	41	62.1	38	57.9	50	57	45
8:56	70	27	69.1	29	66	32	63	41	60.1	39
9:56	77	20	75	23	71.1	26	64.9	42	66.9	32
10:56	81	19	79	21	75	23	69.1	38	70	30
11:56	84	17	82.9	19	78.1	22	71.1	34	72	31
12:56	88	16	84.9	18	80.1	21	73.9	32	75	30
13:56	88	16	86	17	84	19	75	30	77	30
14:56	90	15	87.1	17	82.9	20	75.9	30	77	31
15:56	90	16	88	16	82.9	22	75.9	30	78.1	28
16:56	89.1	16	87.1	17	81	23	75	31	77	28

					Phoenix 2000 Temperature and Humidity Data					
Time	11/13 °F	11/13 %RH	11/14 °F	11/14 %RH	11/15 °F	11/15 %RH	11/16 °F	11/16 %RH	11/17 °F	11/17 %RH
6:56	41	35	46	32	43	36	40	32	43	30
7:56	46	31	48	35	46	36	43	31	43	33
8:56	50	28	53	33	50	37	47	30	50	27
9:56	54	27	58	34	53	31	52	28	54	22
10:56	58	29	61	32	56	29	54	27	56	21
11:56	58	27	63	34	57	24	58	26	58	21
12:56	62	25	64	35	61	27	60	20	58	18
13:56	62	24	66	37	60	28	62	20	62	16
14:56	63	23	66	36	63	24	62	18	63	16
15:56	64	21	65	34	62	21	63	18	63	14
16:56	64	21	64	34	61	21	61	19	62	16

APPENDIX D: Calculation of Vehicle Specific Power Adjusted

Vehicle Emissions

Procedure illustrated using data from Chicago 1997 and 1998

1997 (Measured)	VSP Bin	Mean NO (ppm)	No. of Measurements	Total Emissions
	-5	247	228	56316
	-2.5	235	612	143820
	0	235	1506	353910
	2.5	285	2369	675165
	5	352	2972	1046144
	7.5	426	3285	1399410
	10	481	2546	1224626
	12.5	548	1486	814328
	15	598	624	373152
	17.5	572	241	137852
	20	618	92	56856
			15961	6281579
		Mean NO (ppm)		**394**

1998 (Measured)	VSP Bin	Mean NO (ppm)	No. of Measurements	Total Emissions
	-5	171	126	21546
	-2.5	231	259	59829
	0	252	753	189756
	2.5	246	1708	420168
	5	316	2369	748604
	7.5	374	3378	1263372
	10	418	3628	1516504
	12.5	470	3277	1540190
	15	487	2260	1100620
	17.5	481	1303	626743
	20	526	683	359258
			19744	7846590
		Mean NO (ppm)		**397**

1998 (Adjusted)	VSP Bin	'98 Mean NO (ppm)	'97 No. of Meas.	Total Emissions
	-5	171	228	38988
	-2.5	231	612	141372
	0	252	1506	379512
	2.5	246	2369	582774
	5	316	2972	939152
	7.5	374	3285	1228590
	10	418	2546	1064228
	12.5	470	1486	698420
	15	487	624	303888
	17.5	481	241	115921
	20	526	92	48392
			15961	5541237
		Mean NO (ppm)		**347**

APPENDIX E: Calculation of Model Year Adjusted Fleet Emissions

Procedure illustrated using data from Chicago 1997 and 1998

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.

1999				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
11/15	12:05	1.02	.91	.76
11/16	6:55	1.02	1.06	.98
11/16	10:00	.99	.80	.84
11/17	6:00	1.37	1.04	1.03
11/17	12:28	1.1	.99	.92
11/18	5:50	1.4	1.1	.98
11/18	13:00	1.18	1.0	.98
11/19	6:00	1.47	1.18	1.08
11/19	13:00	1.14	.95	.82

2000 (FEAT 3002)				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
11/13	8:00	1.48	1.22	1.68
11/13	12:30	1.04	0.96	1.06
11/14	6:00	1.47	1.25	1.66
11/14	12:30	1.18	1.00	1.29
11/15	5:40	1.62	1.33	1.76
11/15	12:45	1.17	0.98	1.23
11/16	5:35	1.52	1.30	1.68
11/16	12:20	1.24	1.10	1.50
11/17	6:00	1.76	1.55	2.34
11/17	11:07	1.27	1.11	1.66

2000 (FEAT 3005)				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
11/13	9:30	1.62	1.35	3.87
11/13	12:50	1.47	1.30	2.32
11/14	9:50	1.42	1.22	2.60
11/14	12:20	1.33	1.16	2.15
11/15	9:15	1.71	1.45	3.90
11/15	12:20	1.39	1.19	2.70
11/16	7:05	1.86	1.60	4.30
11/16	12:10	1.43	1.25	1.62
11/17	7:00	2.23	1.87	2.66
11/17	11:05	1.30	1.35	1.72