On-Road Remote Sensing of Automobile Emissions in the Phoenix Area: Year 2

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

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

January 2001

Prepared for:

Coordinating Research Council, Inc.
3650 Mansell Road, Suite 140
Alpharetta, Georgia 30022
Contract No. E-23-4

EXECUTIVE SUMMARY

The University of Denver conducted a five-day remote sensing study in the Phoenix, AZ area in the fall of 1999. 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.

Five days of fieldwork (November 15-19, 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 18,894 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 18,520 contained measurements for HC and NO.

The mean percent CO, HC, and NO were determined to be 0.31%, 0.014%, and 0.057%, respectively. The fleet emissions measured in this study exhibit a gamma distribution, with the dirtiest 10% of the fleet responsible for 78%, 79%, and 49% of the CO, HC, and NO emissions, respectively.

This was the second year of a five-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 location similar to the Denver, Chicago and L.A. Basin sites has been used for this year.

The two sites were compared, and this revealed that they had somewhat different fleet characteristics. One of the more evident differences was that the 1999 site had slightly older vehicles. These differences led to higher average emissions at the 1999 site. A comparison with another on-road remote sensing instrument was also attempted. This comparison with SmogDog measurements showed that it correlated well with FEAT data when the measurements were binned by model year.

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 1996, on-road vehicles were the single largest source for the major atmospheric pollutants, contributing 60% of the CO, 29% 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 piston. 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 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 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 in the same region.

The exhaust plume path length and density of the observed plume are highly variable from vehicle to vehicle, and are dependant 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. This study reports measured emissions as %CO, %HC and %NO in the exhaust gas, corrected for water and excess oxygen not used in combustion. However, these percent emissions can be directly converted into mass emissions per gallon by the equations shown below.

$$\text{gm CO/gallon} = 5506\times\%\text{CO}/(15 + 0.285\times\%\text{CO} + 2.87\times\%\text{HC})$$

$$\text{gm HC/gallon} = 8644\times\%\text{HC}/(15 + 0.285\times\%\text{CO} + 2.87\times\%\text{HC})$$

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

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 difference in emissions calculated from the concentrations of pollutants reported here are equivalent to a difference calculated from the masses of the pollutants.

Another useful conversion is from percent emissions 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:

$$\frac{\text{moles pollutant}}{\text{moles C}} = \frac{\text{pollutant}}{\text{CO} + \text{CO}_2 + 3\text{HC}} = \frac{(\text{pollutant}/\text{CO}_2)}{(\text{CO}/\text{CO}_2) + 1 + 3(\text{HC}/\text{CO}_2)}$$

Next, moles of pollutant are converted to grams by multiplying by molecular weight (e.g., 44 g/mole for HC since propane is measured), and the moles of carbon in the exhaust are converted to kilograms by multiplying (the denominator) by 0.014 kg of fuel per mole of carbon in fuel, assuming gasoline is stoichiometrically CH_2.

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.[6,7] The NO channel used in this study has been extensively tested by the University of Denver, but we are still awaiting the opportunity to participate in an extensive blind study and instrument intercomparison to have it independently validated. Tests involving a late-model low-emitting vehicle indicate a detection limit (±3σ) of 25 ppm for NO, with an error measurement of ±5% of the reading at higher concentrations. 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 1999, under CRC contract no. E-23-4. Measurements were made for 5 consecutive weekdays, from Monday, Nov. 15 to Friday, Nov. 19, 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 first two days of measurements were made at a location earlier on the ramp than indicated in Figure 1, and the uphill grade was 3.3%. On the third day, we moved to the location in Figure 1, which was as far up the ramp as possible; there the road grade was 3.0%. We remained at this new location for the remaining days. Measurements were generally made between the hours of 6:00 and 16:30, except for Monday, which consists of afternoon measurements only. This was the second year of a 5-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 1999, 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 18,894 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	25,369		
Valid Measurements Percent of Attempts	22,748 89.7	22,313 87.9	22,698 89.5
Submitted Plates Percent of Attempts Percent of Valid Measurements	19,556 77.1 86.0	19,189 75.6 86.0	19,494 76.8 85.9
Matched Plates Percent of Attempts Percent of Valid Measurements Percent of Submitted Plates	18,894 74.5 83.1 96.6	18,561 73.2 83.2 96.7	18,852 74.3 83.1 96.7

The percent validity at this new site is significantly higher than at the Year 1 site. The majority of vehicles at the old site were traveling at higher speed and low power. These factors led to large reductions between attempted measurements and valid measurements since vehicle exhaust plumes were very small and resulted in a large number of measurement attempts being invalidated by the sensor's software. The new site is better suited for on-road sensing as the vehicles are traveling at a lower speed and higher load so that exhaust plumes are large enough to be measured and not invalidated. Furthermore, the new site is more similar to the on-road remote sensing sites in Chicago, Riverside and Denver.

Table 2 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.

Table 2: Data Summary

	1999	1998*
Mean CO (%) (g/kg of fuel)	0.31 (38.3)	0.28
Median CO (%)	0.06	0.07
Percent of Total CO from Dirtiest 10% of the Fleet	77.8	70.7
Mean HC (ppm) (g/kg of fuel)	135 (2.64)	190
Median HC (ppm)	90	90
Percent of Total HC from Dirtiest 10% of the Fleet	79.0	65.5
Mean NO (ppm) (g/kg of fuel)	572 (8.12)	360
Median NO (ppm)	167	120
Percent of Total NO from Dirtiest 10% of the Fleet	49.1	56.0
Mean Model Year	1994.0	1993.3
Mean Speed (mph)	34.6	37.2
Mean Acceleration (mph/s)	1.22	-0.7
* Data from previous site.		

Figure 2 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 68% of the fleet (for NO), and as much as 92% of the fleet (for CO). The fact that the cleanest 92% of the vehicles are responsible for only 28% 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 is represented by the consistent high values of percent of total emissions from the dirtiest 10% of the fleet (See Table 2). The occurrence of a large number of negative values in HC measurements led to the value of the percent of total emissions from a ≤200 ppm emissions category being not significant. Thus, the lowest category was chosen to be ≤400 ppm.

The inverse relationship between vehicle emissions and model year has been observed at a number of locations around the world, and Figure 3 shows that the fleet in the Phoenix area, both this year and in 1998, 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, 8] 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, in the 1999 Phoenix measurements none of the three pollutants show a tendency for the mean and median emissions to increase for the newest model year.[9]

Plotting vehicle emissions by model year, with each model year divided into emission quintiles results in the plots shown in Figure 4. 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.[10] The results shown here continue to demonstrate that broken emissions control equipment has a greater impact on fleet emissions than vehicle age. The occurrence of a large number of negative measurements, especially for CO and HC, has caused the lowest emission quintiles to have negative average values. An analysis and possible cause of this noise is discussed in Appendix D.

An equation for determining the instantaneous power of an on-road vehicle has been proposed by Jimenez[11], which takes the form

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

where SP is the vehicle specific power in kW/metric tonne, *slope* is the slope of the roadway (in degrees – 1.7º at second location at 1999 site), *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 5. The solid line in Figure 5 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, emissions seem to level off as a function of VSP. NO emissions, however, seem to have less of a dependence on VSP compared to 1998 measurements. There has recently been significant analysis of the data to determine the cause of this discrepancy. One possibility is that changing car to truck ratios cause the VSP plots to flatten out since cars and trucks have differing emissions. This possibility is further discussed in Appendix H.

Table 3 provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured. Of the 18,894 records used in this fleet analysis, 8,674 (46%) were contributed by vehicles measured once, and the remaining 10,220 (54%) records were from vehicles measured at least twice.

Table 3. Number of measurements on repeat vehicles.

Number of Times Measured	Number of Vehicles
1	8,674
2	1,986
3	1,125
4	505
5	124
6	19
7	8
8	1
8+	5
Total individual vehicles	12,447

Site Comparison

On-road vehicle emissions from a given fleet are dependent on a range of variables. Fleet composition, load on vehicles and the number of vehicles in a cold start mode are a few of the factors that vary with measurement site and significantly affect fleet emissions. We have chosen sites in all cities where cold start mode vehicles are impossible or at least very unlikely. In the Phoenix area, we have measured vehicles at three 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 current 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 was approximately a quarter of the way down the ramp compared to the location during the last three days, which was as far up the ramp as possible.

Fleet composition is a potential difference between sites. For example, one site might have an older fleet relative to the other, perhaps because of socioeconomic differences among the motorists traveling the two routes. The overall average model year, 1993.3 in 1998 and 1994.0 in 1999, indicates an older fleet at the new site, 5 years versus 4.7 years. Another way to determine fleet age composition is to look at model year distribution. Figure 7 shows such a distribution, and indicates that in fact the 1998 fleet may have been newer at the time of measurement because it contained a larger percentage of the newest cars (0-2 years old) as compared to the 1999 site. Another difference in fleet composition is the number of diesel vehicles. It is found that at the 1998 site 1.2% of the vehicles measured burned diesel, while that value is 3.6% at the 1999 site.

Figure 6 gives the VSP distribution for the three locations. This figure illustrates why the first year site was abandoned; many of the vehicles are under very low load, and the resulting emission measurements have a high level of uncertainty because the exhaust plume size is small. These highly uncertain measurements are discarded and appear as invalids ('X' flag) especially HC and NO. The first location on the new ramp used during the current year does not have many very low load vehicles, but it does not have vehicles under high load either. Thus, the second spot on the new ramp is the most ideal location in terms of VSP since vehicles are under higher loads.

Using vehicle specific power, it is possible to eliminate the influence of load and of driving behavior from the mean vehicle emissions for the 1998 and 1999 databases. Table 4 shows the mean emissions from vehicles in the 1998 database and from vehicles measured at the two locations in 1999 with specific powers between 0 and 20 kW/tonne. Note that these emissions do not vary considerably from the mean emissions for the entire 1998 and 1999 databases, as shown in Table 2. Also shown in Table 4 are the mean emissions for the two 1999 locations adjusted for specific power. This correction is accomplished by applying the mean vehicle emissions for each specific power bin in Figure 5, for each of the two locations in 1999, 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 E. It can be seen from Table 4 that the mean VSP adjusted emissions at the first location in 1999 is similar for CO and HC to the 1998 fleet average. At the second location, HC measurements are still quite similar to 1998, but CO values seem to be somewhat higher. There is curious deviation from 1998 values in terms of NO also, as the average is significantly lower at the first location in 1999 and significantly higher at the second. These results indicate that the second location, or alternatively the last three days of measurements in 1999, contains a dirtier fleet of vehicles.

Table 4. Specific power adjusted fleet emissions (0 to 20 kW/tonne only).

	1998	1999 1st Location (measured)	1999 1st Location (adjusted)	1999 2nd Location (measured)	1999 2nd Location (adjusted)
Mean CO (%)	0.25	0.27	0.25	0.32	0.37
Mean HC (ppm)	153	135	151	135	166
Mean NO (ppm)	379	333	275	652	521

Fleet composition cannot account for differences between the two locations on the 1999 ramp because presumably the same fleet is being measured at the two locations. We have checked this and found that the two locations have very similar model year and fuel type profiles. One difference between the two sets of measurements in 1999 is the temperature and humidity. As seen in Appendix C, the last three days of measurement in 1999 were cooler and more humid than the first two days. This may account for the apparent higher NO measurements at the second location.

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 year 1984 to 1999, as measured in 1998 and 1999. Applying the vehicle distribution by model year from 1998 to the mean emissions by model year from 1999 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 F. Both the CO and NO emissions show a noticeable deterioration effect, though the NO effect is much greater than should be expected and most likely is due to other fleet characteristics, as is the apparent decrease in HC emissions from 1998 to 1999.

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

	1998	1999 (measured)	1999 (adjusted)
Mean CO (%)	0.24	0.27	0.30
Mean HC (ppm)	165	121	126
Mean NO (ppm)	335	546	584

Comparison with SmogDog Data

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 1998 and in 1999 in the Phoenix area, our FEAT 3000 unit was set up, and a Hughes SmogDog operated for the Arizona Department of Environmental Quality was present for one day each year. In 1998 they were very closely spaced. In 1999 the SmogDog was at the second location, approximately 200 m farther up the ramp.

Model year binned correlation plots were constructed for two measured pollutants: CO and HC. The SmogDog did not measure NO, so there are not any NO comparisons. The vehicles measured by the SmogDog had license plate readings. These license plates were matched with entries from the FEAT database in order to obtain model year data. Only valid measurements were included in the analysis. Thus, only data with valid flags (V) were included from the FEAT data set. In the case of the SmogDog, measurement flags were not reported so readings of “0” and “9999” were discarded.

Figures 8 and 9 show that the model year averaged correlation between FEAT and SmogDog units is quite good with high r^2 values. The small amount of scatter present is due to the small sample size. License plate matching to obtain model year on the vehicles measured by the SmogDog yielded less than two thousand vehicles with model year information for each of the two years of measurement. Because of 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.[12] Close proximity in 1998 and a 200 m separation in 1999 seem to affect the correlations in the expected way.

The CO correlations have slopes approximating unity, indicating that the two instruments measure carbon monoxide similarly and accurately. The HC slopes, on the other hand, are approximately three. A factor of two here is accounted for by the fact that the SmogDog reports HC in hexane equivalents as opposed to FEAT, which reports in propane equivalents. If the SmogDog values are multiplied by the factor of two, the correlation slope becomes approximately 1.5. Still, this small amount of departure from unity is not accounted for. Furthermore, both CO and HC plots contain non-zero intercepts. The intercepts indicate an offset in the SmogDog averaged measurements. One reason for this discrepancy may be that the SmogDog does not record negative values of emissions readings. As noise in the measurements can affect the data in either direction, very low emitting vehicles can be registered as having negative emissions. When the overall fleet data set is averaged, these artificially negative values cancel out other artificially positive values. Not allowing values to go below zero skews the data when the whole data set is averaged.

CONCLUSION

The University of Denver successfully completed the second year of a 5-year remote sensing study in Phoenix. Five days of fieldwork (November 15-19, 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 18,894 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 18,520 contained measurements for HC and NO.

The mean measurements for CO, HC, and NO were determined to be 0.31%, 140 ppm and 570 ppm, respectively with an average model year of 1994.0. As expected, the fleet emissions observed in this study exhibited a typical skewed distribution, with the dirtiest 10% of the fleet contributing 78%, 79%, and 49% 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 negative correlation. More revealing was the relationship between NO emissions and vehicle specific power, showing a strong positive correlation when a significant number of vehicles were available. Of the 18,894 records in the database, only 54% arise from vehicles measured more than once.

A comparison of the 1998 site to this year's site revealed that the two sites had somewhat different fleet characteristics.   One of the more evident differences was that the newer site had slightly older vehicles. These differences led to higher average emissions at the 1999 site. Finally, a comparison with another on-road remote sensing instrument, SmogDog, showed that it correlated well with FEAT data when the measurements were binned by model year.

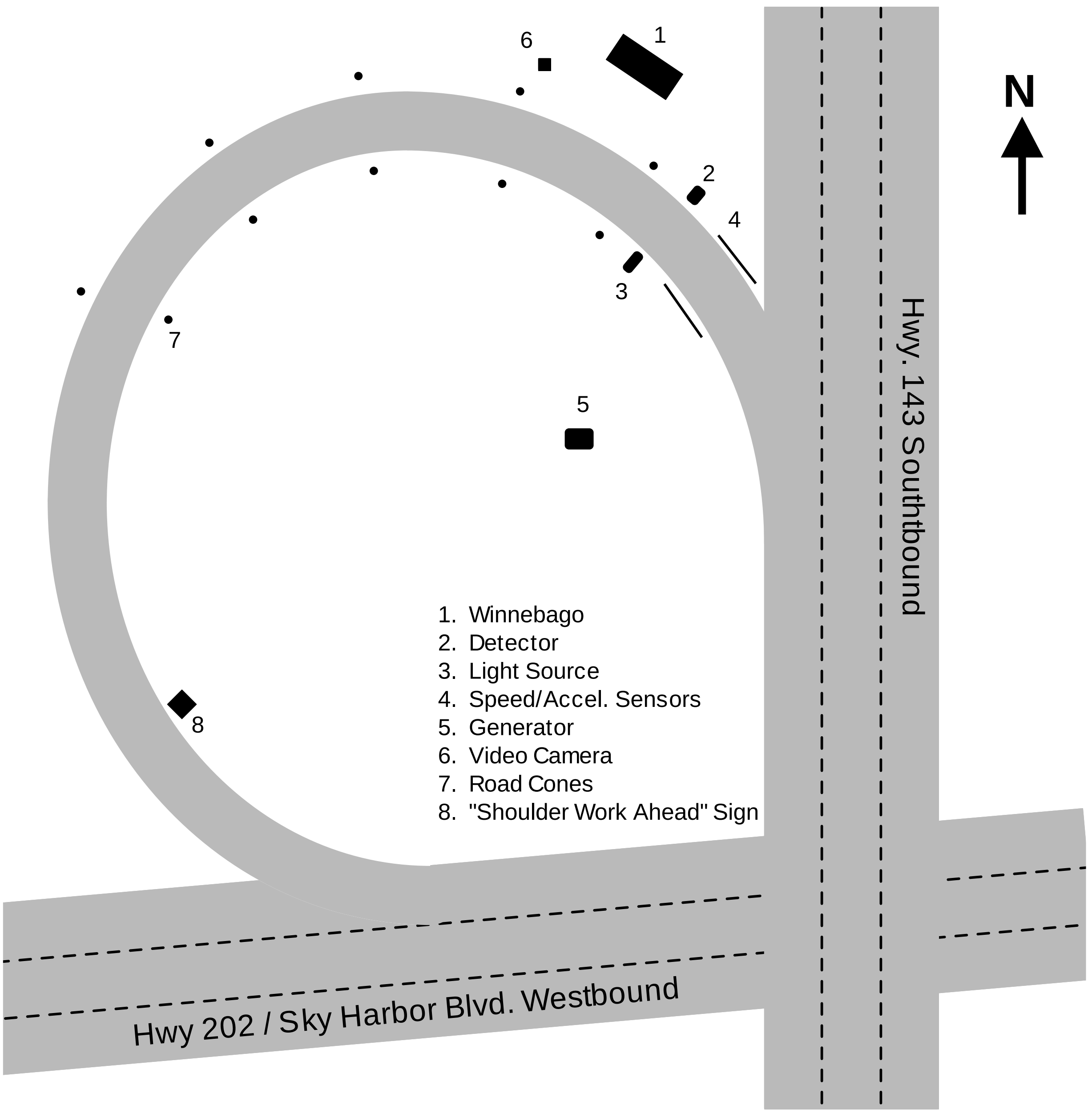


Figure 1: Area map of the on-ramp from Hwy 202 to Hwy 143 in the Phoenix area. The remote sensor and safety equipment configuration is that during the last three days of measurements.

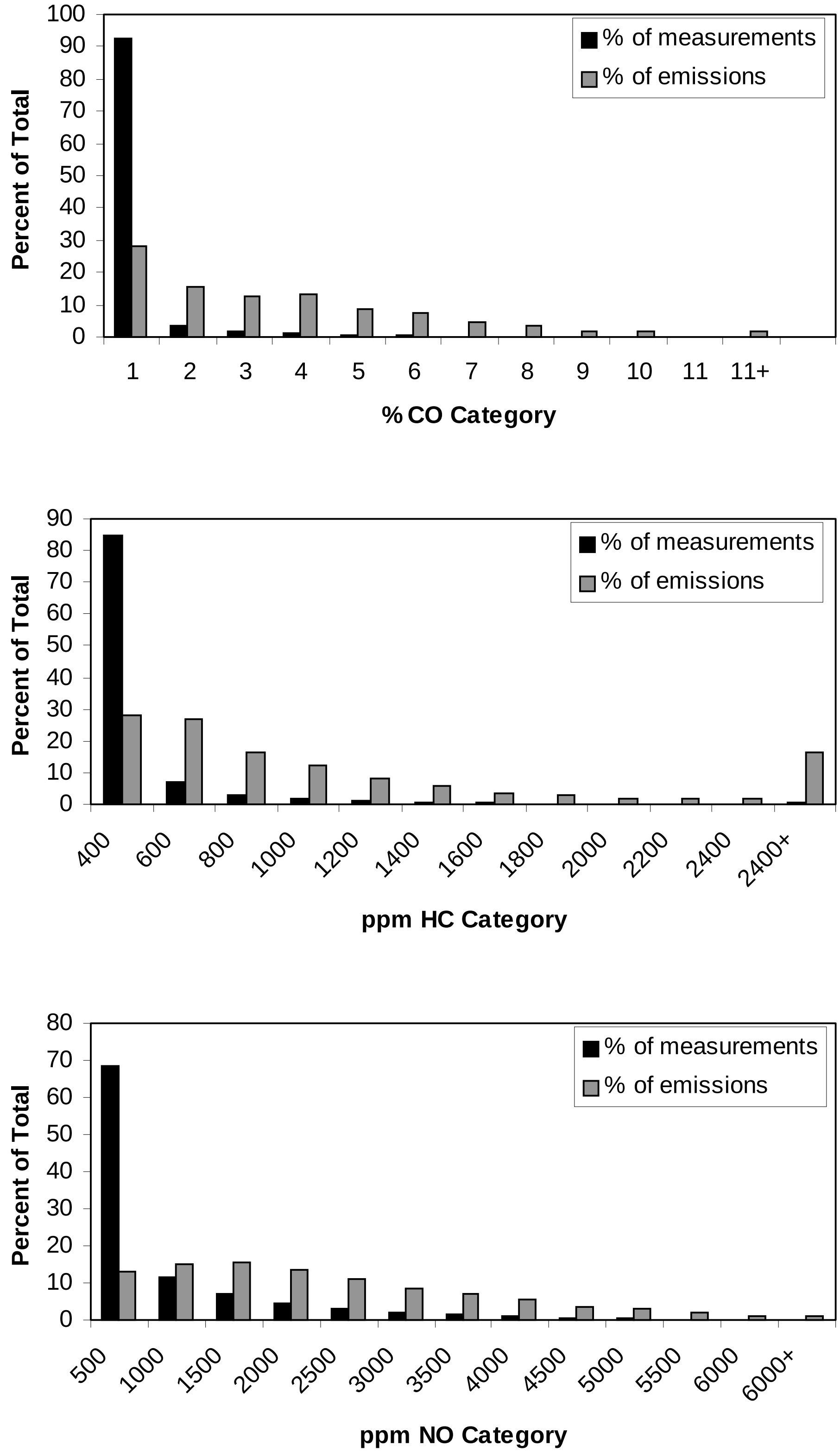


Figure 2. Emissions distribution showing the percentage of the fleet in a given emissions category (black bars) and the percentage of the total emissions contributed by the given category (gray bars).

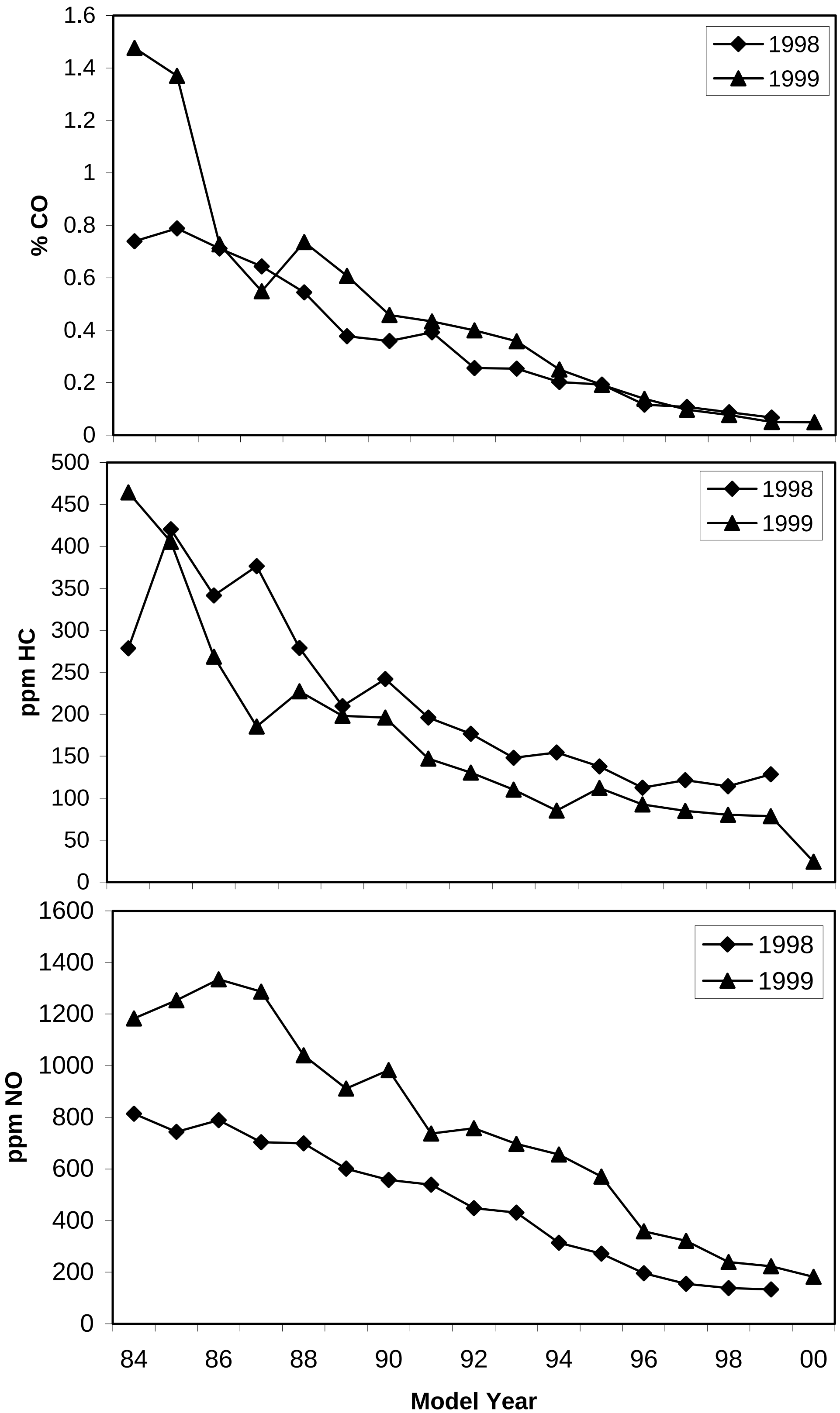


Figure 3. Mean vehicle emissions illustrated as a function of model year.

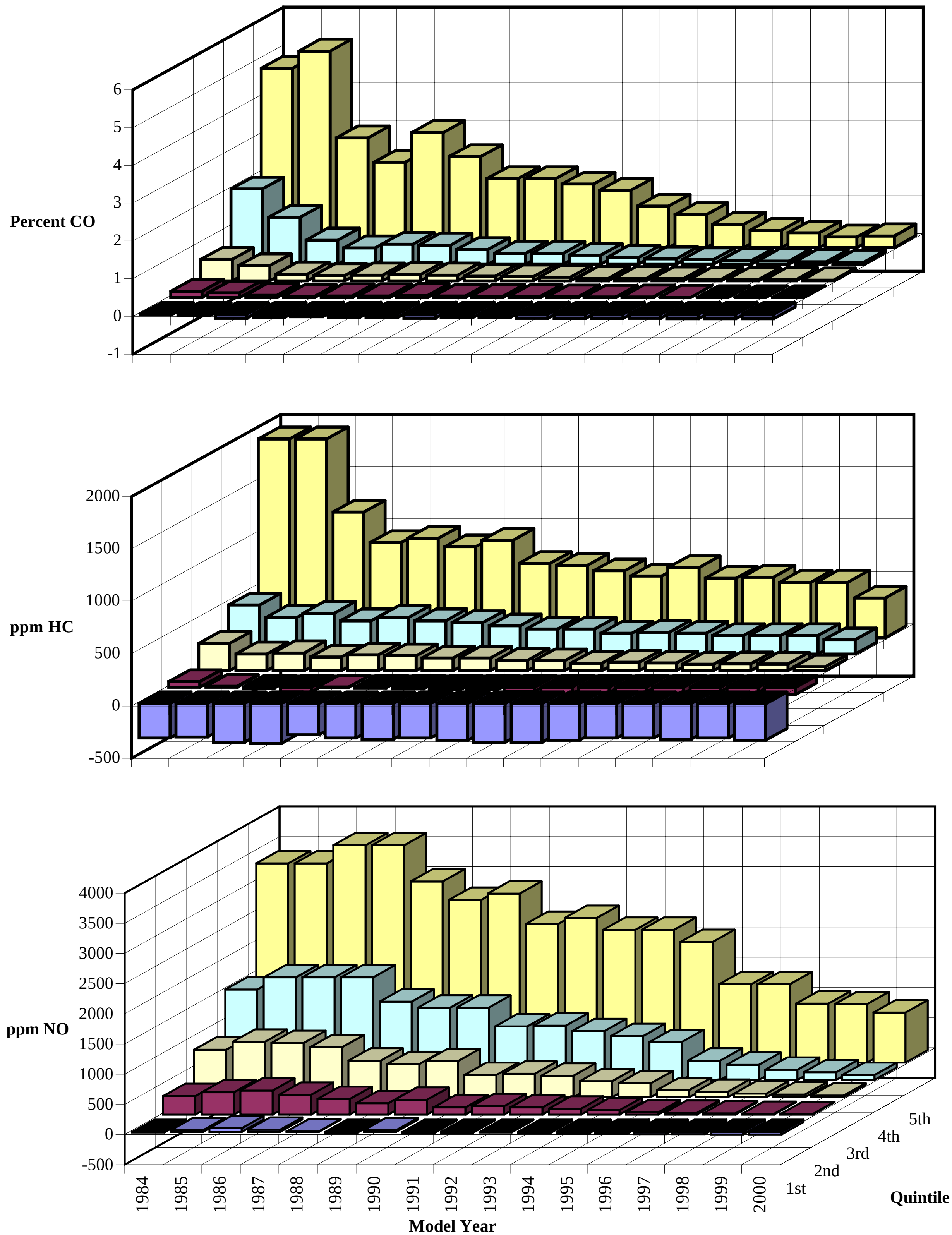


Figure 4. Vehicle emissions by model year, divided into quintiles.

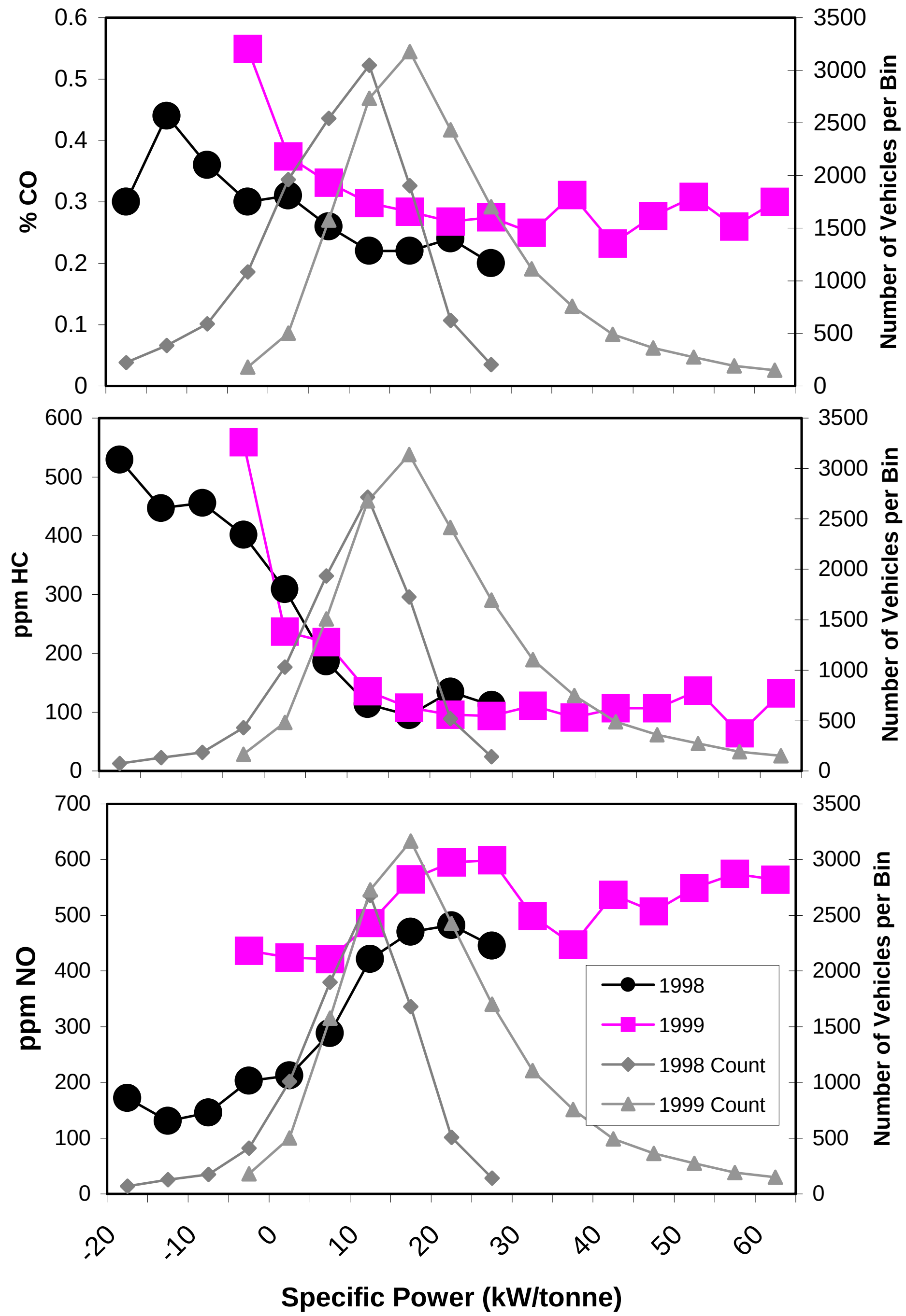


Figure 5. Vehicle emissions as a function of vehicle specific power.

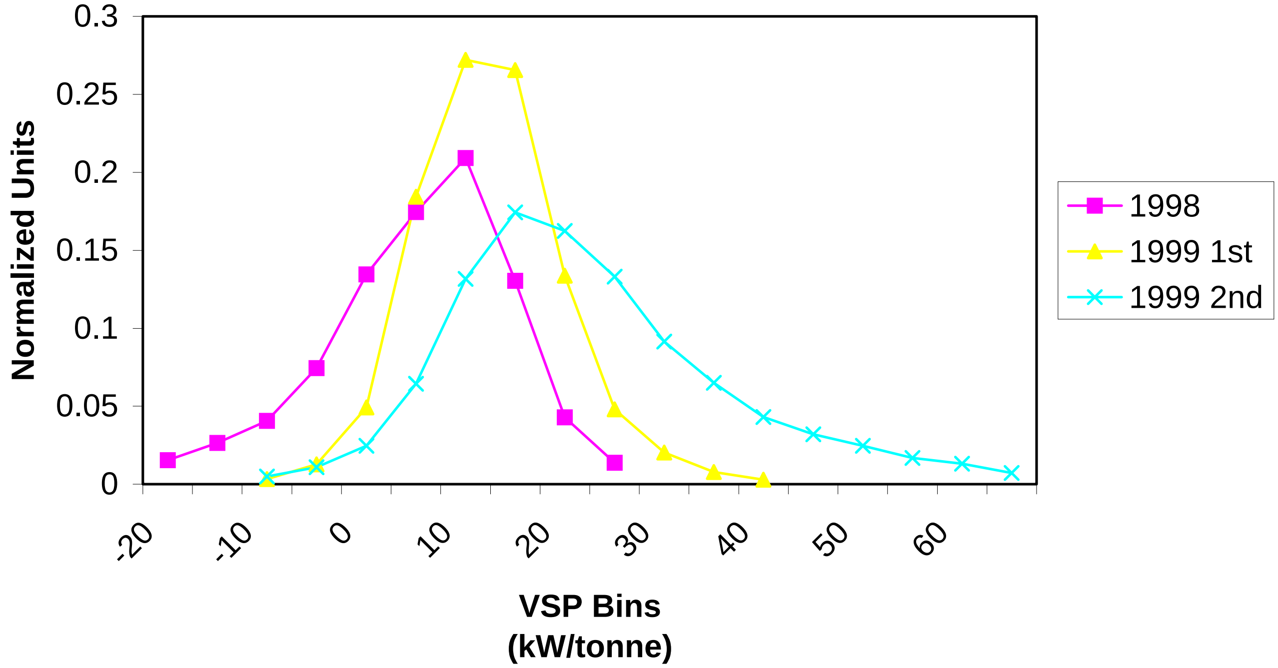


Figure 6: VSP distribution of vehicles at three measurement locations in Phoenix.

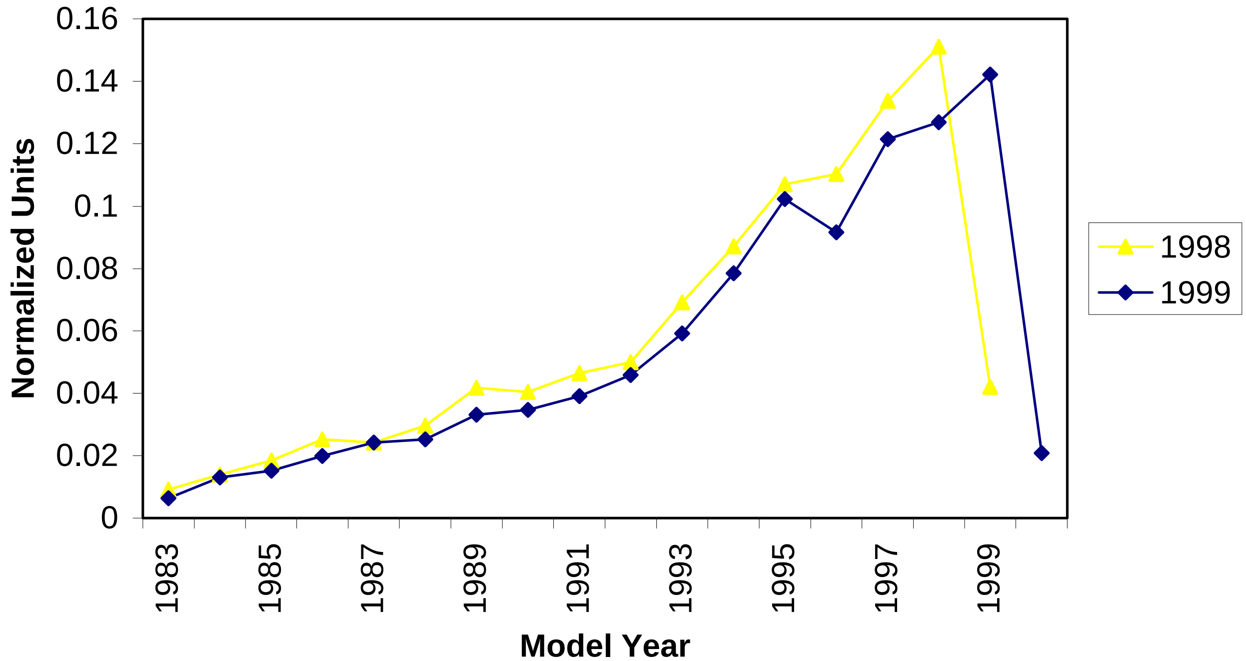
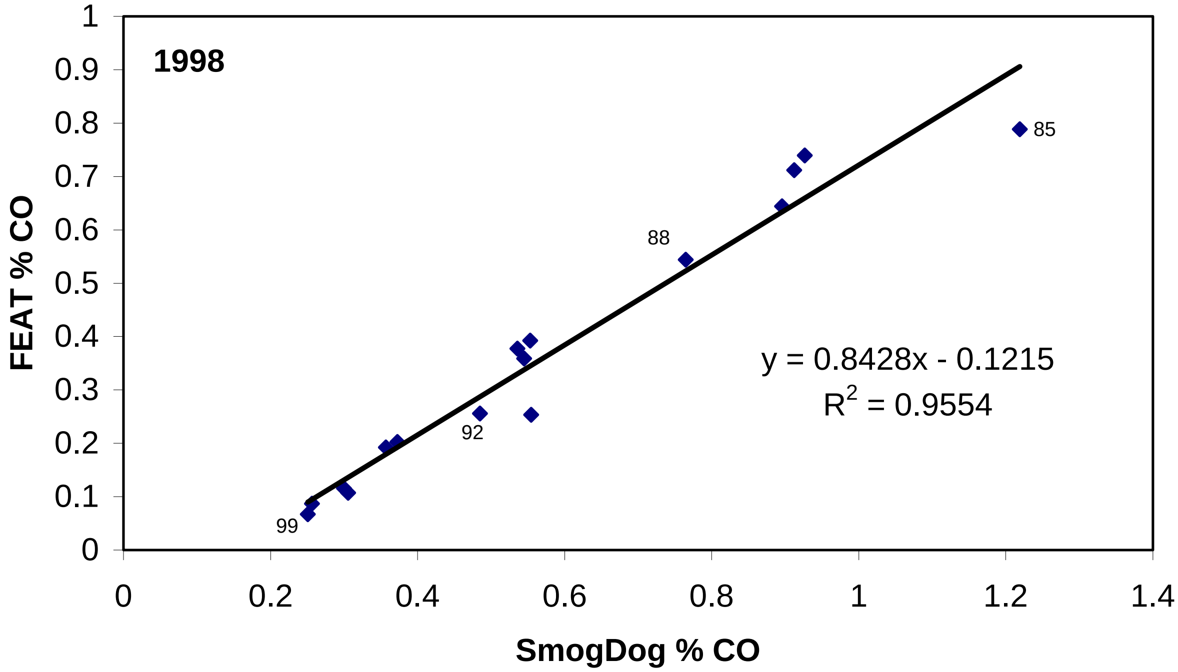


Figure 7: Model year distribution at the two sites.



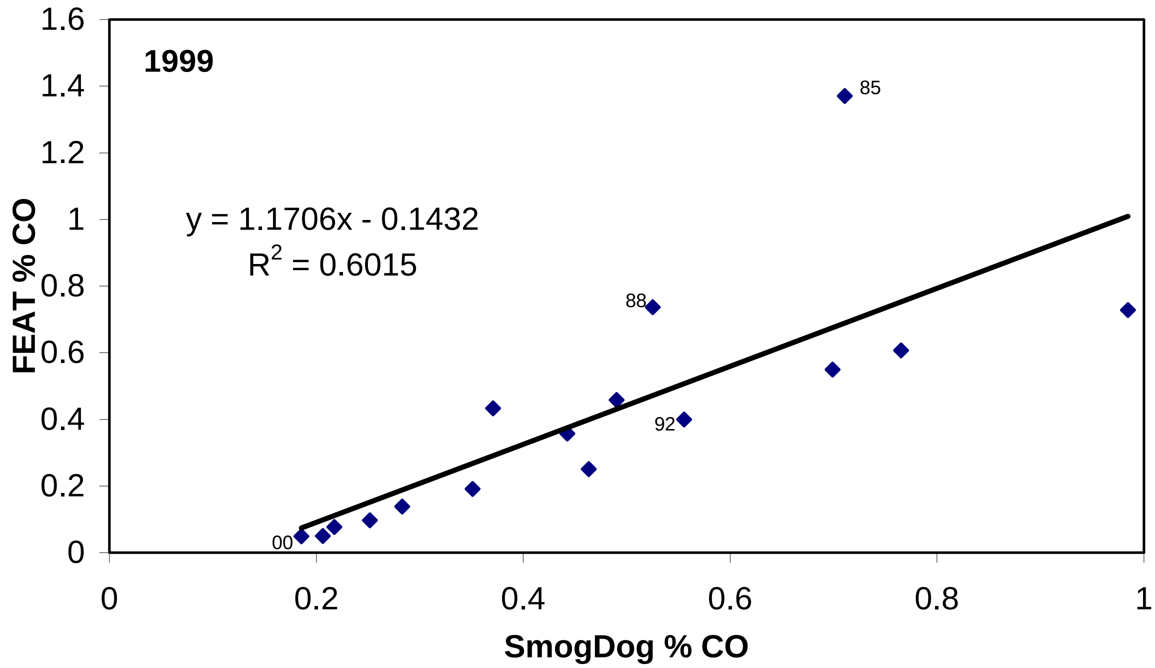


Figure 8: Correlation between FEAT and SmogDog CO measurements in Phoenix during two years of study. Data points are model year bins, four of which are labeled. Model years with less than 20 vehicles have been omitted.

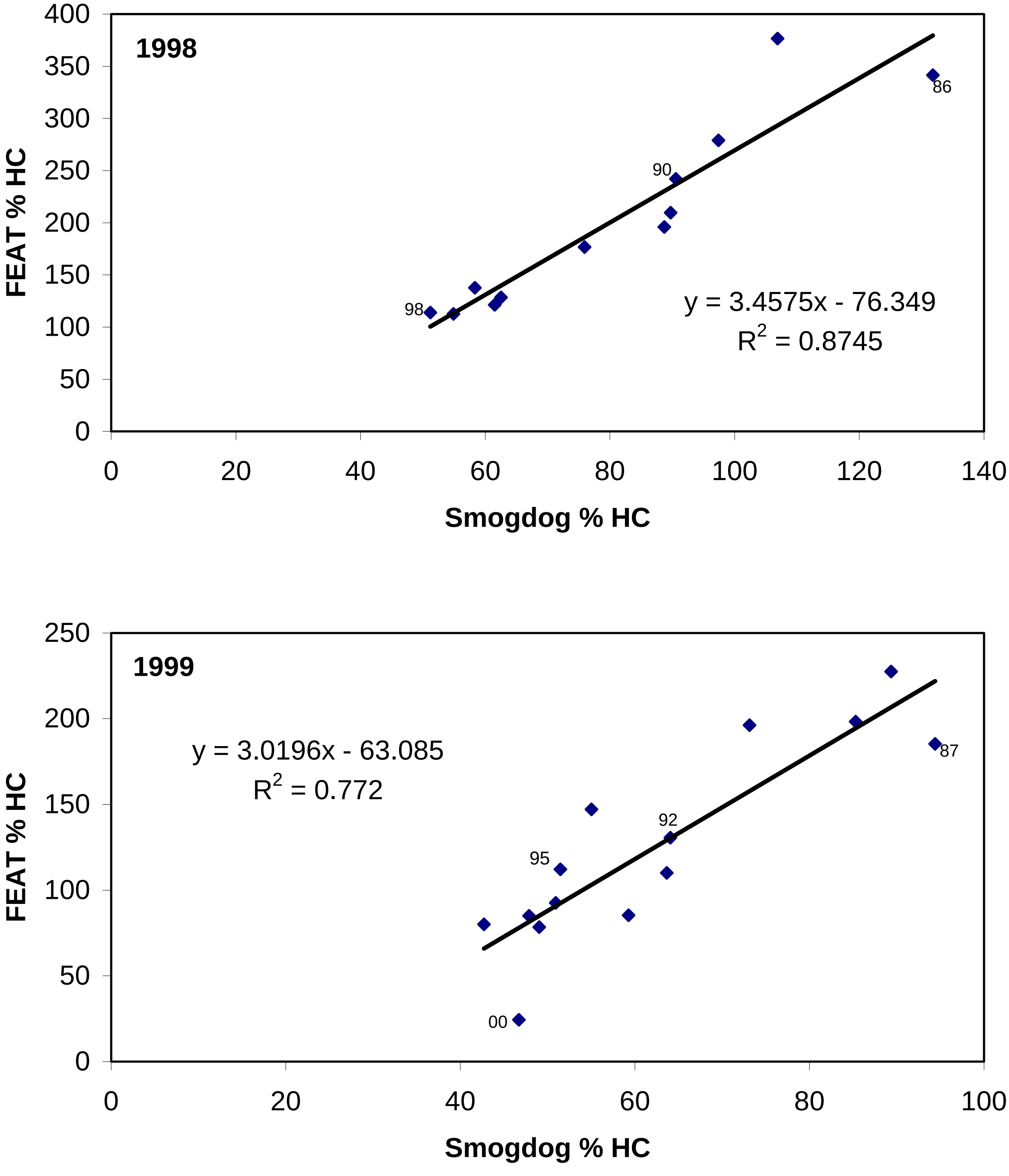


Figure 9: Correlation between FEAT and SmogDog HC measurements in Phoenix during two years of study. Data points are model year bins, four of which are labeled. Model years with less than 30 vehicles have been omitted.

LITERATURE CITED

1. United States Environmental Protection Agency. *National Air Pollution Emission Trends, 1900-1996.* EPA-454/R-97-011. December 1997.

2. Heywood, J.B. *Internal Combustion Engine Fundamentals.* McGraw-Hill: New York, 1988.

3. Lefohn, A.S.; Shadwick, D.S.; Ziman, S.D. *Environ. Sci. Tech.* **1998**, 32, 276A.

4. Bishop, G.A.; Stedman, D.H. *Acc. Chem. Res.* **1996**, 29, 489.

5. Popp, P.J.; Bishop, G.A.; Stedman, D.H. *J. Air & Waste Manage. Assoc.*, submitted Sept. 1998, In Press.

6. Lawson, D.R.; Groblicki, P.J.; Stedman, D.H.; Bishop, G.A.; Guenther, P.L. *J. Air & Waste Manage. Assoc.* **1990**, 40, 1096.

7. Ashbaugh, L.L.; Lawson, D.R.; Bishop, G.A.; Guenther, P.L.; Stedman, D.H.; Stephens, R.D.; Groblicki, P.J.; Parikh, J.S.; Johnson, B.J.; Haung, S.C. In *PM10 Standards and Nontraditional Particulate Source Controls*; Chow, J.C; Ono, D.M., Eds.; Air and Waste Management Association: Pittsburgh, PA, 1992; Vol. II, 720.

8. Zhang, Y.; Stedman, D.H.; Bishop, G.A.; Beaton, S.P.; Peterson, J.E.; McVey, I.F. *J. Air & Waste Manage. Assoc.* **1996**, 46, 25.

9. Popp, P.J.; Bishop, G.A.; Stedman, D.H. *On-Road remote Sensing of Automobile Emissions in the Chicago Area: Year 2*, Final report to the Coordinating Research Council, contract E-23-4, 1999.

10. Ashbaugh, L.L.; Lawson, D.R. presented at the 84th Air and Waste Management Association meeting: Vancouver, B.C., reprint No. 91-180.58, June 1991.

11. Jimenez, J.L.; McClintock, P.; McRae, G.J.; Nelson, D.D.; Zahniser, M.S. In *Proceedings of the 9th CRC On-Road Vehicle Emissions Workshop*, San Diego, CA., 1999.

12. Pokharel, S.S.; Bishop, G.A.; Stedman, D.H. Presented at the *10th CRC On-Road Vehicle Emissions Workshop*, San Diego, CA, 2000.

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 ±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 ±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 ±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.

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_99.dbf database.

The phnx_99.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.
Make	Manufacturer of the vehicle.
Model	Manufacturer's vehicle model.
GVW	Gross vehicle weight.
Fuel	Fuel type G (gasoline), D (diesel) and N (natural gas).
Exp_date	License expiration date.

City Registrant's mailing city.

State Registrant's mailing state.

Zip Registrant's mailing zip code.

Vin Vehicle identification number.

Emiss_flag Indicates vehicle within Arizona's I/M testing area.

County Abbreviation of Arizona county vehicle is registered in.

APPENDIX C: Temperature and Humidity Data.

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
5:56	60.1	46	63	37	60.1	42	57	53	55.9	46
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

APPENDIX D: Noise Study

A relatively large amount of negative emission measurements were recorded in the current year of study in the Phoenix area. In order to better understand the origin of these negative values, the distribution of the data was studied. The following graphs show the

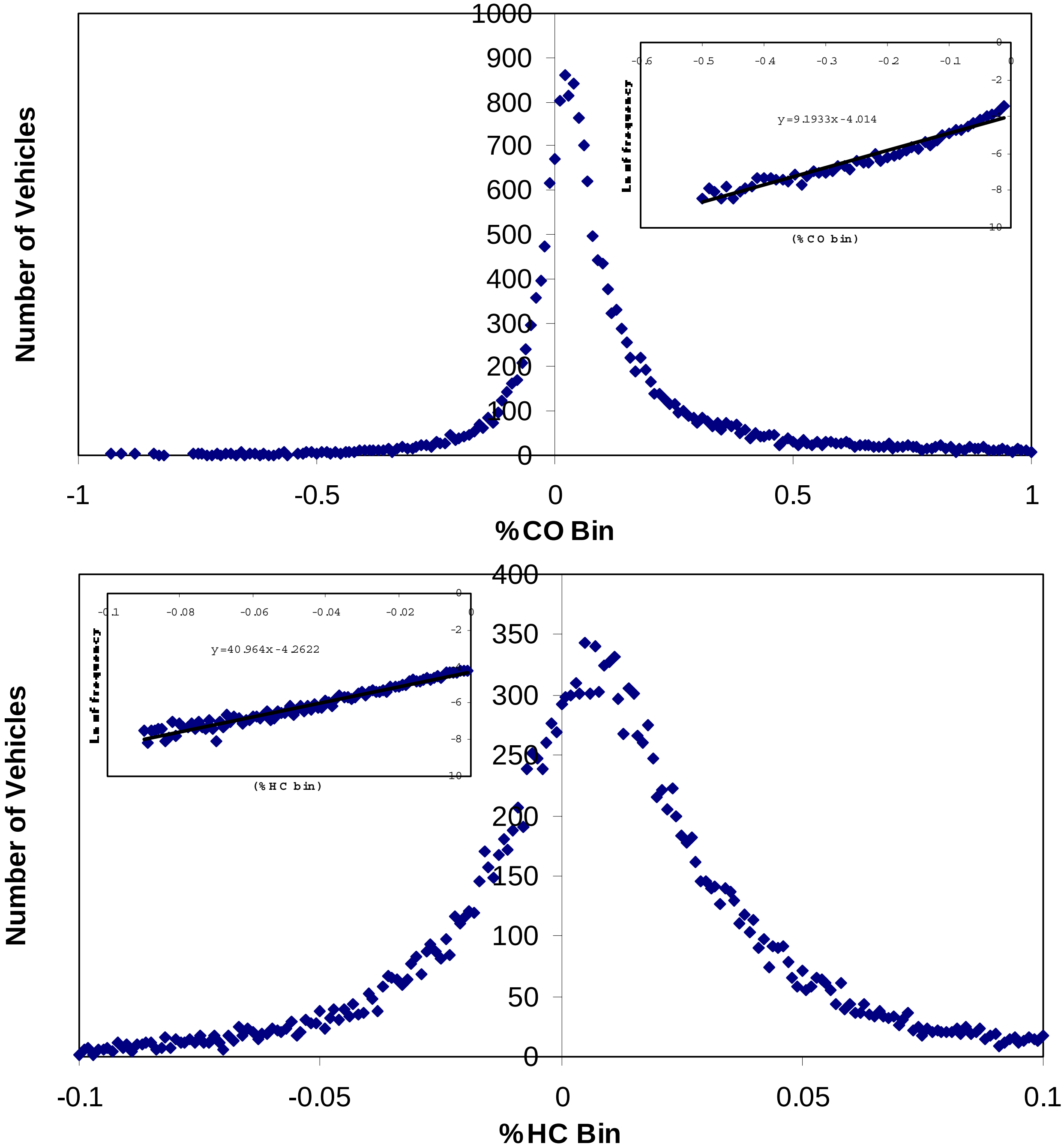


Figure D1: Distribution of CO and HC measurements from the whole Phoenix 1999 database. Insets are log plots of the negative portion of the data.

distribution of the data as well as log plots of the negative portion of the data. Looking at the distributions one can see that there is a significant number of negative measurements with both pollutants, and HC seems to have more negatives than CO. This is illustrated by the fact that at the HC negative cut-off value (-0.1), below which all measurements are labeled invalid by the data acquisition software, there is still a significant number of HC readings while CO negatives seem to have trailed off by the CO cut-off value (-1.0).

The shape of the distribution indicates that the negative values are the result of noise and not an offset. This is illustrated by the fact that the peak of the distribution is at a positive emission value and the negative portion of the curve is steeper than the positive. Since even the lowest emitting cars do not clean the air significantly, negative emission values are not real. Rather, if they are assumed to be a result of instrument noise, the steep curve on the negative side is the noise distribution and the shallower slope on the positive side of the curve is the sum of the noise and actual emissions distribution.

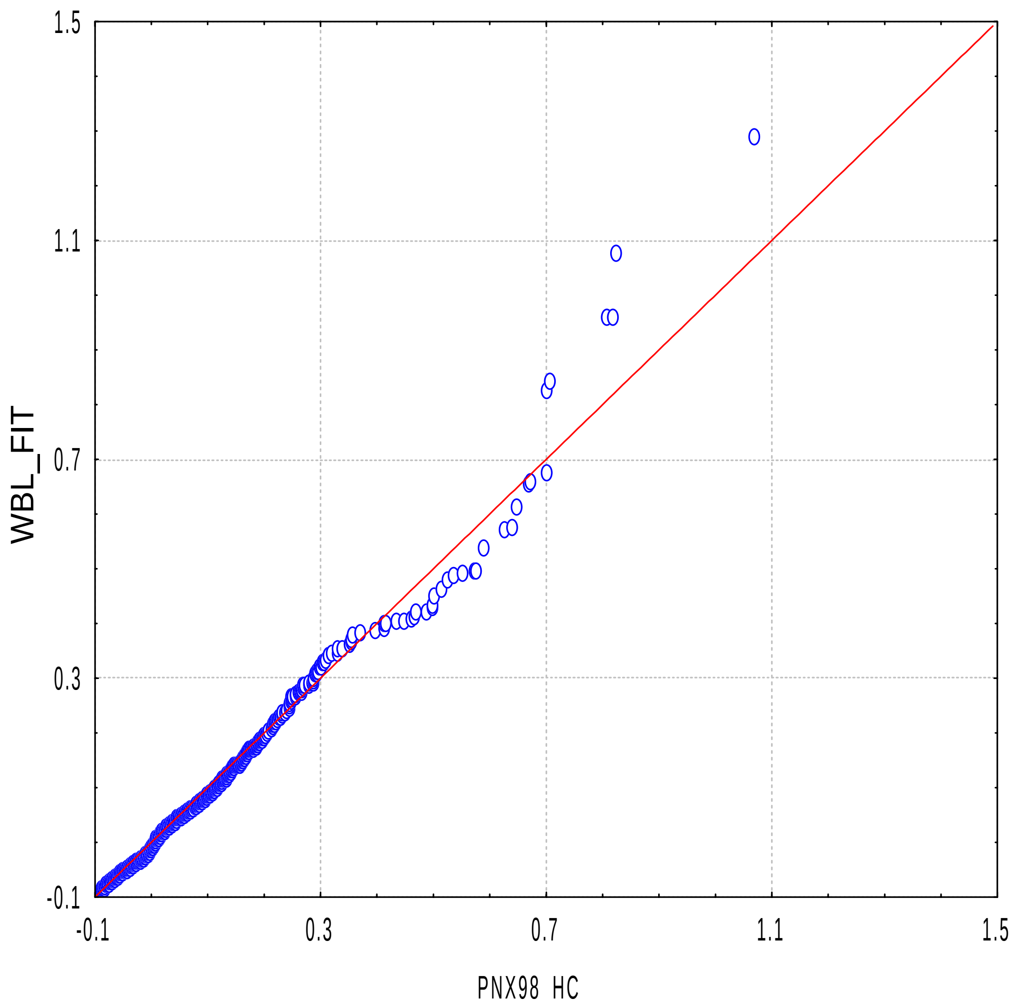


Figure D2: Quantile-quantile plot of Phoenix 98 HC data with y=x line. The fit has Weibull parameters of 0.0021 for scale, 0.34 for shape and 0.003 for location. The Laplace factor is 0.018.

A more systematic method of studying the distributions to look at noise is to plot the log of the distribution as a function of distance from the mean. Such plots for the negative portion of the curve are included as insets in the main distribution plots. These graphs give a measure of the width of the distribution (slope). A list of such slopes and the reciprocals of the slopes for several sets of data are given in Table D1.

The full data and noise curve has only been modeled and reported once before by Jimenez *et al*.[i] There the authors report a numerical convolution of a γ-distribution, which models the data, and a normal distribution, used to model the noise. We experimented with various noise distributions including Gaussian (normal), Cauchy, logistic, and student t. The distribution function coming closest to a realistic description of the noise was the Laplace. The Laplace distribution, which is a two-sided exponential, seems to model the noise more closely than the Gaussian.

Previously, we had modeled all on-road vehicle emissions data with the γ-distribution.[ii] The current study indicates, however, that the HC data are better modeled with the related Weibull distribution, which has an extra location parameter. For data distribution models we tried the β, X^2, exponential, extreme value, F, log-normal, Pareto and Rayleigh distribution functions before settling on γ for CO and NO (in agreement with Zhang *et al*.[ii]) and Weibull for HC.

The evidence of the excellent fit of the models (Laplace plus γ or Weibull) is in the quantile-quantile plot above (Figure D2). Such a plot is constructed by rank sorting the actual and fit data and plotting the nth value from each distribution against one another. Thus, the lowest actual HC measurement is plotted against the lowest value found in the fit, the second lowest measurement value against the second lowest fit value, and so on. The fact that the data points fall on a straight line with slope of 1 indicates that the model fits the data extremely well. The fit that uses a Weibull distribution function to model the overall distribution, rather than using a γ function, gives better correlation in the quantile-quantile plots for various HC databases.

Table D1: Log plot slopes and Laplace factors.

Data Set	Slope	Reciprocal of Slope	Laplace Scale Factor
Phoenix 99 CO	9.2	0.109	0.1
Phoenix 99 NO	169	0.0059	0.006
Phoenix 99 HC	41	0.0244	0.024
Phoenix 98 HC	60	0.0167	0.018
Denver 96 HC	38	0.0263	0.03
Denver 97 HC	42	0.0238	0.0205
Denver 99 HC	76	0.0132	0.0142
Denver 00 HC	71	0.0141	0.015
Chicago 98 HC	39	0.0256	0.026
Chicago 99 HC	81	0.0123	0.014

[i] Jimenez, J.L.; Koplow, M.D.; Nelson, D.D.; Zahniser, M.S.; Schmidt, S.E.; *J. Air & Waste Manage. Assoc.* **1999**, 49, 463.
[ii] Zhang, Y.; Bishop, G.A.; Stedman, D.H. *Environ. Sci. Technol*. **1994**, 28, 1370.

Table D1 also includes scale parameters for the Laplace distribution fit that best models the noise seen in the data. In order to arrive at this fit factor, each data set was fit to a combination of a distribution that describes the actual vehicle emissions profile and a distribution that models the noise in the measurements. For CO and NO these are three parameter fits; for HC there are four parameters. One of the parameters in fits for all three pollutants is the Laplace scale factor, which describes the width of the noise distribution. The other Laplace parameter (the mean) is set at zero since we expect the noise to be symmetric. The other two parameters in the CO and NO fits are the γ-distribution's shape and scale values. The shape describes how skewed the distribution is, while the scale sets the range for the distribution. The Weibull distribution used to model the HC data also has shape and scale parameters in addition to a location parameter, which shifts the distribution on the x-axis.

As can be seen from the table, the slope of the line in the log plots can be used to compare one distribution to another. The slope is in fact by definition the Laplace factor. A smaller slope, and thus a larger reciprocal, indicates a higher level of noise. In fact, the value of the reciprocal closely resembles that of the Laplace factor which best fits the data. This correlation is illustrated in Figure D3 below.

On the plot below, there is one point each for HC, NO and CO in Phoenix in 1999, as indicated on the graph, and seven other points representing other HC measurements. These other measurements were: Phoenix 98, Denver 96, Denver 97, Denver 99, Denver 00, Chicago 98, and Chicago 99. An interesting characteristic of this set of HC data is that they seem to fall into two distinct groups: one group with lower noise (factor $\approx$0.025, 250 ppm) and one with higher noise (factor $\approx$0.015, 150 ppm). This grouping of the data seems to indicate that the instrument has two modes of operation, one more noisy than the other.

We have developed a hypothesis as to the cause of this noise. Since the four IR channels in the instrument are detected separately, if the channels are not aligned perfectly movement of the instrument can cause the measured intensities of different wavelengths to drift in independent directions. This independent drift would cause noise in the HC data, for example, if the CO_2 channel moved one direction and the HC channel moved the other direction during the passage of a vehicle across the instrument location. Since all pollutants are ratioed to CO_2, an apparent increase in the CO_2 signal accompanied by an apparent decrease in the HC signal (due to instrument movement) as a vehicle passes by would result in a negative HC measurement. A source of movement of the instrument might be vibration caused by large vehicles that pass by and shake the roadbed or buffet the instrument with a wind gust. Though the FEAT instrument is stable relative to the ground, one mode of motion is available in the current design. This is the swinging of the instrument box relative to its legs, which remain stationary. We plan to correct for this by adding support to the structure.

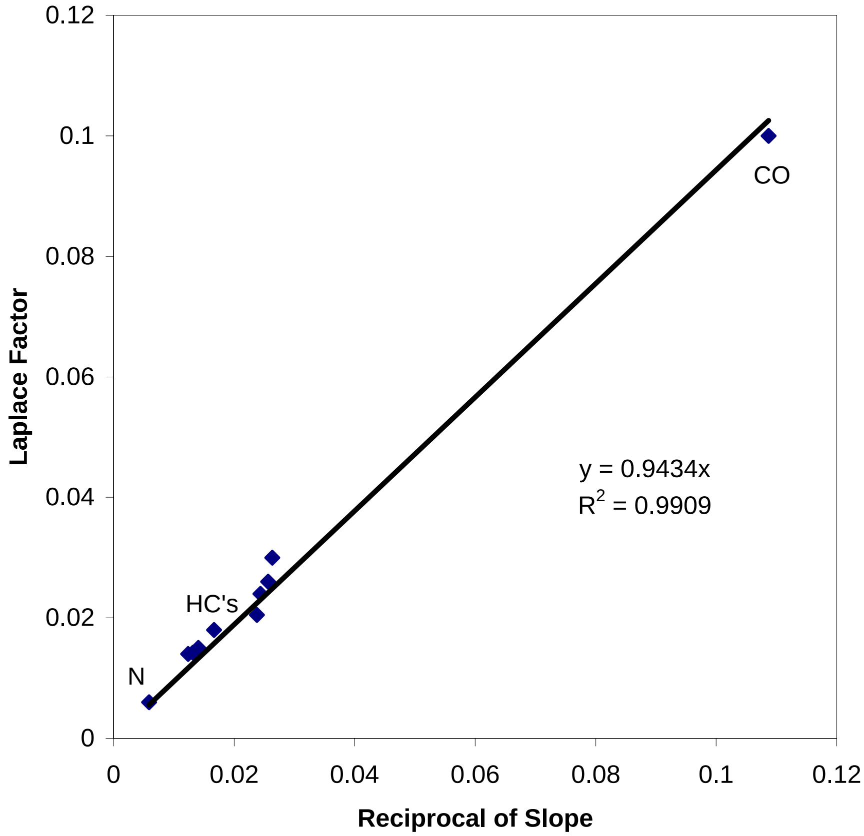


Figure D2: Plot of the fit Laplace factor versus the reciprocal of the negative log plot. Included are the three measured pollutants in Phoenix 1999 and additional HC values from other sites and times listed in the text above.

APPENDIX E: 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 F: 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 G: Field Calibration Record.

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

APPENDIX H: Car and Truck Distribution Analysis

During the normal course of data analysis of the 1999 Phoenix remote sensing data we plot emissions as a function of vehicle specific power (VSP). These plots are contained in the main body of the report in Figure 5. The shape of the plots for CO and HC looked very similar to plots contained in previous reports for other cities. The plot for ppm NO versus VSP had a shape which deviated markedly; it was flatter across the VSP range, from the location used in the previous year. Concern was raised that perhaps the new ramp used in 1999 or the fact that two different monitoring sites at the new ramp may have contributed to flatten the plot.

The two monitoring locations (site 1 and site 2) where located in the bottom third of the ramp (site 1, Nov. 15 and Nov. 16) and the top third of the ramp (site 2, Nov. 17 - Nov. 19). The basic driving characteristics varied with site one have slightly lower speeds (mean speeds of 32.5 mph and 35.5 mph for site 1 and site 2) and much lower acceleration rates (mean accelerations of 0.34 mph/s and 1.58 mph/s for site 1 and site 2). The observed driving characteristics at the two sites concurred with the measured speed and acceleration values. Site 2 being much closer to the entrance to the expressway, many vehicles were accelerating to match speeds with the merging traffic.

One hypothesis which was put forward to explain the observation was that the car/truck ratio was different between site 1 and site 2. Partial support for this explanation was based on the fact that the successful measurement rate was higher at site 2 than site 1. With lower loads at site 1 it could be argued that smaller engine passenger cars were more likely to be underrepresented in the site 1 data and thus the car to truck ratio would look different at site 1.

To test this hypothesis we set about to characterize cars and trucks in the Phoenix database. Ideally, one would like to differentiate between cars and trucks based on their federal emissions certification classification. This is not directly possible since the best information we have to accomplish this task is contained in the vehicle identification numbers (VIN) for 1983 and newer models and it does not directly indicate certification standards. Using data provided by the National Insurance Crime Bureau (NICB) it is possible to decipher positions 1 through 3 of each 1983 and newer vehicle VIN and assign a car or truck designation. Unfortunately, the NICB publishes these data to help with vehicle thefts and registration fraud and not for emissions research.   As such, this designation, which we have defined, is a subjective one. Vehicles identified by the NICB as passenger cars or light-duty trucks have been designated as such in our classification. We have also chosen to include vehicles identified as MPV's, vans and SUV's as ‘trucks’ whether they were listed in the truck section of the NICB passenger vehicle identification manual or not. Incomplete chassis were categorized based on make. For example, Ford and Chevy incomplete chassis were ascribed to the ‘truck’ category while Cadillac incomplete chassis (limousines) were defined as cars. Pitfalls in this approach are that a few vans and incomplete chassis are misassigned. We are also aware that while all of Subaru's vehicles are listed as passenger cars in the NICB book, many of these vehicles were certified to truck emission standards and the only way to determine the certification standard is to examine the vehicle's emission sticker located under the hood.

Using the above definition vehicle VIN from Phoenix, Chicago, Denver and Riverside were decoded and vehicle type classified. This process labeled 97% of the vehicles in Phoenix, 99% in Chicago, 96.25% in Denver and 95.4% in Riverside. The majority of vehicles which are not decoded are those which were manufactured prior to 1983 and therefore the Riverside database, which has the oldest fleet, has the largest number of unidentified vehicles.

Using the car and truck classifications there are several interesting qualitative observations that one can make. At all of the CRC cities the fleet ages of cars are older than the trucks by about 0.75 model years. Fleet average g/kg emissions, driven by the age, are therefore higher for cars than trucks. When the ages are normalized by model year the trucks have higher g/kg emissions than the cars. The car to truck ratio varies from 2:1 in Chicago to 1:1 in all of the remaining cities.

Now pertaining to the original question as to the shape of the emissions versus VSP graphs, we find in Phoenix that the car to truck ratio changes from 7% less cars than trucks at site 1 to 10% more cars than trucks at site 2. So the emissions measurement capture rate has resulted in fewer cars being measured at the lower loaded site 1. Taking this into account though does not explain the observed shape of the NO emissions versus VSP graph.

Figure H1 shows the results of plotting the number of cars or trucks against VSP and shows a quite remarkable result. At two of the locations, Phoenix and Riverside, there is a very large VSP difference observed between the cars and trucks. This difference is further expanded at Phoenix's site 2 where the largest speeds and accelerations are observed. One variable which may account for the observed differences is the level of congestion at the various sites. Denver and Chicago have the highest levels of congestion with vehicles at both sites most often following closely behind another vehicle. The sites in Riverside and Phoenix, on the other hand, have low traffic volumes which result in a free and unconstrained flow of traffic. The observed car and truck differences are seen to be nearly identical at the Riverside and Phoenix site 1 locations. As the congestion increases, the ability for vehicles to exhibit marked differences in driving behavior diminishes to the point where all pass the measurement site under similar speeds and accelerations as seen in Denver.

The differences in driving behavior observed in Phoenix and Riverside lead to large changes in the car to truck ratio across the VSP plots. For similar age distributions this will result in comparable changes in emissions than those observed in Chicago and Denver since the age normalized emissions are different for cars and trucks. These observed on-road driving differences have important implications for current computer models, which have emissions derived from dynamometer studies. Dynamometer derived emission factors are liable to over estimate on-road emissions because of the dynamometer requirement that trucks follow the same speed/time trace as cars when on-road trucks have now been found to behave quite differently from cars.

Recent analyses by Slott and ourselves indicate that age distributions are not constant across the VSP curves either. This interesting and unexpected observation deserves further investigation and may account for the unexpected NO versus VSP data.

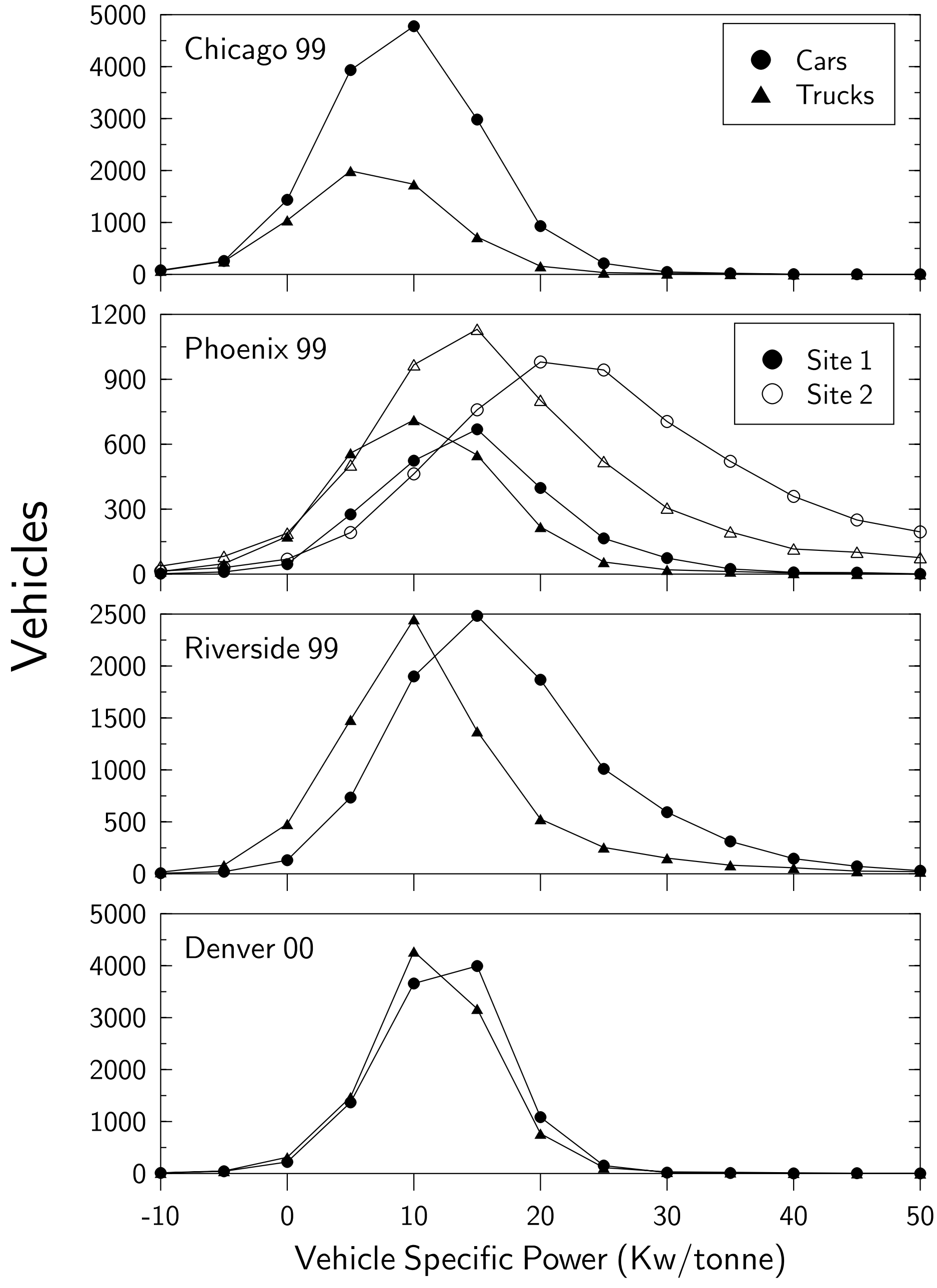


Figure H1. Vehicle distribution as a function of VSP group at four CRC measurement sites.